Project title:	Optimising greenhouse environment and energy inputs for sweet pepper production in the UK – a commercial demonstration of the use of thermal screens and advanced climate control. (Extension to PC 227)	
Project number:	PC 227a	
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Annual report:	Final report, January 2007	
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Date project commenced:	December 2004	
Date completion due:	January 2007	
Keywords:	Sweet pepper, temperature integration, thermal screens, humidity, energy efficiency, Fusarium, carbon dioxide, boiler management, heat store, insulation.	

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Headline

Investment in energy saving technology and constant attention to climate control set points delivered an energy saving of 24% and a payback on investment in less than 18 months on a sweet pepper nursery in the Lee Valley.

Background and expected deliverables

Escalating energy costs, the Climate Change Levy (CCL), and increasing pressure to reduce the environmental impact of energy use has led to a sustained interest in energy saving technologies for producers of protected crops. The HDC has funded over 20 energy saving projects for the protected cropping sector over the last five years. This project built on knowledge gained from PC 227 and trials with other crops to demonstrate the savings that can be achieved with sweet peppers.

Specific objectives of the project were:

1. To establish a range of environmental control set points that fully exploit the energy saving potential of temperature integration whilst optimising crop response.
2. To establish the level of best practice energy consumption could realistically be achieved on a commercial pepper nursery.
3. To quantify what effect if any these energy saving techniques have on crop yield, quality, scheduling and disease levels.
4. To stimulate the commercial uptake of advanced climate control techniques and thermal screens in the pepper sector by communicating the results of the work to growers in the UK.

Results

Note, where appropriate this section of the report makes reference to the results from PC 227 (2005). For detailed information about the results from 2005 the Final Report for PC 227 (July 2006) should be consulted.

Summary of results:

- Moveable (permanent) screens saved an additional 90 kWh/m^2 p.a. of gas compared to temporary screens.
- Refinement of thermal screen control set points increased the energy saving achieved by 61 kWh/m^2 p.a.
- Insulating the heat stores gave an energy saving of 26kWh/m^2 from Week 20 - 35 without affecting the availability of CO_2.

- The total amount of energy used to grow a crop of sweet peppers in a greenhouse built in 2001 with a moveable thermal screen between Weeks 51 - 44 inclusive was 515 kWh/m^2.
- Temperature integration can be successfully applied to a sweet pepper crop.

Temperature integration delivered energy savings of 24 kWh/m^2 p.a. in 2005.

Research method

The project was undertaken at Valley Grown Nursery, Nazeing, Essex. Temperature integration trials were carried out in a 4,000 m^2 greenhouse built in 1999 (Block 3). Moveable (permanent) thermal screens, using non-voided Ludvig Svensson SLS10 Ultra Plus material, were installed in late 2004. Blocks 4 - 6 were used as the control. These blocks covered an area of 15,444 m^2 and were built in 2001 with the same design of moveable screens as used in Block 3. The whole site was heated with a low pressure hot water system and mains gas fired boiler, and controlled by a Priva Integro v723 computer.

Historical energy, greenhouse environment and crop data for the whole nursery were also used in the comparisons.

Results

Thermal screens

Analysis of historical data in combination with data collected throughout PC 227 and PC 227a allowed the energy saving of the moveable screen over and above that from the temporary screen to be quantified with different screen control strategies.

Up to and including 2004

The moveable screen was closed whenever the outside temperature was below 8°C AND light levels were less than 175 W/m^2. With this strategy moveable screens delivered an energy saving of 29 kWh/m^2 over that achieved with fixed screens.

2005

Daytime - The screen was closed whenever a heating pipe temperature greater than 60°C was required to maintain the required greenhouse temperature. The screen was opened, regardless of the pipe temperature, whenever the light level was above 175 W/m^2.

Night-time - The screen was only opened if constantly gapped over 5% and the vents were open to achieve satisfactory humidity control.

With this strategy moveable screens delivered an energy saving of 52 kWh/m^2 compared to fixed screens. The additional saving over and above the 2004 screen control strategy was 23 kWh/m^2. There was a slight reduction in yield during the early part of the year in the compartment with moveable screens compared to the compartments with fixed screens. This was recovered by Week 26 as the screens delivered more reliable temperature control and therefore better control over plant development.

2006

Daytime - During the day the screen was closed whenever a heating pipe temperature greater than 50°C was required to maintain the required greenhouse temperature. A higher pipe temperature threshold of 60°C was chosen for a period of three hours around mid-day (typically 11:30 - 14:30) to ensure a period of high plant activity every day.

The screen was opened, regardless of the pipe temperature, whenever the light level was above 175 W/m^2.

Night-time - The same strategy was used as was employed in 2005.

With this strategy moveable screens delivered an energy saving of 90 kWh/m^2 more than achieved with fixed screens. This was a 61 kWh/m^2 improvement over that achieved in 2004.

Table 1 below details the moveable screen control set points applied early in 2006. The temperature difference set points were gradually increased as the crop developed and humidity control became more difficult.

Table 1 – Thermal screen control set points

Description	**Time period**	**Value**	**Range**
Inside – outside temperature difference	10:30 - 14:00	9°C	n.a.
	14:00 - 10:30	7°C	n.a.
Light influence on temperature difference	All the time	9°C increase	0 – 200 W/m^2
Wind influence on temperature difference	All the time	3°C decrease	3 – 6 m/s
Radiation limit	All the time	175W	n.a.

Humidity control

The basic humidity control strategy sequence was to gap the screen first, then open the vents and finally increase the minimum heating pipe temperature. In practice, to achieve stable control, vent opening had to start before the screen reached the maximum gap allowed, and the minimum pipe temperature increase had to be initiated at the same time that the vents started to open. The intention was to only open the vents once the screen was gapped by at least 5%.

Table 2 – Screen humidity gap set points

Description	**Time period**	**Value**	**Range**
Humidity gap	Daytime	10%	3.5 – 2.8 g/m^3
Humidity gap	Night-time	10%	2.6 – 2.0 g/m^3
Outside temperature influence on gap size	All the time	75%	3 – 10ºC

The gap size required to achieve satisfactory humidity control was less when the ambient temperature was colder. This was implemented automatically using an outside temperature influence on screen gap size as described in the last row of the table.

Figure 1 – Ventilation temperature humidity set points

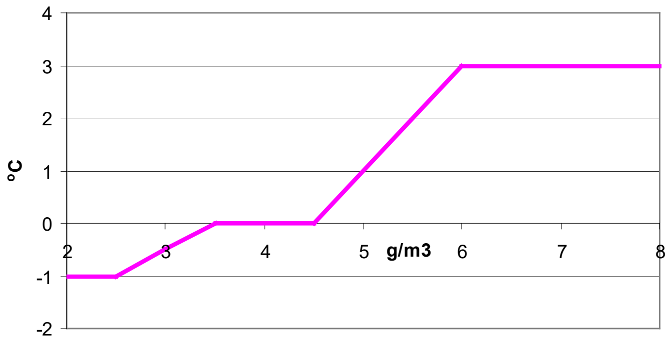
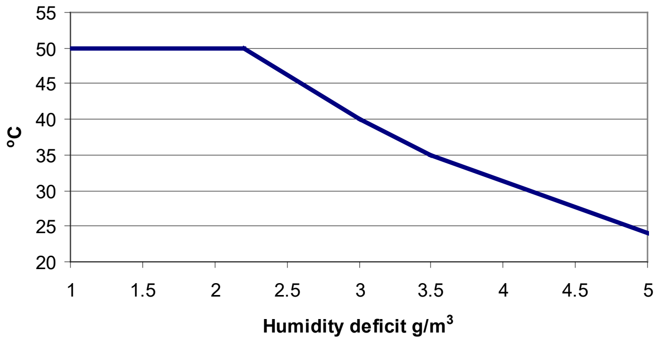


Figure 2 – Minimum pipe temperature humidity set points

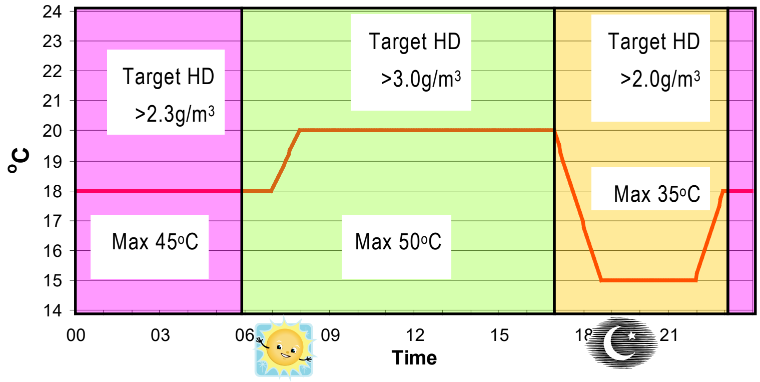


The humidity influences shown in Figures 1 and 2 above are typical of those applied during the daytime when the target humidity deficit was 3.0 - 3.5 g/m^3.

The increase in ventilation temperature when the HD was >4.5 g/m^3 was part of the temperature integration strategy.

Figure 3 below shows the target HD at different times of the day with the highest minimum pipe temperature that was allowed during each period.

Figure 3 – Target humidity deficit & minimum pipe temperature



The minimum pipe temperature was allowed to increase to 60°C during prolonged periods of poor daytime humidity. Very little minimum pipe heat was allowed during the pre-night period to ensure that the pre-night temperature was consistently achieved.

Temperature integration

2005

To allow energy savings to be achieved even when solar gain was low the greenhouse heating temperature was increased during the night when the screens were closed and heat loss was low. This allowed the temperature during the day to be decreased when the screens were open and heat loss was high; thereby saving energy. Humidity control was delivered using the approach described above.

This strategy resulted in an energy saving of 24 kWh/m^2. However, a sudden drop in light levels combined with a high fruit load and low daytime temperatures caused the head of the crop to become weak and no fruit were set for several weeks. This led to an overall yield reduction of 4.4%.

2006

A more traditional approach to TI was adopted. The ventilation temperature was increased whenever the HD was above 4.5 g/m^3 to take maximum benefit of solar gain. The maximum ventilation temperature allowed was 26°C. However, this proved to be difficult to control and deliver a stable greenhouse climate so it was reduced to 25°C.

TI was only allowed to reduce the heating temperature from immediately after the pre-night period to one hour before sunrise. The minimum heating temperature allowed was 16°C and the integrating period was three days.

Although there was no corresponding yield penalty in 2006 the energy savings were minimal compared with the control treatments. This was mainly because a TI ventilation strategy had also been adopted on the whole nursery leaving little opportunity to demonstrate any further advantages of the principles of TI in Block 3.

Heat stores & CO_2

The heat stores at Valley Grown Nursery were insulated in April 2006 with 50mm of Rockwool™ type insulation clad with aluminium sheet. As in previous years heat destruction in the glasshouse was allowed during the summer months to ensure that a satisfactory level of CO_2 could be generated for enrichment. It was not possible to make a valid yield comparison with previous years. However, the CO_2 levels achieved in 2006 were similar to those achieved in 2005 so no yield penalty would have been expected. Energy saving between Weeks 20 - 35 as a result of heat store insulation was 26 kWh/m^2. Although it was not possible to determine the whole season energy saving it was estimated to be at least 40 kWh/m^2.

