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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:

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Grower Summary

Headlines

The first full year of commercial trials of a fan and duct heating and ventilation system installed in a tomato greenhouse in East Yorkshire delivered:

- a heat energy saving equal to 59kWh/m^2 of gas (12.8%) which is worth £1.53/m^2
- high electricity use of 11kWh/m^2 which costs £0.77/m^2
- a 7.6% yield increase worth £1.85/m^2
- a payback on investment of 7.6 years (assuming that all heat is from boilers). The payback period reduces to 3 years where low-grade heat sources already exist e.g. CHP
- 60% of the total heat demand of the greenhouse using water of 40^{o}C or less and 95% using 50^{o}C or less
- lower disease levels
- minimal impact on the way the crop is managed.

Background and expected deliverables

This report summarises the findings of the second year of commercial trials of a three year project that investigated the performance of a ducted heating and ventilation system installed in a 1Ha tomato greenhouse in Humberside.(Note that the first reported period of the trial was only a part year).

The project follows on from PC 256 which examined the potential for using closed glasshouse technology in the UK. This concluded that ducted air heating and ventilation systems could offer significant advantages over conventional greenhouse design including:

- Reduced energy consumption
- Improved crop yield
- Reduced pest and disease problems
- Increased opportunities to use alternative heat sources.

Objectives

The aims of the project are to investigate the ability of ducted air delivery systems to:

- Reduce energy use in heated glasshouses
- Reduce CO_2 emissions associated with glasshouse production
- Expand the opportunities for glasshouse businesses to use alternative heat sources
- Improve crop yield and quality
- Reduce disease incidence and therefore the use of crop protection chemicals.

Summary of the project and main conclusions to date

Materials and methods

The project comprises three parts:

- Research, development and design of a commercially acceptable ducted air heating and ventilation system for the trial greenhouse at a commercial nursery in the UK
- Installation of the selected system at the trials site
- Commercial trials to investigate system performance and crop response.

The project is being carried out at tomato growers Mill Nursery Ltd in East Yorkshire. Previous reports (PC 278 Interim report, 2008 and PC 278 Annual Report 2008, 2009) cover items 1, 2 and the first part year of commercial trials in 2008. This report details the first full year of commercial trials in 2009.

Trial site and equipment

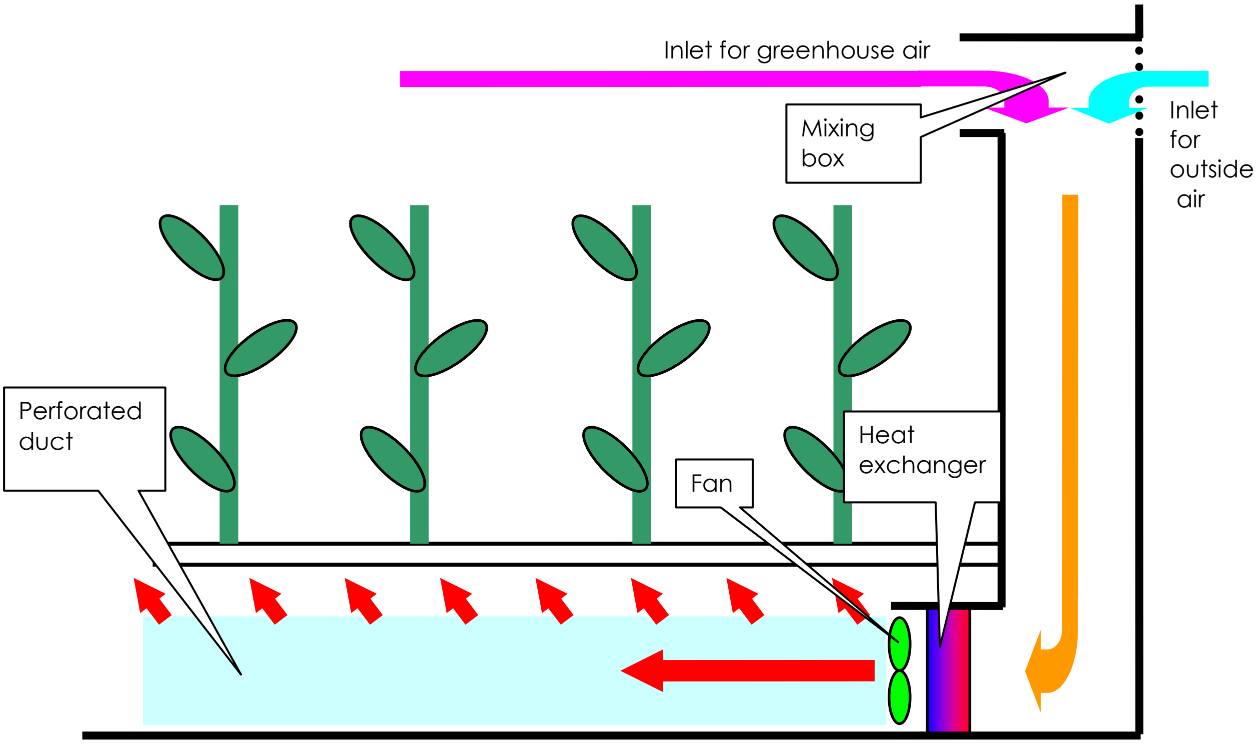
Site

The project is being carried out in two adjacent 1Ha greenhouse compartments. A fan and duct system was installed in one compartment and is being compared with an adjacent and otherwise identical compartment which has a conventional heating and ventilation system.

Equipment

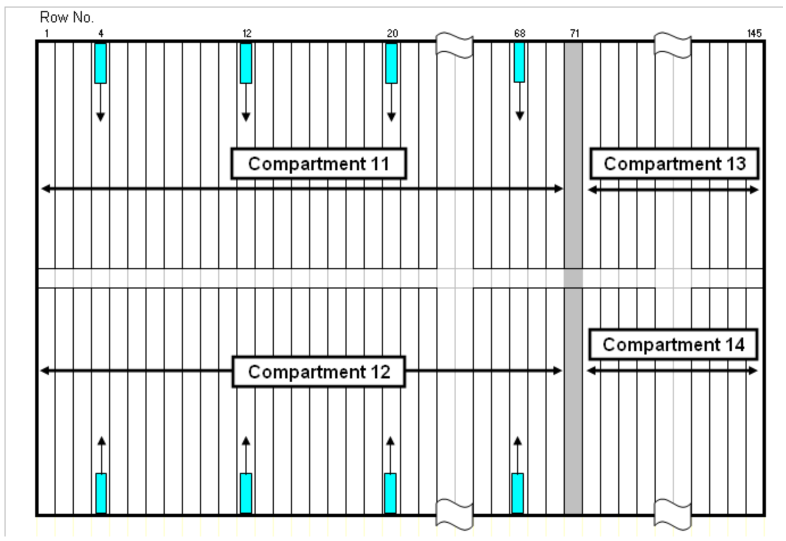
Figure 1 shows a single air handling unit (AHU) of the type installed at Mill Nursery.

Figure 1 – Air handling unit schematic



Collectively these components are called an Air Handling Unit (AHU). Each of the AHUs installed can deliver 6,000m^3/hr and 25kW of heat. The installation at Mill Nursery uses 18 of these AHUs arranged as shown in Figure 2.

Figure 2 – AHU layout



The whole installation has a heating capacity of 450kW/Ha and delivers an airflow of 108,000m^3/hr (2 air changes per hour). It should be noted that the fan and duct installation is not capable of satisfying all the heating and ventilation needs of the greenhouse and the existing pipe rail heating system and roof vents continue to be used.

Results

Temperature uniformity

Figures 3 and 4 show the temperature uniformity achieved in the fan and duct compartment and conventionally heated compartment respectively during January 2009.

Figure 3 – Fan and duct compartment (CMP12)