The amount of heat destroyed to ensure adequate CO_2 availability was equal to 52 kWh/m^2 of gas. This was determined by calculating the difference between the energy used in the heat destroying blocks with Block 3 where heat was not allowed to be destroyed.

This also showed that heat destruction can increase night-time greenhouse temperatures during the summer by as much as 3°C. This at a time when it is often difficult to achieve sufficiently low temperatures. Although this was not a focus of this project evidence suggested that there was an improvement in yield in Block 3 resulting from better temperature control during the summer. It might be concluded therefore that heat destruction can be detrimental to crop yield in some conditions.

Best practice energy use

Best practice techniques to achieve lowest energy use are currently considered to include:

- Modern, well maintained Venlo type greenhouse.
- State of the art climate control computer.
- Automatic oxygen trim controlled boiler.
- Insulated heat storage.

- Moveable thermal screen.
- Continued attention to detail on climate control computer set points.
- Temperature integration.

Although TI did not achieve energy savings compared to the rest of the nursery in 2006 much of its underlying principles were, in fact, being adopted wholesale on the site. It is therefore considered to form part of best practice energy use.

Energy use in the most modern greenhouse block on the nursery (built 2001) was 515 kWh/m^2 (Weeks 51 - 44 inclusive). If heat had not been destroyed in this block energy use would have been 463 kWh/m^2. This compares favourably with the 2001 Dutch energy use targets for sweet pepper growers of 446 kWh/m^2. Dutch targets for 2006 have fallen to 410 kWh/m^2 so further improvement needs to be made to reach this level of performance.

Disease monitoring

A major concern amongst growers of protected crops when applying any energy saving measure is the effect on humidity and therefore disease levels. Detailed monitoring carried out by Dr Tim O'Neill of ADAS Consulting Ltd showed that the only disease of any significance on the nursery was *Fusarium oxysporum*. TI had no significant impact on disease levels in 2005. In 2006 the incidence of stem lesions by Week 27 in Block 3 (TI) was 7.7% compared to 4.2% in Blocks 4 - 6. Analysis of humidity data for this period showed no difference between Blocks. This suggests that the higher disease incidence could not be attributed to TI. Further work on the biology and control of Fusarium stem and fruit rot of pepper is continuing in a separate project (PC 260).

Financial benefits for growers

Thermal screens

The installation of a moveable thermal screen was shown to give energy savings of 29 – 90 kWh/m^2 compared to a fixed screen. The saving achieved was highly dependent on the screen control strategy applied.

The additional capital saving from avoiding the annual installation cost of a temporary screen also has to be added; this is estimated to be £0.70/m^2. The table below shows the total value of these savings per m^2 of greenhouse area for a range of gas prices.

Table 3 – Financial benefit of moveable screens

Gas price p/kWh	**Saving - £/m^2**
1.0	0.99 – 1.60
1.5	1.14 – 2.05
2.0	1.28 – 2.50
2.5	1.43 – 2.95
3.0	1.57 – 3.40

The use of moveable screens results in an early season yield decrease. The financial penalty associated with this is dependent on the nursery's marketing agreement. However, a price differential of £0.40/kg (early season minus mid season price) is considered to be typical. If this applies to a nursery's marketing agreement £0.40/m^2 should be subtracted from the saving figure in Table 3 above.

The capital cost for a moveable screen is currently in the range of £4/m^2 - £5/m^2. Based on a conservative energy saving and a gas price of 1.5 p/kWh, the simple payback on the screen investment is around three years. This increases to four years when the early season yield reduction is taken into account.

In some cases a major upgrade of the greenhouse climate control computer may also be required to facilitate the efficient operation of the screen. This brings other benefits unrelated to the screen such as reduced energy use and improved cropping through better greenhouse climate control. Its costs have not been included as part of the payback calculations associated with the screen in this study.

Climate control computers

In addition to improved control of the greenhouse environment, modern climate control computers have many features to help save energy. This was demonstrated in the additional energy saving from optimised screen control of 61 kWh/m^2. At a gas price of 1.5 p/kWh this is worth £8,500 per Ha. Getting the most from a climate control computer requires a good understanding of the dynamics of greenhouse climate control and a working knowledge of the application of the computer software.

The cost of upgrading or replacing an existing climate control computer is between £5,000 and £15,000 per Ha. However, even at the higher cost the saving delivered through improved screen control alone would pay back this investment in 2 - 3 years.

Insulated heat stores

Insulating the heat stores at Valley Grown Nursery was shown to give an energy saving of 26 kWh/m^2 between Weeks 20 - 35. It is estimated that the whole season saving would have been at least 40 kWh/m^2.

The heat stores on the nursery comprised three large tanks and one small horizontally oriented tank with a total capacity of 750 m^3. The total energy saving for the nursery from insulating the heat stores between Weeks 20 - 35 was 728,000 kWh. At a gas price of 1.5 p/kWh this is worth £11,000 p.a. The cost of insulating the heat stores was £27,000 giving a payback within 2.5 years.

Conclusions

Movable thermal screens versus fixed screens

- Moveable screens saved an additional 29 – 90 kWh/m^2 of gas over a fixed screen installation depending on the control strategy adopted.
- Optimising moveable screen control set points can save an additional 61 kWh/m^2 compared to a simple fixed outside temperature control strategy.
- A yield reduction of 1 kg/m^2 can be caused during the early part of the season. However, this is recovered by mid season due to improved control over greenhouse temperature.
- The payback on installing a moveable screen is 3 - 4 years.

Temperature integration

- Temperature integration can be successfully applied to sweet peppers. This is endorsed by the fact that the host nursery adopted many of the principles on the whole nursery in 2006.
- Temperature integration gave energy savings of 24 kWh/m^2 (6%) p.a. in 2005.
- An increase in *Fusarium oxysporum* incidence was recorded in 2006. However, it was not caused by TI.

Insulated heat stores

- The energy saving delivered between Week 20 and Week 35 was 26 kWh/m^2. The saving over a complete cropping year is estimated to be over 40 kWh/m^2.
- There was no impact on the CO_2 levels achieved in the greenhouse.
- The destruction of heat in a greenhouse affects the ability to achieve the required temperature during the summer. Indications are that this has a negative impact on crop management and therefore yield.
- Heat destruction to increase CO_2 availability accounted for 52 kWh/m^2 of gas consumption.

Modern climate control computer

- These are a vital component in delivering the maximum benefit from almost any energy saving investment.
- Continued attention to detail and fine tuning of set points will deliver significant energy savings and ensure the best possible growing environment.

Best practice energy use

- Total gas use in a greenhouse built in 2001 with moveable thermal screens was
  515 kWh/m^2 (Weeks 51 - 44 inclusive).

Action points for growers

Growers should consider the following actions:

- Investigate the feasibility and cost of installing moveable thermal screens.
- Investigate the feasibility and cost of insulating heat stores.
- Invest in staff training to take full benefit of their existing climate control computer.
- Compare the features and ease of use of their existing climate control computer with those of new or upgraded systems.
- Gradually implement the principles of temperature integration to gain confidence in its application.

Science Section

Introduction and background

A wide range of cost and consumer driven environmental demands continue to require significant reductions in energy use in protected horticulture.

- In spite of significant reductions in the cost of heating fuel in the second half of 2006 energy continues to be a large cost for many growers of protected crops.
- The Climate Change Levy Discount Scheme allows growers to claim an 80% reduction in the Climate Change Levy (CCL). However, growers must achieve a 12% reduction in energy use over the period 2004 to 2010 to receive the discount.
- Consumer awareness of the link between carbon emissions and global warming is high. So reduced/low carbon production methods will be a vital marketing tool in the near future.

Industry statistics indicate that there are around 85 Ha of heated sweet pepper production in the UK. Taking this production area and assuming that 75% of it is heated by gas, the impact of securing and maintaining an 80% CCL rebate is estimated to be worth over £460,000 per annum to the pepper sector. Assuming that the same 75% of growers achieve the 12% reduction in energy use this is worth a further £1m per annum.

HDC work in other protected cropping sectors showed that a number of ‘state of the art’ techniques are capable of providing energy and cost savings. The most promising techniques are temperature integration and thermal screens. PC 227 (2005) was carried out to demonstrate the risks and benefits of applying these technologies to sweet pepper production. Significant energy savings were delivered by thermal screens. Although temperature integration also gave energy savings there was a yield penalty. Despite this, the experience gained by the project team made them confident that temperature integration could be applied without compromising yield. The project was therefore extended to cover a second year (2006) to demonstrate that this could be achieved.

The science section of this report focuses on the second year of trials (2006). A complete set of results relating to the first year are given in the annual report for PC 227 (2005).

Summary of PC 227 (2005) results

Thermal screen

The energy consumption of a greenhouse compartment equipped with a fixed screen in 2004 was compared with 2005 when a moveable thermal screen was installed. Taking account of different weather conditions the results showed that in 2005 the moveable thermal screen delivered an energy saving of 52 kWh/m^2 over that achieved by the fixed screen.

In addition, the energy consumption of a second greenhouse compartment already equipped with a moveable thermal screen in 2004 was compared with 2005 when control set points were more finely tuned. The results showed that an additional saving of 25 kWh/m^2 was possible through a greater focus on thermal screen set points.

There was a tendency for the crop grown with moveable screens to yield less than one grown with temporary screens up to Week 22. At one point this difference was as much as 1 kg/m^2. However, moveable screens allowed more reliable climate control and therefore better control of plant development. This helped the yield to recover and from Week 26 onwards the total yield was almost identical.

The energy consumption (gas only) of a greenhouse growing sweet peppers with a moveable thermal screen (no TI) was shown to be 565 kWh/m^2 between Weeks 51 - 41 inclusive.

The thermal screen control strategy allowed it to open during daylight hours whenever a heating pipe temperature of 60°C or less could maintain the required greenhouse temperature. This was considered to be a conservative approach and there was no doubt that additional energy savings could be achieved.

Temperature integration

The conventional approach to TI is to accumulate temperature credits during the daytime using free heat from solar gain, and compensating for this with a lower temperature during the night when heating costs are higher. This delivers the correct required 24-hour average at lowest energy cost.

With a moveable thermal screen the energy saving logic is, in many conditions, turned on its head. The night-time heat loss with the screen closed maybe in fact, lower than that experienced during the day when the screen is open. Therefore it may pay to run temperatures higher at night than during the day. This alternative approach to TI was used in 2005 and delivered an energy saving of 24 kWh/m^2 (6%).

However, this strategy contributed to a period of poor crop development when a significant and prolonged drop in light levels occurred. What transpired in the greenhouse was several days of low average daytime temperature combined with low light levels. Although the crop did not suffer any long term damage, several weeks of minimal growth caused a 4.4% reduction in yield.

Despite this setback and using the experience gained, the project team were confident TI could be successfully applied to a sweet pepper crop without any yield penalty.

Disease

The most common disease affecting crops on the nursery in 2005 was a Fusarium fruit and stem rot caused by *F. oxysporum*. This was the first documented case of the disease in the UK. The disease had previously been reported in the Netherlands, and very probably has occurred in the UK for at least three years. This resulted in a new HDC project (PC 232a) to investigate its biology and control.

Detailed recording of disease incidence showed that there was no significant difference in disease levels between the TI treatment and a crop grown using a conventional heating strategy.

Objectives

The overall objectives of this project were to obtain independent information on the performance of a sweet pepper crop and the energy savings that could be achieved when growing under moveable thermal screens whilst using dynamic climate control.

The original objectives of PC 227 remained. These were:

1. To establish (and successfully apply) ranges of environmental control set points that would fully exploit the energy saving potential of temperature integrating control strategies whilst optimising crop response.
2. To establish the lowest energy consumption that could be realistically achieved on a commercial pepper nursery using screens and advanced control strategies.
3. To quantify the effect of these techniques, if any, on crop yield, disease, quality and scheduling.
4. To stimulate commercial uptake of advanced climate control techniques and thermal screens in the pepper sector by communicating the results of the work to growers in the UK.

The specific additional objectives of PC 227a were:

1. To apply the knowledge gained during Year 1 of the project and to optimise crop performance especially in relation to temperature integration.
2. To continue to develop the thermal screen operating strategy to optimise energy savings and crop performance.

Research method

Overview of location facilities and cropping

Greenhouse

The project was undertaken at Valley Grown Nursery, Nazeing, Essex as was the preceding trial PC 227 (2005).

The layout of the nursery and the size of each greenhouse block are shown in Figure 4 below. Blocks 4 - 6 included a moveable thermal screen (Ludvig Svensson SLS10 Ultra Plus) which were installed when they were built. Blocks 1 - 3 used a temporary screen until the start of the 2004/05 cropping season when a moveable screen of the same type as the one used in Blocks 4 - 6 was installed.

The temperature integration part of the project took place in Block 3.

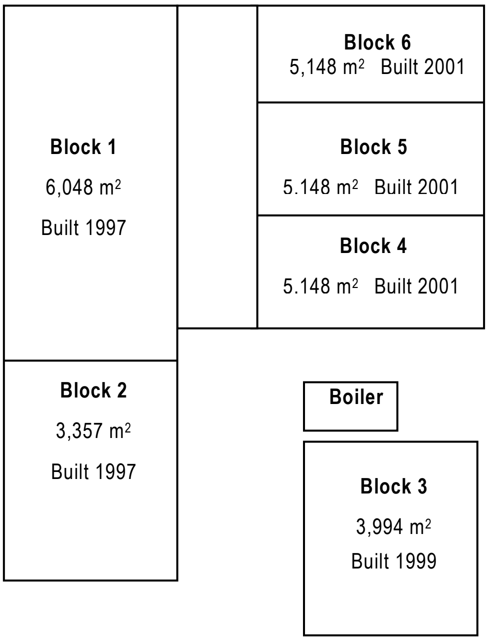


Figure 4 – Valley Grown Nursery site layout

Environmental control

Each greenhouse block had its own independent heating and ventilation system and a separate measuring box with wet and dry bulb sensors. The climate control computer was a Priva Integro version 723.

Crop

In 2005 all the plants were grown on the floor in mineral wool growing media. Hanging gutters were subsequently installed on the whole nursery ready for the 05/06 season.

Greenhouse Block 3 was the focus of the project. The variety Special was grown in Block 3 and Blocks 4 - 6 which served as a direct comparison for the trial.

- Block 3 – planted on 8th December 2005, removed on 9th November 2006.
- Blocks 4 - 6 – planted on 30th November 2005, removed on 5th November 2006.

Data collection

Greenhouse environment and weather data

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

Data collected and analysed included:

Greenhouse set points and equipment operation

- Set points – heating & ventilation temperature.
- Heating pipe temperature.
- Vent position.
- Screen position.

Greenhouse environment

- Temperature.
- Humidity deficit.
- CO_2.

Temperature and humidity deficit were measured at two positions:

1. 30 cm below the top of the crop. These measurements were used by the climate control computer to control the heating, ventilation and screens.
2. 30 cm above the growing media. These measurements were used to provide more information on conditions experienced by the crop.

Weather data

- Temperature.

- Solar radiation.

Energy

A heat meter was installed in the final heating loop of Block 3 and measured the amount of heat energy delivered (as hot water). The heat meter was connected to the climate control computer which allowed energy data to be automatically recorded and downloaded using the same system used to collect environment and weather data. The site gas meter was also read on a weekly basis.

Crop data collected

Nursery staff carried out weekly crop recording based on a sample of 20 plants in each greenhouse block.

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

Historical data

Comprehensive data from 2002 onwards was available from the nursery. This included:

- Gas consumption – for the whole site.
- Average daily greenhouse temperature – in each block.
- Average daily pipe temperature – in each block.
- Weather conditions.

Test protocol

Comparison with previous years

Data available allowed the amount of gas used by each greenhouse compartment to be calculated from 2002 onwards. In addition, degree day weather correction enabled comparison of different years' energy use by allowing for variations in greenhouse temperature and weather conditions.

Temperature integration

Temperature integration control methods were applied in greenhouse Block 3. The energy saving achieved was assessed as described in section 8.3.1 above. The yield was compared with Blocks 4 - 6, where the same variety was grown.

In addition the performance of the greenhouse blocks was compared with data from previous years.

Additional areas of work

Due to continued investment in energy saving by Valley Grown Nursery Ltd it was possible to assess the impact of insulating the heat stores on energy use and crop yield / management.

Prior to April 2006 the heat stores were not insulated. Historically this has been common practice on edible crop nurseries. The justification was that the heat loss from un-insulated tanks allowed more gas to be burnt and therefore more CO_2 was available for CO_2 enrichment. However, this is wasteful and with significantly higher gas prices in 2006 the decision was taken to insulate them with 50mm of mineral wool insulation and aluminium cladding.

Insulating the heat stores has two significant knock-on effects on the greenhouse environment and boiler operation:

1. To maintain the same CO_2 levels in the summer more heat had to be destroyed overnight in the greenhouse.
2. The heat store would fill more quickly therefore heat store and boiler management would become more important.

The data collected for the thermal screen and TI components of this project allowed the energy saving delivered by insulating the heat stores to be calculated. In addition, heat destruction was not allowed in Block 3 which allowed the true energy cost of CO_2 to be determined.

Results

Climate control strategy

The climate control set points described in this report were derived specifically for the project and were periodically adjusted to adapt to prevailing conditions. As such it should not be assumed that they will deliver a satisfactory level of control in any other greenhouse. They may however serve as a useful starting point for any grower wishing to adopt this approach.

Thermal screen control

Summary of 2005 strategy

The thermal screen control strategy was tested in Block 3 and applied to the remainder of the nursery once fine tuned and approved by Gary Taylor (VGN Managing Director). This typically introduced delays of one week whenever a significant change in strategy occurred.

In 2005 the screens were controlled in a conservative manner to balance energy savings with crop performance (light loss). The set points were designed to open the screen when the pipe temperature required, maintaining the greenhouse temperature, was less than 60°C during any daylight hour. An overriding radiation limit was also set to open the screens whenever the light level exceeded 175 W/m^2 irrespective of the outside temperature.

2006 strategy

Week 49 (2005) to Week 5 (2006)

The thermal screen was closed 24 hours a day for one week following planting in Week 49 (8th Dec) to minimise plant stress. From Week 51 onwards the screen control set points were adjusted so that the screens only opened during the daytime when:

1. Between 10:30 – 14:00, less than 60°C pipe temperature was required to maintain the greenhouse temperature.
2. All other daylight hours, less than 50°C pipe temperature was required to maintain the greenhouse temperature.

Point 1 was to ensure that the plants were guaranteed an active environment for at least two hours per day. However, it also ensured that excessive plant stress due to high pipe temperatures (>60°C) was also avoided.

Point 2 was to maximise energy savings when light levels were expected to be low. An overriding radiation limit was also set. This allowed the screens to open whenever the light level was above 175 W/m^2 irrespective of the outside temperature and therefore the pipe temperature. It was extremely rare for this set point to open the screens as they tended to open before the light level exceeded 175 W/m^2.

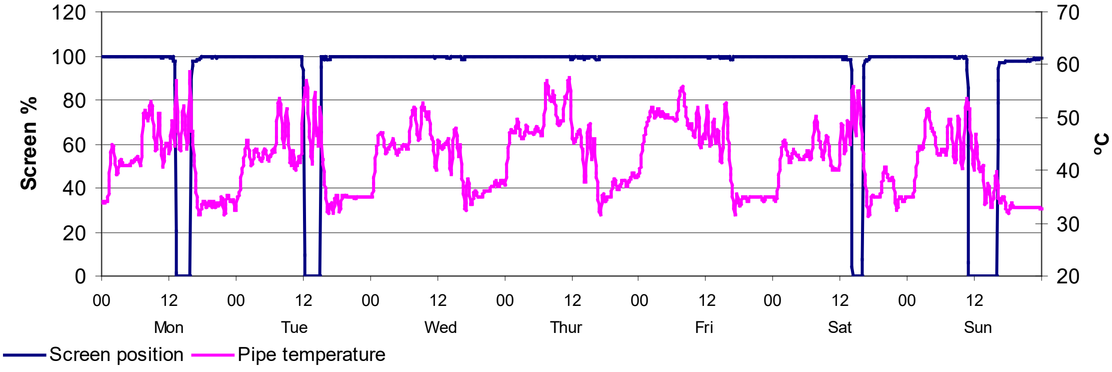
The screen was closed overnight as long as satisfactory humidity control could be achieved. If conditions were such that the screen had to be constantly gapped with venting above it to control humidity, set points were adjusted so that the screen opened completely. Table 4 below gives an overview of the set points that were applied.

Table 4 – Thermal screen control set points

Description	Time period	Value	Range
Inside – outside temperature difference	10:30 - 14:00	9°C	n.a.
	14:00 - 10:30	7°C	n.a.
Light influence on temperature difference	All the time	9°C increase	0 – 200 W/m^2
Wind influence on temperature difference	All the time	3°C decrease	0 – 6 m/s
Radiation limit	All the time	175 W	n.a.

Figure 5 below shows the screen operation and associated pipe temperature in Week 5. The screen opened around mid-day on Monday and Tuesday when a pipe temperature of around
50 - 60°C was required. From Wednesday to Friday a pipe temperature of around 45°C was required at mid-day even though the screens were closed. Opening the screens would have required an extra 15 - 20°C pipe temperature to compensate for the extra heat loss i.e. 60 - 65°C therefore the screens remained closed. During this time the outside temperature rarely rose above 2°C. On Saturday and Sunday the outside temperature increased and the screens opened once again around mid-day.

Figure 5 – Screen operation in Week 5



Week 6 onwards

The need for active humidity control began in Week 6. The approach taken to control humidity in 2005 was successful and was used again in 2006.