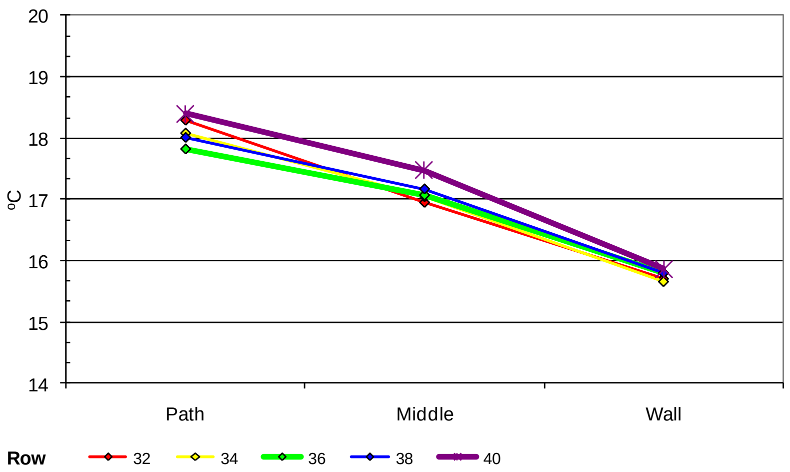
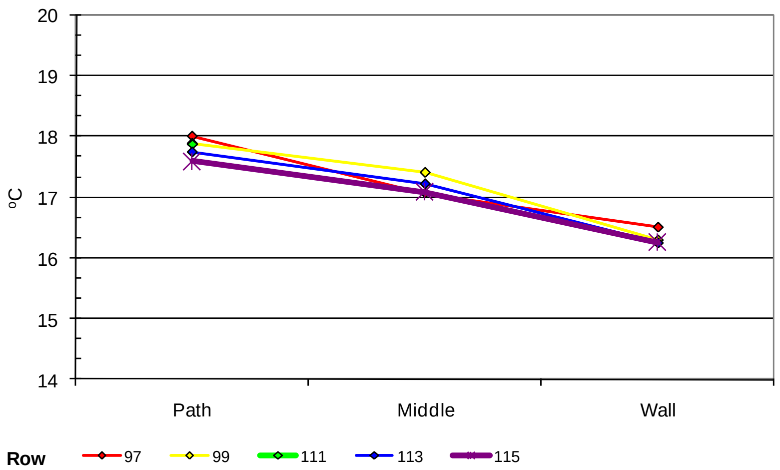


Figure 4 – Conventionally heated compartment (CMP14)

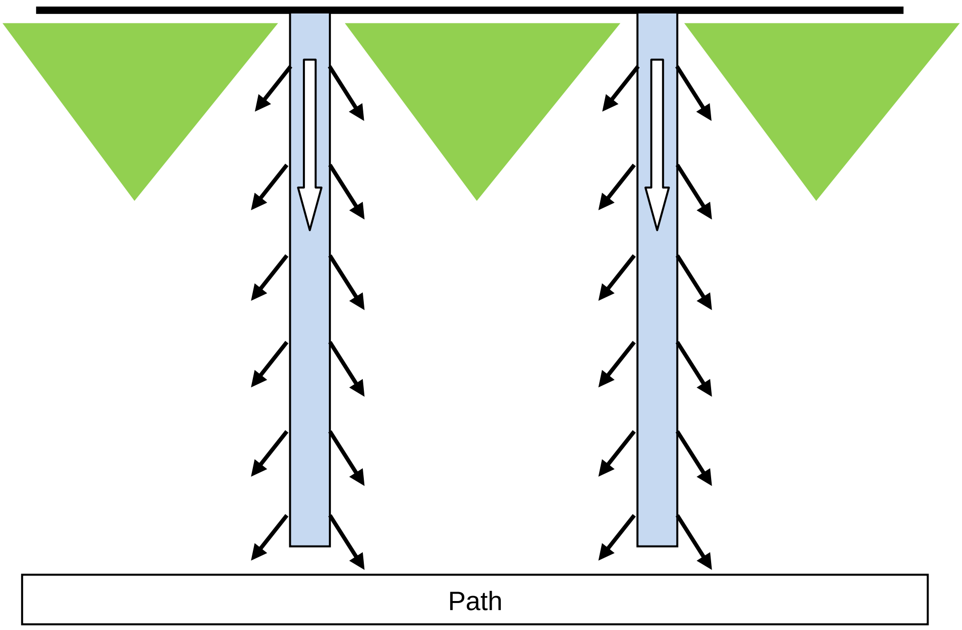


Both compartments were colder close to the wall of the greenhouse than close to the central path. However, the difference between the path and wall in the fan and duct compartment was 2.3°C compared to 1.5°C in the conventionally heated greenhouse. Continued monitoring showed that this trend occurred whenever the greenhouse vents were closed and the heat demand was high. As such it was prevalent from January to late March. This had a significant affect on plant development close to the greenhouse wall in the fan and duct compartment.

Progress in this area was hampered by the limited testing window (requiring cold weather) combined with a modify–test–analyse cycle of 2-3 weeks.

Figure 5 below is a plan view of two ducts as they were originally installed. As the air within the duct is travelling towards the path, it leaves the duct at an acute angle, not at 90^{o} as might be expected intuitively. This left a dead-zone (green triangles).