The 10:30 to 14:00 time period was gradually expanded to cover the period from sunrise + 1 hour to sunset – 1 hour. The inside / outside temperature difference set point was also increased to 10°C. The night-time set point remained at 7°C. These set points were fine tuned as the crop developed and the need for humidity control increased.

Screen gapping for humidity control was also used. The humidity control strategy was to gap the screen first, then open the vents and finally increase the minimum heating pipe temperature. In practice, to achieve stable control, vent opening had to start before the screen reached the maximum gap allowed, and minimum pipe temperature increase had to be initiated at the same time that the vents started to open. Typical screen gap set points are shown in the table below.

Table 5 – Screen humidity gap

Description	**Time period**	**Value**	**Range**
Humidity gap	Daytime	10%	3.5 – 2.8 g/m^3
Humidity gap	Night-time	10%	2.6 – 2.0 g/m^3
Outside temperature influence on gap size	All the time	75%	3 – 10°C

The target HD's were 3.0 g/m^3 and 2.3 g/m^3 during the day and night respectively. Gapping started before these levels were reached to give more stable control and avoid cyclical operation. The amount of screen gap required to achieve satisfactory humidity control in cold ambient conditions was less than when conditions were milder. This was automatically implemented using an outside temperature influence on screen gap size as described in the last row of the table. This helped to automatically avoid 'over gapping' on cold nights when cyclical screen movement could occur. The full 10% gap was allowed when the outside temperature was higher.

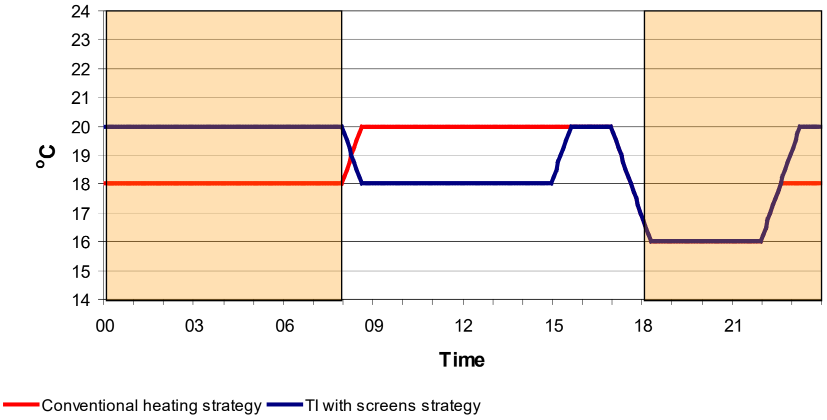
As the crop developed and humidity control became increasingly difficult the day and night
inside - outside temperature difference set points were gradually increased to 14°C and 12°C respectively. Although the frequency and duration of screen closing reduced, they regularly closed overnight up to Week 22. Occasional closing occurred up to Week 26 when the night-time outside temperature was unseasonably low.

Temperature integration strategy

Summary of 2005 strategy

Figure 6 below shows the temperature integration (TI) strategy (blue line) applied in 2005. For comparison the conventional strategy (red line) is shown on the same figure. The shaded area shows when the screens were normally closed.

Figure 6 – TI with screens strategy (2005)



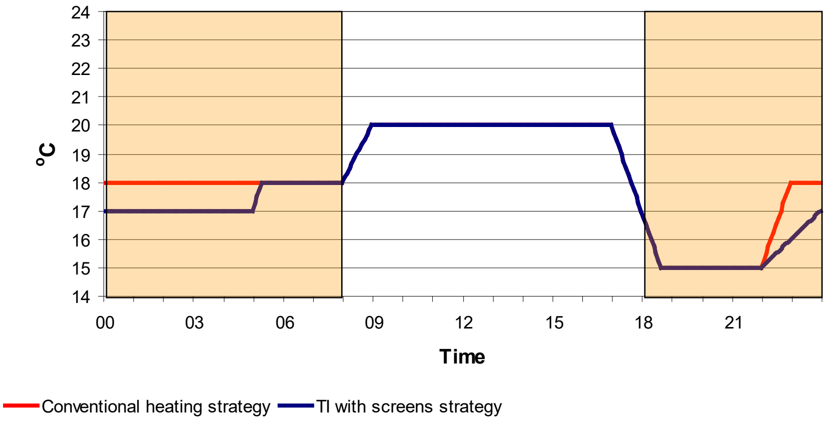
To maximise the energy saving from using TI during the night-time, the heating temperature was increased whilst the screen was closed and heat loss was low. This allowed ‘cheap’ degree-hour credits to be accumulated early in the season when free credits from solar gain were not available. TI was then allowed to offset the credits during the daytime by reducing the heating temperature by up to 2°C. To ensure a consistent pre-night effect TI was not allowed to affect the heating temperature from two hours before sunset until four hours after sunset. TI was allowed to integrate temperature credits over a five day period.

This strategy contributed to a period of poor crop development when a significant and prolonged drop in light levels occurred. The effect on the greenhouse environment was several days of low average daytime temperature combined with low light levels. Although the crop did not suffer any long term damage several weeks of minimal growth caused a reduction in yield that was not recouped.

Summary of 2006 TI strategy

Figure 7 below shows the TI heating strategy adopted in 2006. This reverted to a more traditional TI strategy and TI was not allowed to reduce the daytime temperature. Any temperature credits accumulated were only allowed to be used during the night-time. The minimum heating temperature allowed was 16°C and for the majority of the trial it was only allowed to be 1°C below the conventional control strategy. In addition, to reduce the likelihood of several days of low average temperature the integrating period was reduced from five days to three days.

Figure 7 – TI with screens strategy (2006)



As described in detail in section 3.2.2 the ventilation temperature was increased to 26°C during the daytime when humidity conditions were good to help accumulate temperature credits. This was reduced to 25°C in Week 16 following difficulties in delivering a stable greenhouse climate whilst it was still quite cold outside. This essentially meant that there was little difference between the control strategies in Blocks 3 and Blocks 4 - 6.

Humidity control strategy

Venting

Once active humidity control was required the ventilation temperature was set 1°C above the heating temperature at all times. This helped to make the application of humidity influences to the ventilation temperature simpler because the difference between heat and vent was always the same regardless of the time of day.

Table 6 - Ventilation temperature humidity influences

Time period	**Value**	**Range**
Daytime	-1.0°C	4.0 – 2.8 g/m^3
Night-time	-1.0°C	2.8 – 2.0 g/m^3

The humidity influences were configured to start to have an effect before the humidity deficits reached unsatisfactory levels. This was because applying an influence (-1.0°C) over a small humidity range (say 3.0 – 2.8 g/m^3) can give unstable control due to the rapidly varying ventilation temperature.

Under TI, the ventilation temperature was increased to a maximum of 26°C as the humidity deficit increased from 4.5 to 6.0 g/m^3. This applied at all times except during the pre-night period to ensure the required temperature reduction was consistently achieved. This approach delivered a higher daytime greenhouse temperature in response to high light conditions whilst ensuring good humidity control. The VGN Managing Director considered this to be a good strategy and its application was extended to the whole nursery albeit at a slightly reduced level of 25°C.

Minimum ventilation set points were also applied to guarantee some air exchange and aid air movement when humidity conditions were especially poor regardless of greenhouse temperature. These were:

- Daytime – 1% minimum vent when the humidity was < 2.8 g/m^3.
- Night-time – 1% minimum vent when the humidity was < 2.3 g/m^3.

Minimum pipe temperature

Table 7 – Minimum pipe temperature set points

Description	**Time period**	**Value**	**Range**
Basic minimum pipe temperature	All the time	30°C	n.a.
Humidity influence	Daytime	-6°C +20°C	4.0 – 4.5 g/m^3 3.5 – 2.8 g/m^3
Humidity influence	Night-time	+15°C	2.8 – 2.0 g/m^3
Humidity influence	Pre-night period	+5°C	2.5 – 2.0 g/m^3

These influences restricted the minimum pipe temperature to a maximum of 50°C during the daytime. This was increased to 60°C during prolonged periods (several days) when the HD was consistently below 3.5 g/m^3.

The -6°C influence during the daytime was to ensure that the circulation pump turned off when conditions were good.

Greenhouse environment

Temperature

Figure 8 – Average 24-hour temperature

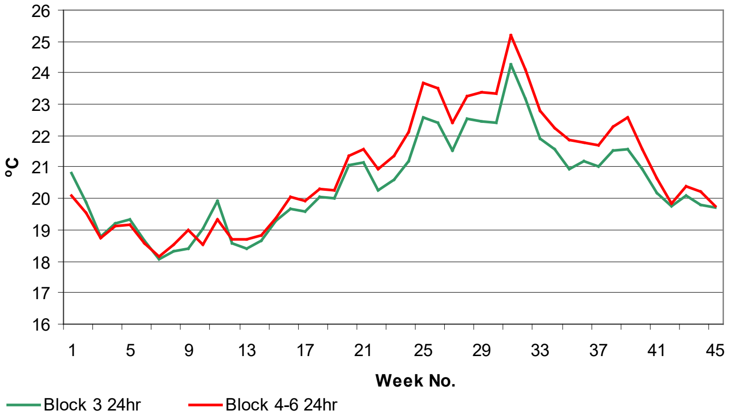


Figure 9 – Average day temperature

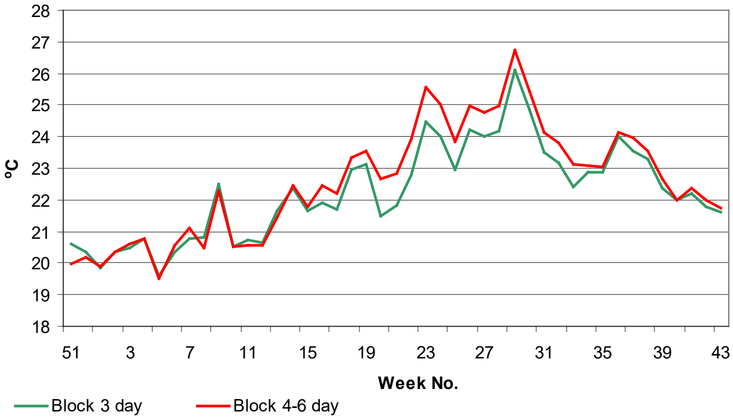
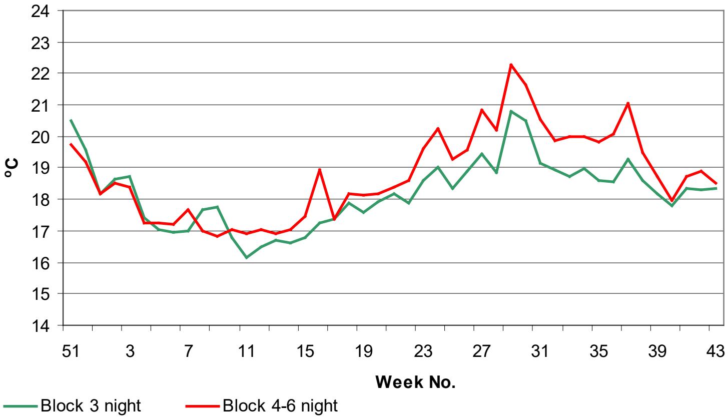


Figure 10 – Average night temperature



Up to Week 11 there was little difference between Block 3 (TI) and Blocks 4 - 6. From Week 11 to 17 Block 3 was around 0.5ºC colder during the night. This was due to the use of TI. TI was turned off in Week 17 once the target average greenhouse temperature could not be maintained. However, for the majority of the remainder of the year Blocks 4 - 6 were consistently warmer during all periods than Block 3.

Table 8 below shows the average day, night and 24-hour temperatures in the two blocks during the period from Week 20 – 35 inclusive in 2004 and 2006. Historically Blocks 4 - 6 have tended to be slightly warmer because they are less exposed than Block 3. However, the difference was greater during 2006 especially during the night. This was due to the fact that heat was not destroyed in Block 3 in 2006. The only heat used was that required for humidity control. This meant that the temperature in Block 3 was closer to the desired temperature than in Blocks 4 - 6. This was considered to be an important factor in the yield improvement in Block 3 discussed later in this report.

Table 8 – Historical temperature data (Week 20 - 35)

		24-hour	Day	Night
2004	Block 3	21.5	22.8	19.1
	Blocks 4 - 6	22.0	23.3	19.5
	Difference	***0.5***	***0.5***	***0.4***
2006	Block 3	21.9	23.5	18.9
	Blocks 4 - 6	22.7	24.2	19.9
	Difference	***0.8***	***0.7***	***1.0***

Humidity

Up to Week 8 the average day and night-time humidity deficit (HD) in Block 3 was slightly higher than in Blocks 4 - 6. TI was not turned on during this period so this was simply due to differences between the greenhouse blocks and the crop. From Week 8, TI was turned on and there was sufficient solar gain for it to have an impact. Restricted ventilation during the day and less heat during the night meant that the difference reduced. Between Weeks 11 and 17 when TI was having the greatest effect the daytime HD in Block 3 was lower than in Blocks 4 - 6.

Once TI was turned off in Week 17 the daytime HD was similar in both compartments. However, the night-time HD in Block 3 was significantly lower than in Blocks 4 - 6 lower between Weeks 23 and 38. This coincided with the period when heat destruction, in the form of minimum pipe heat, was happening in Blocks 4 - 6 but not in Block 3.

Figure 11 – Average day humidity deficit

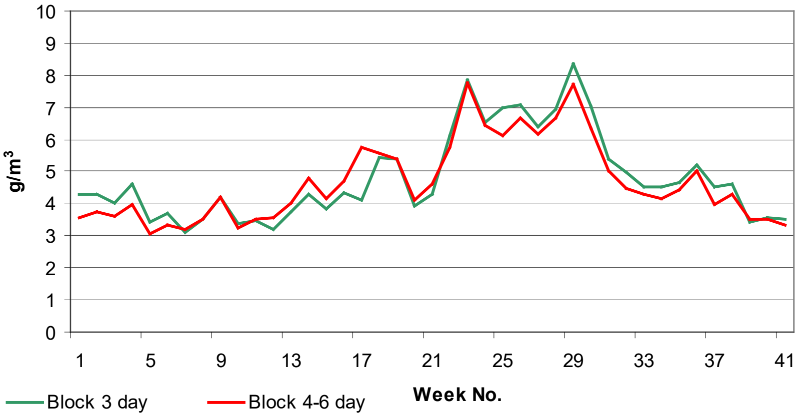
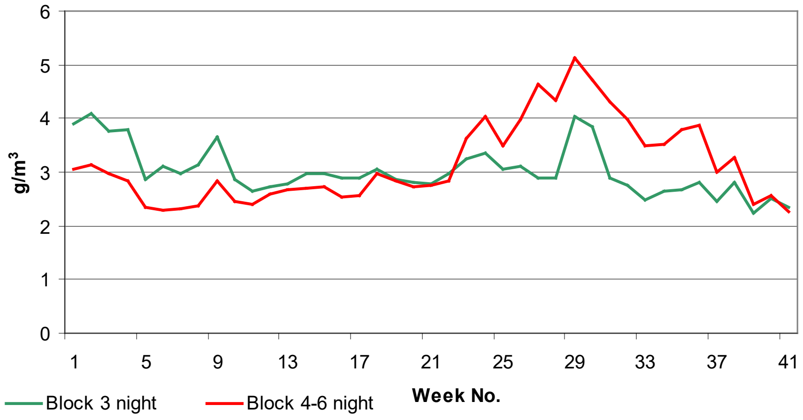


Figure 12 – Average night humidity deficit



CO_2 levels

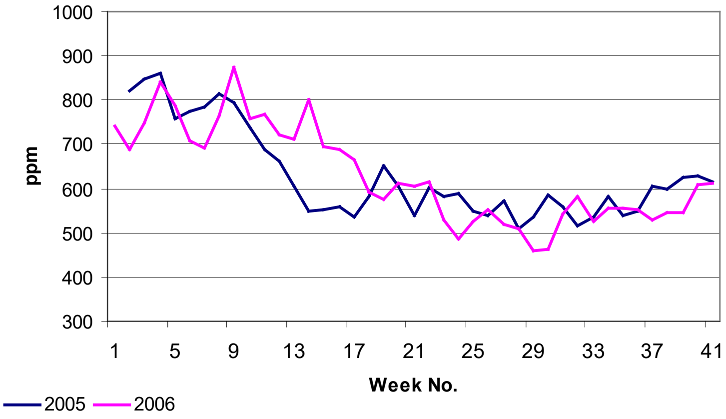
Figure 13 below shows the average daytime CO_2 concentration across the whole nursery. Between Weeks 9 and 18 it was significantly higher in 2006 than 2005. This was not due to higher set points. Insulating the heat stores was completed in Week 18 and the work on heat storage and boiler management started in week 20. Therefore, neither of them could have been responsible for the increase.

There were however two key differences:

1. 2005 Week 21 - Peter Moss from Priva Holland visited the Nursery to review and fine tune background control set points.
2. 2006 – Individual suction pumps were installed on each block to run continuously thereby improving the response and accuracy of CO_2 measurement.

During this period (Weeks 9 - 18) CO_2 availability was not limiting i.e. the heat stores were rarely full at the end of the daytime and were easily emptied overnight. The work carried out by Peter Moss is likely to have reduced boiler on/off cycling and therefore the stability of CO_2 levels in the greenhouse. Improved response and accuracy of CO_2 measurement could also have had a similar effect. It is possible that the actual CO_2 levels achieved in the greenhouse were the same in 2006 as in 2005 and that the difference recorded was just due to measurement error. It was not possible to determine which of these factors was responsible - the most likely answer is they all played a part in the difference measured.

Figure 13 – Average CO_2 level in Blocks 4 - 6



The comments above cast some doubt on the validity of the comparison of CO_2 levels in mid summer (Weeks 20 - 35). However, taking the data at face value the CO_2 level achieved during this period was similar in 2006 to 2005 apart from Week 24 and Weeks 29 - 30. These coincide with significantly higher outside temperatures in 2006 compared to 2005. These will have caused increased and more prolonged venting and reduced the ability to fully empty the heat stores overnight.

Heat store & boiler management

Insulating the heat stores reduced their heat loss. This meant that they reached their maximum temperature (filled) quicker and more often than in 2005. It also meant that the heat stores were rarely completely empty by sunrise. A variety of options were available in dealing with this:

1. Boiler output could be controlled so that the heat store was filled according to a set strategy through the daytime so that it was only full shortly before sunset.
2. Heat could be destroyed during the night by increasing the greenhouse minimum pipe temperature regardless of the need for humidity control.

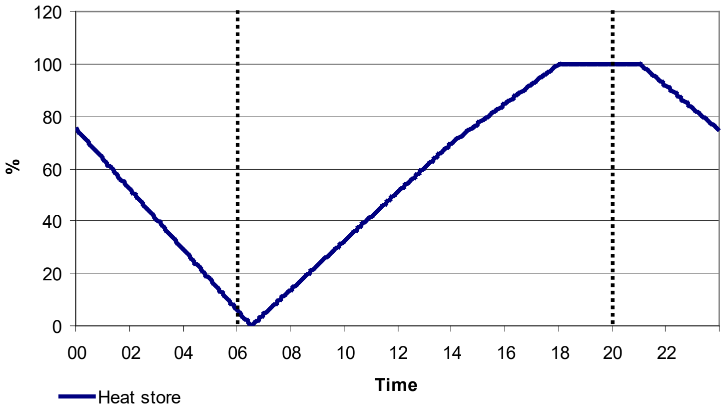
3. If the heat store was full during the daytime heat could be destroyed by increasing the minimum pipe temperature.

In practice many growers tend to use a combination of all three. In this trial, adding heat to the greenhouse during the daytime when temperatures were already too high was not considered to be beneficial for the crop. Therefore a combination of options 1 and 2 were used.

Heat store filling strategy

There are many theories as to which parts of the day plants most efficiently utilise CO_2 and therefore when is the most efficient time of day to use CO_2 enrichment when it is in limited supply. However, that was not within the scope of this project and so a simple heat store filling strategy was used in 2006 (see Figure 14 overleaf).

Figure 14 – Heat store filling strategy



The dotted lines show the approximate times of sunrise and sunset. The strategy adopted in mid-summer was:

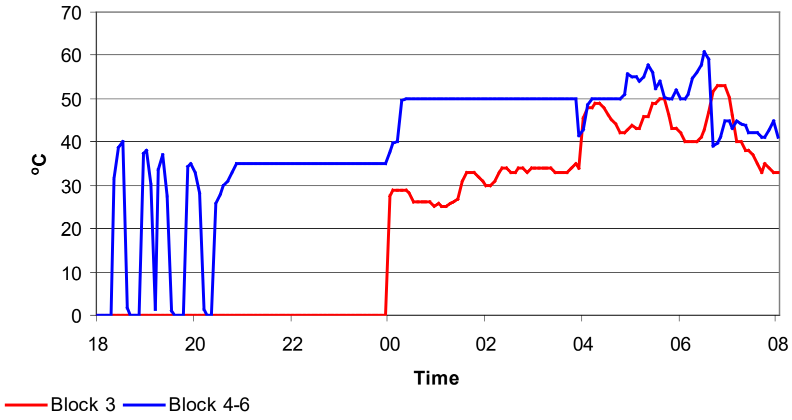
- Start filling the heat store 30 minutes after sunrise.
- Fill at the rate of 10% per hour up to 14:00.
- Fill at the rate of 5% per hour up from 14:00 onwards.
- Aim to fill the heat store two hours before sunset.

The rationale underpinning this strategy was that CO_2 application efficiency would be better during the morning when outside temperatures were lower and less venting was taking place. Afternoon CO_2 application was seen as less favourable because of the high ventilation requirement and the fact that high afternoon temperature and HD could reduce the plant's CO_2 utilisation efficiency. However, CO_2 depletion was avoided at all times.