Figure 5 – Plan view of airflow from the ducts



Further smoke tests showed that there were two dominant air circulation patterns in the greenhouse when the vents were closed (Figure 6). This led to colder air (Circulation 2) accumulating at the wall end of the rows.

Figure 6 – Original air circulation patterns

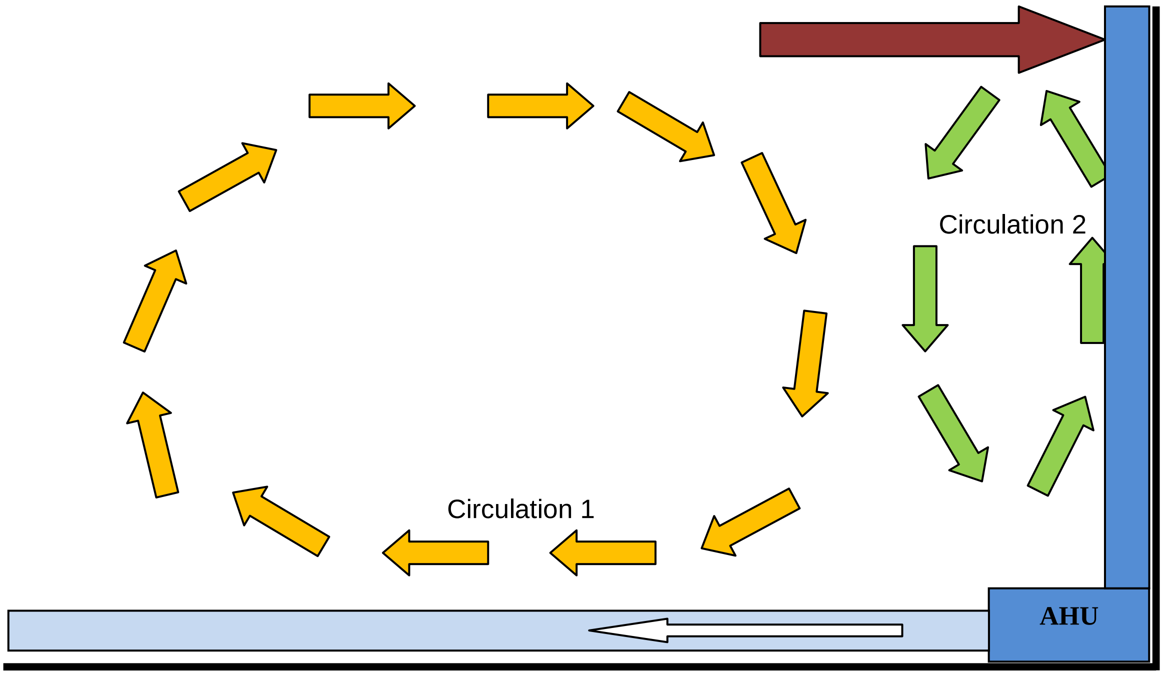


Figure 7 shows the air circulation pattern required. To achieve this:

- Air must leave the outlets at 90^o to the duct.
- Additional ducting or outlets should be installed to 'fill the gap' created by the AHU.

These conditions were provided by:

- Fitting a second larger diameter perforated duct over the existing ducts thereby isolating the final air outlets from the air travelling along the inner duct.
- Installing nozzles to blow some air back towards the wall (Figure 8).