Heat destruction strategy

In addition to filling the heat store Figure 14 also shows the emptying strategy. To ensure that the pre-night temperature drop was achieved the highest minimum pipe temperature allowed from 21:00 to 00:00 was 35°C. From 00:00 to 06:30 it was allowed to increase to 50°C. Heat destruction was allowed in Blocks 4 - 6 but not in Block 3. The effect of this is shown for a single mid-summer day in Figure 15 below.

Figure 15 – Pipe temperatures



During the summer this strategy did not consistently empty the heat store. Therefore CO_2 availability could have been higher. However, balancing this against the energy cost and the negative effect of higher / more prolonged pipe temperatures on the crop meant that it was considered to be the best overall approach by Gary Taylor.

Figure 16 – greenhouse temperature

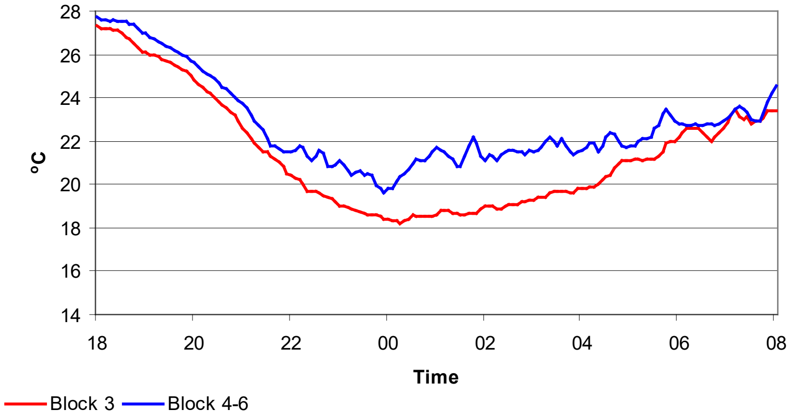
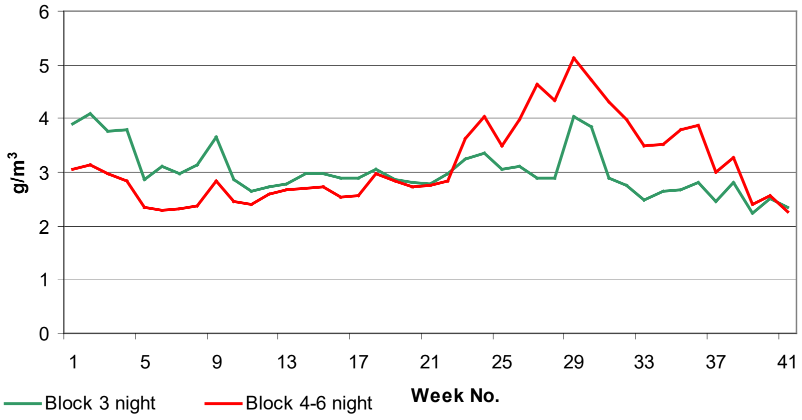


Figure 17 – greenhouse humidity



The effect of heat destruction on greenhouse temperature is shown in Figure 16. Block 3 is 0.5°C cooler prior to heat destruction taking place, this is simply an inherent difference between blocks. However, once heat destruction starts in Blocks 4 - 6 the difference increases to as much as 3°C - this is at a time of year when achieving low greenhouse temperatures is difficult. Heat destruction clearly had a negative impact from this point of view.

A benefit of heat destruction is a higher HD which can help with disease control. Figure 17 shows that while the HD in Block 3 were around 3.0 g/m^3 whereas levels consistently over 3.5 g/m^3 were achieved in Blocks 4 - 6.

Boiler management

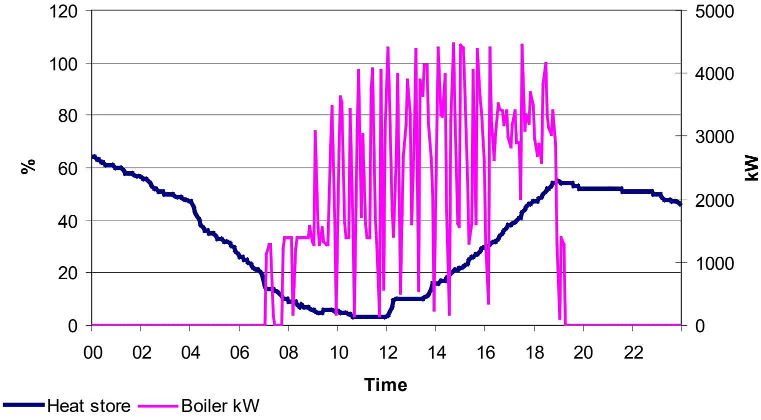
When there is continuous heat demand during the winter the nursery boiler operates continuously. The heat output is automatically adjusted to match the heat demand of the nursery. However, during the day in summer when there is no heat demand but a high CO_2 demand excessive boiler cycling can occur. This is shown in Figure 18 overleaf.

There are two main causes of this:

- Intermittent CO_2 demand when there is limited venting.
- High boiler temperature when the heat store return temperature is high.

In addition to the general wear and tear associated with excessive on/off cycles, every time a boiler starts the combustion fan runs for a brief period to purge the boiler before the burner ignites. The flue gasses are then allowed to stabilise before the CO_2 fans draw them into the greenhouse. Purging also happens when the burner turns off. This causes unnecessary heat loss due to cold air being blown through the boiler. It also wastes CO_2 during the stabilisation phase.

Figure 18 – boiler cycling



In the example shown in Figure 18 above, the heat store was not full so the second point does not apply.

The reason for boiler cycling in this example was that a small amount of venting caused a sudden drop in CO_2 level. The system reacted by asking for maximum boiler output (in this system, set points in the control system allowed the boiler to operate at up to 4,250 kW output when there was a CO_2 demand). The CO_2 level rose rapidly and the boiler shut down again. The solution was to reduce the maximum boiler capacity for CO_2 during periods like this to give more stable boiler operation and CO_2 levels.

Figure 19 – stable boiler operation

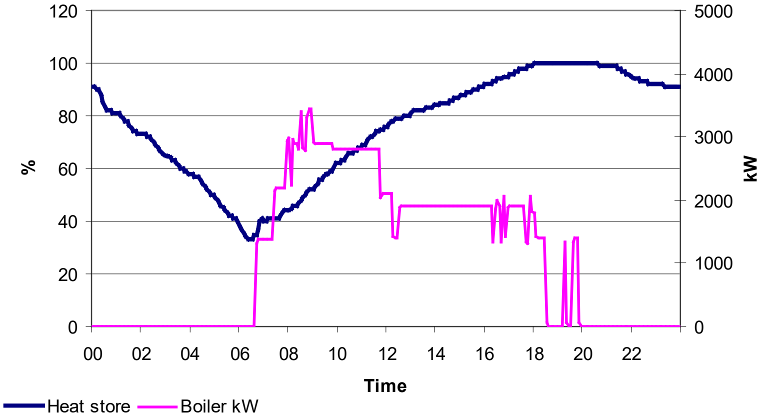


Figure 19 above shows very stable boiler operation that was achieved following fine tuning of a variety of set-points. Although it was not possible to fully empty the heat store prior to sunrise (33% full) and therefore heat storage capacity was limited the boiler operated almost non-stop throughout the day.

Energy use

As in PC 227 (2005) both historical and current year energy use were analysed using:

- Degree-day heating to correct for differences in weather and greenhouse temperature.
- Average heating pipe temperature to allocate whole site gas use to each greenhouse block.

The cropping period in 2006 was longer than in previous years due to a reduced turn around time following the installation of hanging gutters. To ensure a direct comparison between all years the cropping period was defined as from Week 51 to 41 inclusive. This represents the period when the whole nursery had plants in it from 2003 onwards.

Summary from 2005

- Energy saved by using moveable screens instead of fixed screens– 52 kWh/m^2.
- Additional energy saved by improving moveable screen control – 25 kWh/m^2.
- Energy saved using temperature integration – 24 kWh/m^2.
- Heat destruction for CO_2 – 28 kWh/m^2.
- Best practice total gas use with moveable screens (no TI) – 565 kWh/m^2.

Analysis of each energy saving measure

Further refinement of thermal screen control set points

The moveable screens were controlled with a view to saving more energy (as described in section 9.1.1). The energy use in Blocks 4 - 6 (no TI) are considered for this comparison. The heat store was not insulated until Week 18. Therefore to isolate the energy saving associated with screen control the period from Week 51 to Week 17 inclusive was compared with the same period in 2005.

Table 9 – Blocks 4, 5 & 6 winter energy use

	2004/05	**2005/06**
Degree-day heating requirement	1,493	1,491
kWh/m^2 gas consumed	295	257
DD corrected kWh/m^2 as to a base year of 03/04	295	257
Saving compared to 2004/05 – kWh/m^2	n.a.	38 kWh/m^2 (13%)

The additional energy saving was 38 kWh/m^2 equal to 13% of the energy used from Week 51 to 17. This does not include additional savings that would have been achieved towards the end of the season which could not be tracked because of the additional effect of insulating the heat stores during this period.

Temperature integration

TI was applied up to Week 17 which coincidentally was before the heat stores were insulated. This allowed energy use to be compared directly with 2005.

Table 10 – Week 51 to week 17 (TI comparison)

	Average of Blocks 1 & 2				**Block 3**			
	02/03	**03/04**	**04/05**	**05/06**	**02/03**	**03/04**	**04/05**	**05/06**
Degree-day heating requirement	1,460	1,501	1,512	1,505	1,408	1,438	1,430	1,452
kWh/m^2 gas consumed	418	327	290	254	416	308	274	252
kWh/m^2 gas consumed (DD corrected to 02/03)	418	318	280	246	416	302	270	244
kWh/m^2 as % of 02/03	418	318	280	246	416	302	270	244
As % of Blocks 1 - 2					99.5%	94.8%	96.3%	99.2%

- 02/03 - all blocks had fixed screens and TI was not used.
- 03/04 –TI was partially trialled by the nursery in Block 3.
- 04/05 – Movable screens were installed & TI was fully trialled in Block 3 as PC 227.
- 05/06 - TI was fully trialled in Block 3 as PC 227a.

In 02/03 the difference in the degree-day corrected energy use between Blocks 1 - 2 and Block 3 was 0.5%. This increased to 5.2% when TI was trialled in 03/04 and 4.7% in 04/05. However, in 05/06 TI delivered no significant energy saving. There is little doubt that this was due to the nursery adopting a pseudo TI ventilation strategy in Blocks 1 - 2 (described at the start of this section of the report). The marginal additional potential energy saving in Block 3 with the 26°C ventilation temperature compared to 25°C as used in Blocks 1 - 2 was not sufficient to reveal any energy advantage.

The energy saving of insulating the heat stores

It was not possible to determine the total energy saving attributable to insulating the heat stores because of the large number of other energy savings measures that were implemented in 2006. However, from Weeks 20 - 35 TI when the thermal screens had little / no impact on energy use 26 kWh/m^2 less gas was used in 2006 than in 2005. This is attributable to the insulation of the heat stores. It should be noted that this is only part of the total energy saving delivered by insulating the heat stores but it still represents 5% of the total annual energy consumption.

The energy cost of CO_2 enrichment

Between Weeks 20 – 36 inclusive energy use in all blocks was driven by the need to maintain a minimum pipe temperature for humidity control and for heat destruction. Therefore a direct comparison of energy use between Block 3 (no heat destruction allowed) and Blocks 4 - 6 (heat destruction allowed) which were growing the same variety gives a good indication of the amount of energy destroyed and therefore the energy cost of CO_2 enrichment at this nursery.

Table 11 – CO_2 energy data

	Block 3	**Blocks 4 - 6**	**Difference**
kWh/m^2 gas consumed	264	316	52 kWh/m^2

It should be noted that the heat destruction strategy did not guarantee that the heat stores were emptied every night. During the peak of the summer the heat stores were regularly 30 - 40% full at the start of the day. Therefore the figure of 52 kWh/m^2 is expected to be low compared to nurseries that use CO_2 enrichment and heat destruction more intensively.

Best practice energy consumption

The following equipment level delivered is considered to be current best practice energy use for sweet pepper production in the UK.

- Modern Venlo greenhouse.
- Modern climate control computer.
- Modern gas fired boiler with automatically controlled variable speed combustion air fan.
- Insulated heat stores.
- Movable thermal screen (non voided material).
- Temperature integration – although not fully applied, many of the principles were adopted on the whole nursery in 2006.

Table 12 – total energy use, Weeks 51 - 43 (2006)

	kWh/m²
Block 1	524
Block 2	532
Block 3	479
Blocks 4 - 6	502

On average the cropping year was from Weeks 51 - 44, 46 weeks in total. This included warming up the glasshouses prior to planting and periods when the whole nursery was not planted. Allowing for this additional week increases the energy use in the table by 13 kWh/m^2.

As Blocks 4 - 6 are the most modern greenhouse at the nursery their performance represents what is considered to be best practice energy use. The additional week increases the total amount of gas used to 515 kWh/m^2. It should be noted that this includes heat destruction to allow higher levels of CO_2 enrichment. If heat destruction was not allowed the energy used would have been 463 kWh/m^3.

Energy use targets for pepper growers in the Netherlands were 446 kWh/m^2 in 2001 (when Blocks 4 - 6 were built) and 410 kWh/m^2 in 2006. Therefore without heat destruction the energy use in Blocks 4 - 6 was only 3.8% higher than the 2001 target and 12.9% higher than the 2006 target. Although not proven it is likely that growers in the Netherlands do not have to destroy heat to maintain CO_2 levels because CHP is much more widespread (giving more CO_2 per kWh of heat).

Crop data

Figure 20 – Total fruit set

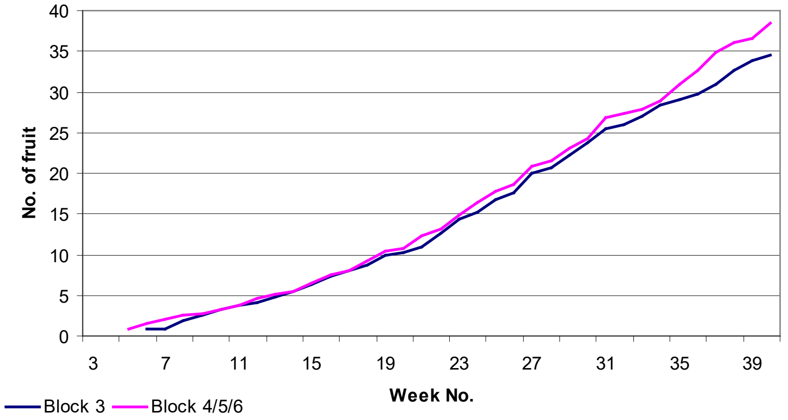


Figure 21 – No. of fruit per plant

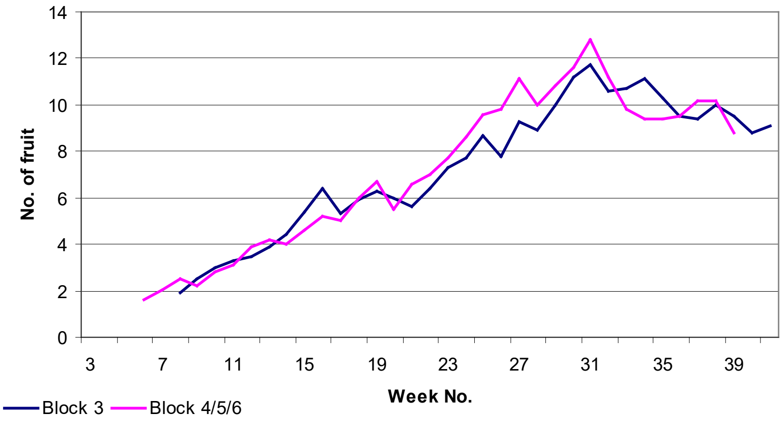
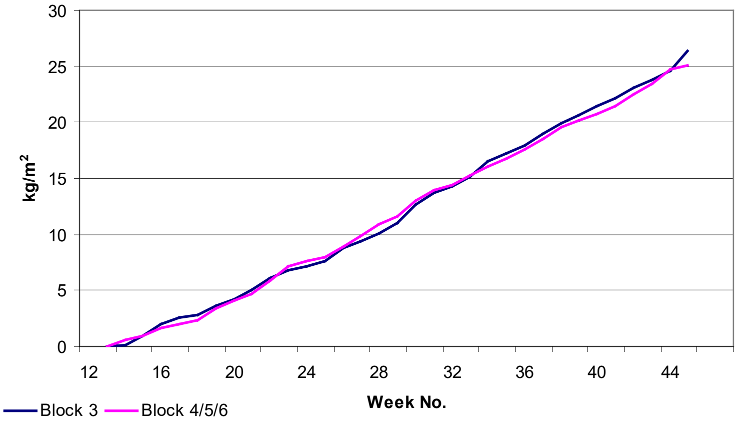


Figure 22 – Yield 2006



Fruit set started one week later in Block 3 due to a later planting date. However, the difference was quickly made up. From Week 19 onwards Blocks 4 - 6 set more fruit than Block 3. This coincides with the onset of higher average greenhouse temperatures in Blocks 4 - 6. This is also reflected in the number of fruit on each plant (Figure 21 which increases in Blocks 4 - 6 relative to Block 3 over a similar period. The fruit set in Blocks 4 - 6 also rises significantly relative to Block 3 from Week 33 onwards which coincides with a slightly lower fruit load per plant.

The total yield in kg/m^2 was higher in Block 3. 26.4 kg/m^2 compared to 25.0 kg/m^2 in
Blocks 4 – 6, representing a difference of 5.6%. This is in spite of the fact that the total number of fruit picked in Blocks 4 - 6 was 18.9 per plant compared to 16.1. Therefore the fruit weight must have been higher in Block 3. The overriding factor affecting this was the higher average temperature in Blocks 4 -

6 which allowed the fruit to ripen faster both reducing fruit weight and allowing the plant to set more fruit.

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.

Summary

Blocks 3 (TI) and Blocks 4 - 6, cv. Special, were regularly assessed for disease during 2006. Fusarium stem rot caused by *F. oxysporum* occurred during the spring and early summer (March-May) and rarely thereafter. During Weeks 13 - 27 (29 March to 7 July), the incidence of Fusarium stem node lesions that developed in Block 3 (7.7% of stems) was significantly greater than in Blocks 4 - 6 (3.2% of stems).

The reason for the difference between compartments in the incidence of Fusarium stem node lesions was unclear. Block 3 was applying TI whereas Blocks 4 - 6 were not. Therefore a greater frequency of high RH periods was expected. However, the environmental data collected showed that the frequency of high humidity periods (>85%RH for 3 and 6 h) during the period of Fusarium stem lesion development was similar in both compartments.

Fusarium stem node lesions were cut out as they occurred and the incidence of girdling lesions and stem death at the end of the season was very low. No other diseases were confirmed.

Results and discussion

Fusarium oxysporum was recovered from around 50% of stem node lesions that occurred across the two monitored bocks. The reason *Fusarium* species were not isolated from a greater proportion of lesions is unknown; no other pathogens were isolated. A few dark-brown to black fruit stalk lesions occurred in the monitored areas, but *Fusarium* was recovered only rarely from this symptom. One extensive stem lesion, spreading over 50 cm along the stem, was found on a plant outside the monitoring areas in April, and *F. oxysporum* was recovered from affected tissues. Fusarium fruit rot caused by *F. oxysporum* was also confirmed in both compartments. The disease most commonly occurred on small aborted fruit but was occasionally found within harvested fruit.

No botrytis stem rot (*Botrytis cinerea*), Sclerotinia stem rot (*Sclerotinia sclerotiorum*), or powdery mildew *(Leveillula taurica*) were observed in either compartment. The incidence of plant death at the end of the season in both compartments was very low and there were no obvious areas of dead or missing plants.

The cumulative incidence of stem node lesions developing between 29 March and 7 June was significantly greater in the energy–saving (Block 3) than the conventionally–heated compartment (Blocks 4 - 6) at all assessment dates.

There was a rapid increase in the incidence of stem lesions in April-May and little increase subsequently. Affected stems occurred throughout the lengths of rows with no evidence of clustering.

An examination of the humidity data from the two compartments during Weeks 14 - 24 (the period preceding and during the rapid rise in the stem lesion occurrence), revealed no difference between the compartments in the frequency of high humidity periods (greater than 85% RH for three or six hours. An examination of the mean night-time humidity deficit for Weeks 1 - 19 indicated a slightly higher deficit, by 0.5-1.0 g/m^3 (lower RH), in the energy-saving compartment; during the day time there was no difference between the compartments. There was therefore no evidence of a higher RH that might explain the greater incidence of Fusarium stem node lesions in the energy-saving compartment. The mean day time and night-time temperatures in the two compartments were also similar. Further work on the biology and control of Fusarium stem and fruit rot of pepper is continuing in a separate project (PC 260).

Discussion

Screens

There is no doubt that moveable (permanent) screens deliver greater energy savings than fixed (temporary) screens. The results show that a conservative approach to moveable screen control (2005) delivers an additional saving of 52 kWh/m^2. This increases to 90 kWh/m^2 when control set points designed to maximise energy saving are used.

The yield in 2005 was shown to be slightly lower (1 kg/m^2) during the early part of the year. However, this was recovered by Week 26 and there was no overall yield penalty. Due to a wide variety of changes on the Nursery and the lack of a direct comparison it was not possible to determine whether the screen control strategy had an effect on yield in 2006. Similarly it was not possible to draw any firm conclusions regarding disease incidence other than that it was not significantly worse than in 2005.

Temperature integration

The TI strategy used in the 2006 trial reverted to the more traditional ‘warmer day – cooler night’ approach. At the same time and following the results from 2005, the ‘warm day’ component of TI was adopted across the whole Nursery. With limited opportunities to reduce the heating temperature during the night in the TI treatment and with the rest of the Nursery adopting at TI type strategy the TI treatment in Block 3 did not show any energy saving over and above that being achieved in the rest of the Nursery in 2006.