Figure 7 – Desired air circulation pattern

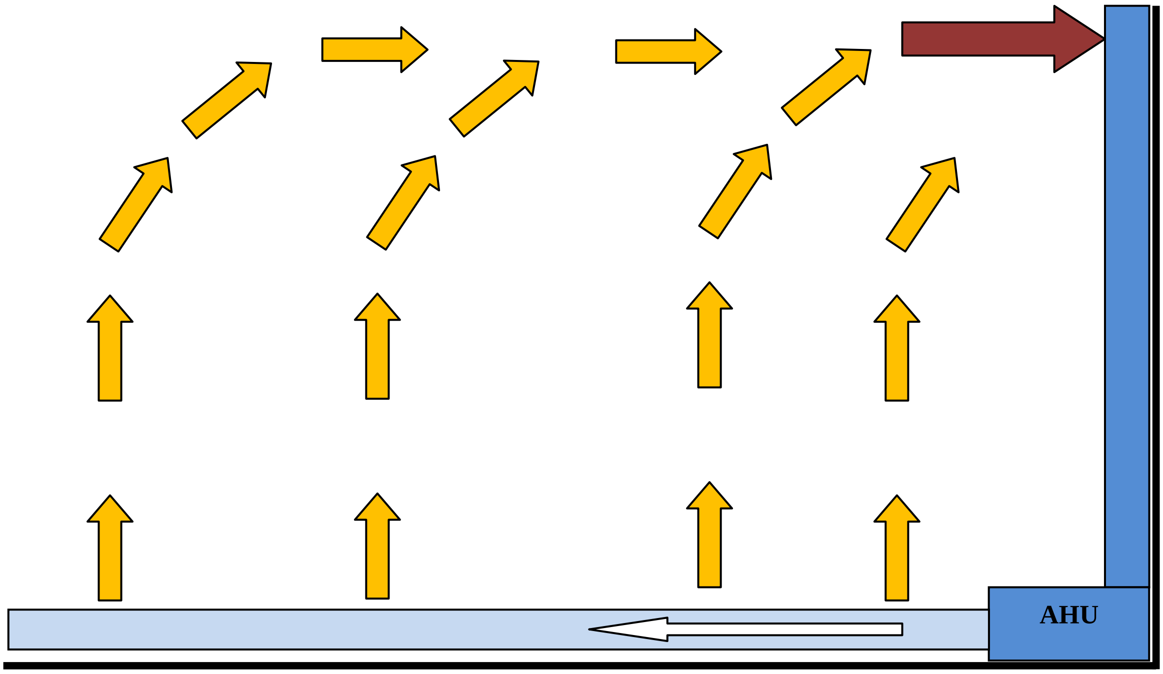
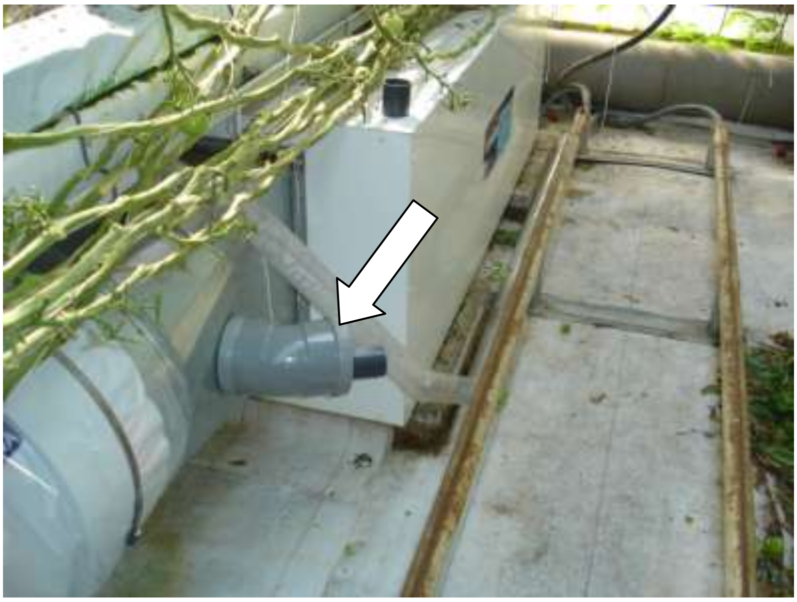


Figure 8 – Nozzle blowing air towards the greenhouse wall



Early work on solving the temperature distribution problem involved a number of modifications to a three duct sample, but this appeared to have little effect. It was concluded that these changes were being overpowered by air movement in the greenhouse as a whole and as such, piecemeal modifications and testing did not yield meaningful results.

The final modifications detailed above were therefore made to the whole installation during August 2009 in an attempt to produce a significant effect.

It was not possible to fully prove the effect of these modifications due to a lack of cold weather before the crop was pulled out in early November. However, data from brief periods of high heat demand showed that the difference between the path and wall in each of the compartments was almost the same: 1.0^{o}C in the fan and duct compartment compared to 0.9^{o}C in the conventionally heated greenhouse. There was however a slightly greater row to row variation in the fan and duct compartment.