Higher disease levels (*Fusarium oxysporum*) were recorded in the TI block in the period between Weeks 13 and 27. However, analysis of the climate data showed that there was little difference between the treatments in terms of humidity, the major disease driver. Therefore the reason for the difference in disease incidence of Fusarium stem node lesions was unclear.

The fact that a significant part of TI was adopted on the whole Nursery in 2006 demonstrates that it offers some benefits to sweet pepper growers. The 6% energy saving delivered in 2005 can therefore be at least partially achieved with the confidence that there will be no impact on yield.

Insulated heat stores & heat destruction for CO_2 enrichment

Heat stores without insulation continue to be used on UK nurseries because they allow more gas to be burnt to produce CO_2 without having to actively destroy as much heat in the greenhouse. However, even when heat destruction is allowed insulated heat stores have been shown to deliver savings of at least 26 kWh/m^2 and most likely significantly more.

Insulating a heat store does not mean that CO_2 availability will be reduced in the summer. It simply means that more heat will have to be actively destroyed. Although heat destruction units are occasionally used, heat is usually destroyed by increasing the minimum pipe temperature regardless of the humidity in the greenhouse. This will deliver better humidity conditions in the greenhouse potentially helping with disease control. Therefore the heat destroyed could be considered as not 100% wasted. However, this project has shown that heat destruction will also lead to higher greenhouse temperatures than required and therefore less control over plant development. Indications are that this can have a negative impact on yield.

Best practice energy use

Energy use in the greenhouse block most recently built on the Nursery (2001) was 515 kWh/m^2 in 2006. This reduces to 463 kWh/m^2 when the heat destroyed to aid CO_2 production is excluded. This compares favourably with a target for sweet pepper growers in the Netherlands of 446 kWh/m^2 in 2001. It is not known for sure whether growers in the Netherlands actively destroy heat for CO_2 but the inference from general discussion is that they do not destroy heat and that they do not rely so heavily on CO_2 enrichment as UK growers. However, they do benefit from a more favourable economic case for CHP and there are without doubt more CHP installations on nurseries in the Netherlands. These have the benefit of providing 70% more CO_2 per kWh of heat produced than a typical boiler. It is therefore likely that they can deliver similar levels of CO_2 enrichment to UK growers without the need to destroy heat.

In 2006 the energy target for Dutch pepper growers was 410 kWh/m^2 (8% less than in 2001). It is not known to what extent improvements in the design of greenhouse structures since 2001 will contribute to additional savings. But it is seems unlikely that they will provide it all. Therefore improvements in the efficiency of energy supply and energy use in the UK must continue to be identified.

Conclusions

Movable thermal screens versus fixed screens

- Moveable screens can save an additional 29 – 90 kWh/m^2 of gas depending on the control strategy adopted.
- Optimising moveable screen control set points can save an additional 61 kWh/m^2 compared to a simple fixed outside temperature control strategy.
- A yield reduction of 1 kg/m^2 can be caused during the early part of the season. However, this is recovered by mid season due to improved climate control. There is no yield penalty overall.
- The energy saving plus the saving on annual replacement costs for temporary screens mean that the payback on installing a permanent screen is less than three years.

Temperature integration

- Temperature integration can be successfully applied to sweet peppers. This is demonstrated by the fact that the host nursery adopted many of the principles on the whole nursery in 2006.
- Temperature integration gave energy savings of 24 kWh/m^2 (6%) p.a. in 2005.
- Although an increase in disease was recorded in 2006 it was not caused by poor humidity conditions. The cause was unknown and continues to be investigated as part of PC 260.

Insulated heat stores

- The energy saving delivered between Week 20 and Week 35 was 26 kWh/m^2. The saving over a complete cropping year is estimated to be over 40 kWh/m^2.
- There was no impact on the CO_2 levels achieved in the greenhouse.
- The destruction of heat in a greenhouse affects the ability to control the greenhouse temperature during the summer. Indications are that this has a negative impact on crop management and therefore yield.
- Heat destruction to increase CO_2 availability accounted for 52 kWh/m^2 of gas consumption.

Best practice energy use

- Total energy use in a greenhouse built in 2001 with moveable thermal screens was
  515 kWh/m^2 (Weeks 51 - 44).
- The total energy use excluding heat destroyed for CO_2 was 463 kWh/m^2.

Appendix 1 - Optimising greenhouse environment and energy inputs for sweet pepper production in the UK – disease monitoring, 2005 (PC 227)

Summary

A glasshouse crop of sweet pepper, cv. Special, in the Lee Valley, Hertfordshire, was regularly assessed for disease during 2006. Fusarium stem rot caused by *F. oxysporum* occurred during the spring and early summer (March-May) and rarely thereafter. During weeks 13-27 (29 March to 7 July), the incidence of Fusarium stem node lesions that developed in a compartment using a thermal screen and advanced climate-control (7.7% of stems), was significantly greater than where the same variety was grown using standard climate-control (3.2% of stems). The reason for the difference between compartments in the incidence of Fusarium stem node lesions is unclear; the frequency of high humidity periods (>85%RH for 3 and 6 h) during the period of Fusarium stem lesion development was similar in the energy-saving and the standard compartment. Fusarium stem node lesions were cut out as they occurred and the incidence of girdling lesions and stem death at the end of the season was very low. No other diseases were confirmed.

Introduction

The use of thermal screens and environmental control set points to exploit temperature integration and save energy will lead to an altered glasshouse climate, notably of temperature and humidity. Both may influence the types of disease that occur and their speed of development in a crop. The objective of this study was to determine and compare the diseases occurring in crops in an energy-saving and a standard glasshouse block.

Methods

Crops

Two glasshouse blocks growing sweet pepper cv. Special, planted in December 2005 on Rockwool slabs in hanging gutters, were examined. The plants originated from Holland. The glasshouses differed in age and dimension. One block was subject to an energy-saving climate control strategy while the other followed the grower’s standard practice. Humidity was measured at 30-50 cm 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

Crops were assessed for disease on 29 March, 28 April, 10 May, 24 May, 7 June, 21 June and 5 July and just before crop pull-out in October. All plants within two pathways in each compartment, comprising over 500 stems, were inspected for stem lesions. All stem node lesions were removed from the two monitoring areas on 29 March and the subsequent increase in lesion number was determined at each assessment time. At each visit, all the stem lesions present were cut out for determination of cause by laboratory tests.

Results and discussion

Fusarium oxysporum was recovered from around 50% of stem node lesions that occurred across the two monitored bocks (Table 1). The reason *Fusarium* species were not isolated from a greater proportion of lesions is unknown; no other pathogens were isolated. A few dark-brown to black fruit stalk lesions occurred in the monitored areas, but *Fusarium* was recovered only rarely from this symptom. One extensive stem lesion, spreading over 50 cm along the stem, was found on a plant outside the monitoring areas in April, and *F. oxysporum* was recovered from affected tissues. Fusarium fruit rot caused by *F. oxysporum* was also confirmed in both compartments. The disease most commonly occurred on small aborted fruit but was occasionally found within harvested fruit.

No botrytis stem rot (*Botrytis cinerea*), Sclerotinia stem rot (*Sclerotinia sclerotiorum*), or powdery mildew *(Leveillula taurica*) were observed in either compartment. The incidence of plant death at the end of the season in both compartments was very low and there were no obvious areas of dead or missing plants.

The cumulative incidence of stem node lesions developing between 29 March and 7 June was significantly greater in the energy–saving than the conventionally–heated compartment at all assessment dates (Tables 2 and 3). There was a rapid increase in the incidence of stem lesions in April-May and little increase subsequently (Table 2). Affected stems occurred throughout the lengths of rows with no evidence of clustering.

During an investigation of pepper stem rot caused by *F. oxysporum* in the Lee Valley in 2006, a grower who had seen stem lesions caused by *F. oxysporum* for several seasons commented that they were more common in one area of a glasshouse that was prone to higher humidity's. Previously, in a crop of sweet pepper affected by a stem rot caused by *Fusarium solani*, it was observed that the affected crop was grown in a glasshouse where the relative humidity fluctuated more than in an unaffected crop (Fletcher, 1994).

An examination of the humidity data from the two compartments during weeks 14-24 (the period preceding and during the rapid rise in the stem lesion occurrence), revealed no difference between the compartments in the frequency of high humidity periods (greater than 85% RH for 3 or 6 hours) (Table 4). An examination of the mean night time humidity deficit for weeks 1-19 indicated a slightly higher deficit, by 0.5-1.0 g/m^3, in the energy-saving compartment; during the day time there was no difference between the compartments (data graphed in main report). There was therefore no evidence of a higher humidity that might explain the greater incidence of Fusarium stem node lesions in the energy-saving compartment. The mean day time and night time temperatures in the two compartments were similar (data graphed in main report). Further work on the biology and control of Fusarium stem and fruit rot of pepper is continuing in a separate project (PC 260).

Reference

Fletcher, J.T. (1994). Fusarium stem and fruit rot of sweet peppers in the glasshouse. *Plant Pathology* **43:**225-7.

Table 1. Pepper: association of Fusarium with different tissues and symptoms in a commercial crop – 2006

Date	No. samples developing Fusarium / No. samples tested		
Sampled	Fruit stalk lesion	Stem node lesion	Stem lesion
March 29	1/15	21/24	-
April 28	1/ 2	2/20	1/1
May 10	0/0	5/24	0/1
May 24	1/10	19/23	-
June 07	0/0	8/14	-
% affected	11.1	52.4	50.0

Table 2. Effect of energy-saving and optimising the greenhouse environment on occurrence of Fusarium stem rot in pepper between 29 March and July 5, 2006

Date assessed[a]	Week number	Cumulative % stems with nodal lesions[b]	
		Energy saving (Block 3)	Control (Block 4)
April 28	17	2.8	0.9
May 10	19	5.0	1.7
May 24	21	6.7	2.7
June 7	23	7.4	3.2
June 21	25	7.7	3.2
July 5	27	7.7	3.2

[a] All stem node lesions were removed from both compartments on 29 March, so the figures presented are lesions developing after this date.

[b] Two pathways (four crop faces) were examined in each compartment, comprising a total of 675 stems in the energy-saving compartment and 528 in the control compartment.

Table 3. Pearson chi-square tests comparing the cumulative incidence of *Fusarium* stem node lesions at different assessment dates in two blocks of pepper, cv. Special - 2006

Date assessed	Chi-square (1 df)	Probability level
April 28	5.29	0.021
May 10	9.55	0.002
May 24	10.24	0.001
June 7	9.88	0.002
June 21	11.02	<0.001

Table 4. Effect of energy-saving and optimising the greenhouse environment on occurrence of high humidity periods – weeks 14-24, 2006

Week	Occurrence of high humidity periods (>85% RH)			
Number	Energy saving (block 3)		Control (block 4)	
	>3h	>6h	>3h	>6h
14	0	0	1	0
15	1	0	0	0
16	1	0	2	1
17	0	0	1	0
18	1	0	0	0
19	6	1	0	0
20	4	1	4	0
21	1	0	2	1
22	0	0	2	0
23	0	0	0	0
24	1	0	1	0
Total	15	2	13	2