Greenhouse environment

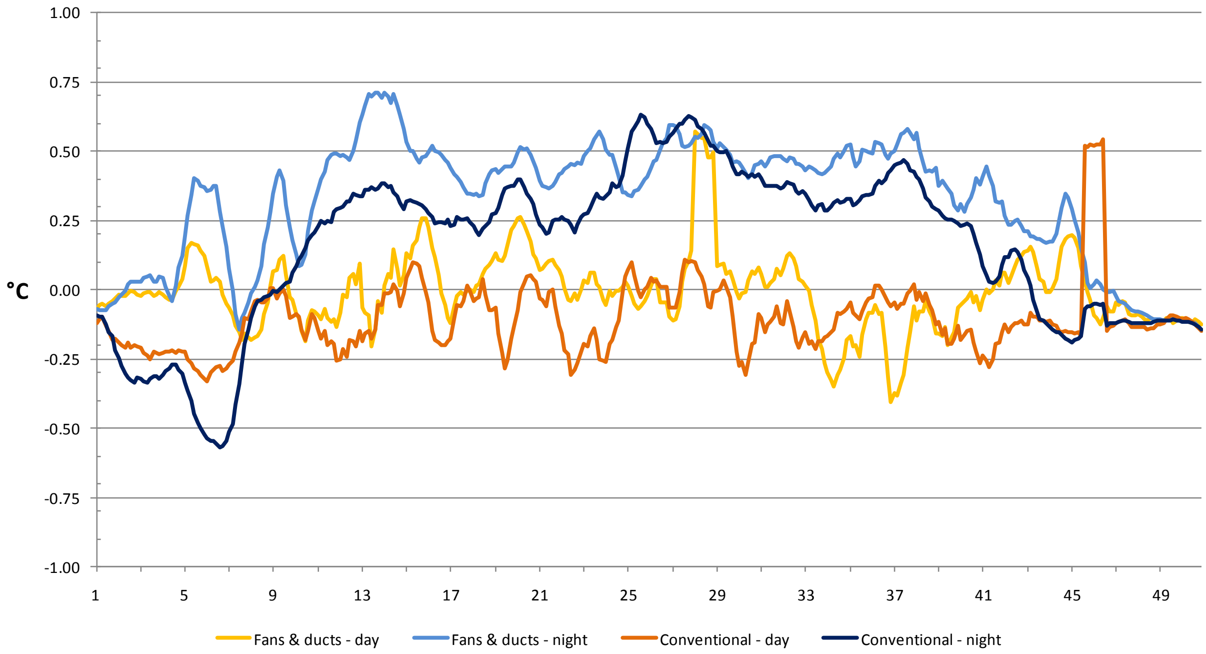
The climate in the trial and control compartments was managed according to the needs of the individual crop in all cases. This meant there were times when greenhouse temperatures in particular were different across the compartments. In general, a lower humidity deficit (HD) was targeted in CMP 12 (fan and duct) than in CMP 14.

Temperature

From the point of view of crop management via greenhouse climate, temperature continued to be the primary tool in both treatments. The greatest differences in temperature strategies occurred between weeks 4 and 12. However, the same ‘rules’ of growing (warm day, cold night for a generative effect etc.) were applied in both compartments.

The fan and duct system was expected to have an affect on the vertical temperature profile within the greenhouse. Figure 9 explores this by comparing the temperatures measured at the top of the crop (standard practice on many nurseries) and the bottom of the crop.

Figure 9 – Weekly average vertical temperature difference (bottom minus top)



Key points are:

- Up to the end of February when the crop was small, slight variation in plant growth determined whether the top measuring box was actually within the crop or suspended in free air. Therefore comparisons up to this point are unlikely to be relevant.
- During the night time it was consistently warmer at the bottom of the crop in both compartments. However, the difference was approximately 0.2°C greater in the fan and duct greenhouse than in the conventional compartment.
- During the daytime there was a slight tendency for it to be cooler at the bottom of the crop in the conventional greenhouse (0.1°C over the whole year). Whereas in the fan and duct compartment there was virtually no difference (0.01°C colder over the whole year).

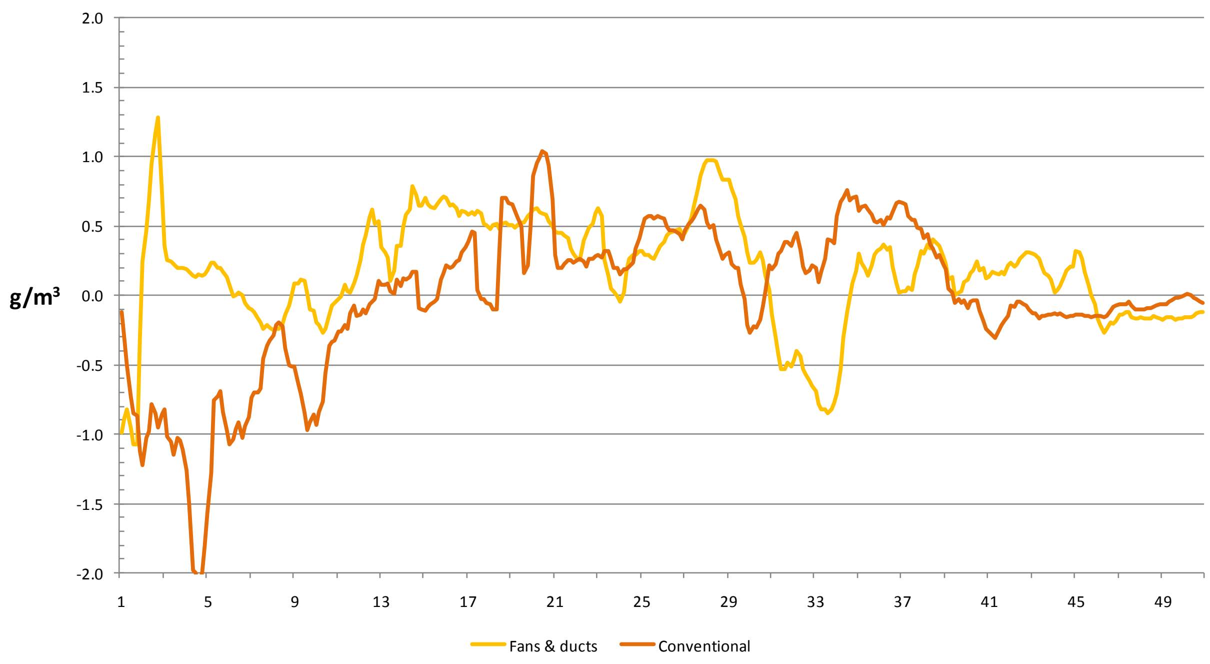
Humidity

At low HDs the grower felt that the environment in the fan and duct compartment was better than in the conventional compartment although the measured HD was almost the same. This provided the grower with the confidence to accept lower HD's in the fan and duct compartment. The target HD in the fan and duct compartment was typically 0.2-0.3g/m^3 lower than in the conventional compartment.

As with temperature, introducing outside air in particular into the bottom of the crop was expected to affect the vertical humidity profile in the greenhouse. Figure 10 shows the difference between the bottom and the top of the plants in each greenhouse during the night time. It is worth noting that:

- There were technical problems for a short period, up to the end of February with the measuring box in CMP14 and in mid-August for measuring box CMP12.
- Up to the end of February the humidity is not generally a significant environmental issue. As a result problems with the bottom measuring box in CMP14 were not noted up to this point.
- A similar and even more subtle problem occurred with the bottom measuring box in CMP12 in mid-August.

Figure 10 – Weekly average daytime vertical HD difference (bottom minus top)



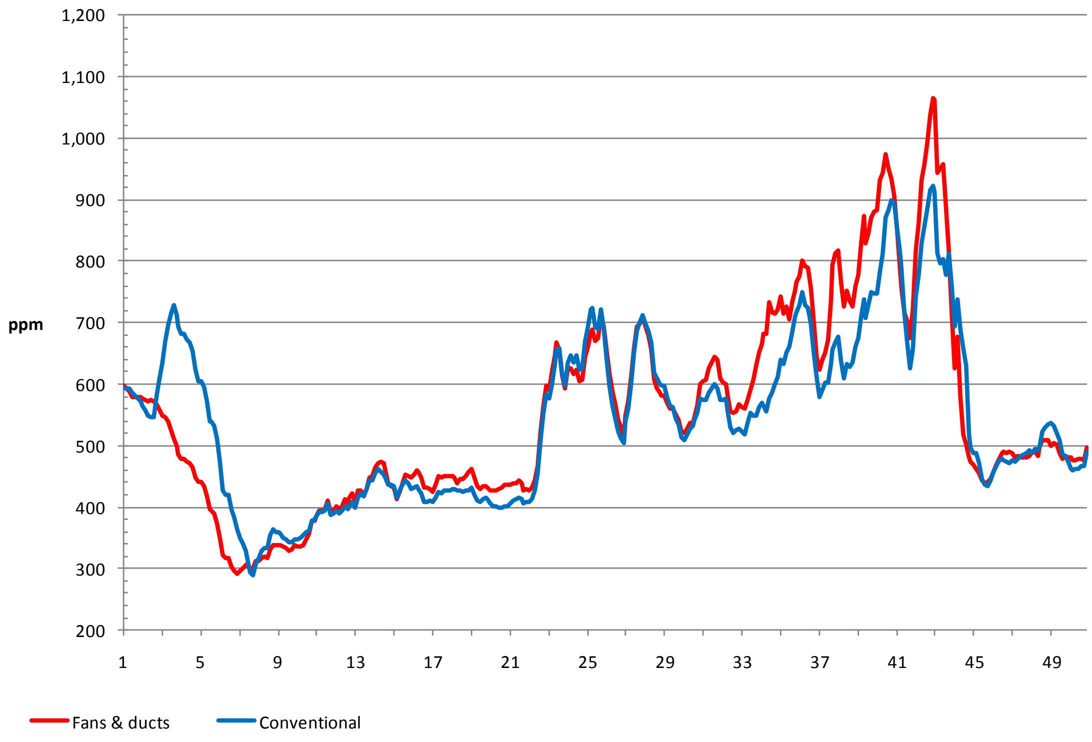
Key points are:

- It was significantly drier at the bottom of the crop, relative to the top, in CMP12 (fan and duct) than in CMP14 during March-April and September-October. This is when the outside air was quite cold which, with the addition of the heat by air delivery system, had good 'drying power' when introduced into the bottom of the crop.
- Through the summer there was little difference between the compartments. In this period the vents were open for most of the time giving good air movement even without fans.

CO_2

Both compartments are served by a single CO_2 enrichment system. This is controlled on the basis of the highest of the two CO_2 measurements taken in the compartments. The availability of CO_2 enrichment was extremely limited until the end of May due to CHP problems on the nursery.

Figure 11 – Daytime CO_2 concentration



Key points are:

- Up to the end of February the measurement equipment in CMP 14 was faulty. During this period similar levels would be expected in both compartments.
- Slightly higher CO_2 levels in CMP12 during April and May.
- Higher CO_2 levels in CMP12 from August to September. This was assumed to be the result of reduced venting at each end of the day due to lower HDs being accepted in CMP 12.

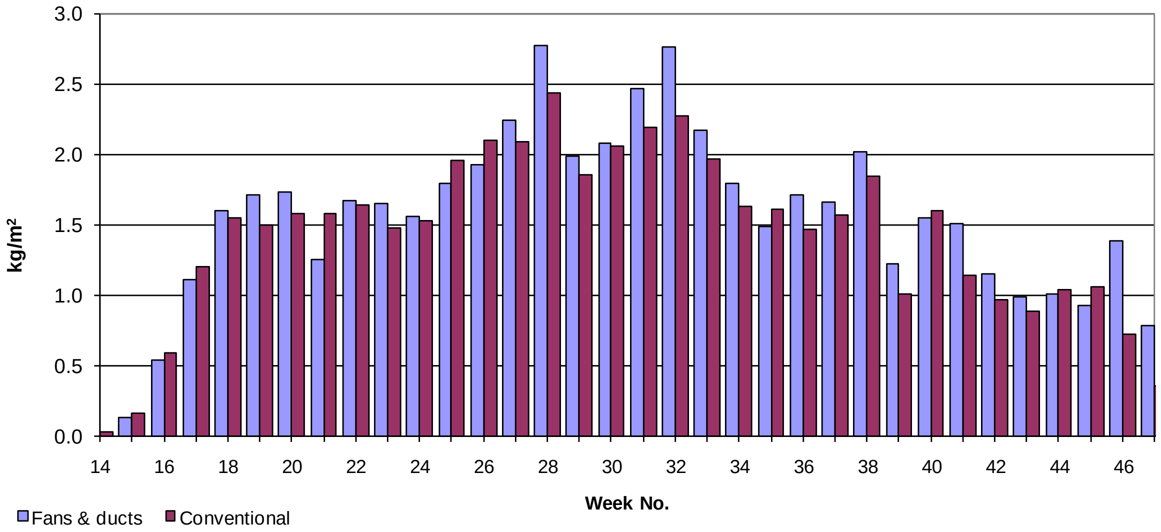
Crop data

The grower felt that the crop in the fan and duct compartment tended to be more generative than in the conventional compartment. However, there was no clear trend in the crop registration data to confirm this. The data of greatest significance are:

- The total number of trusses produced per plant were almost identical (0.07 difference).
- The fruit load per plant was higher in the fan and duct compartment from week 21 to week 33. This coincided with the oldest truss on the plants in the fan and duct compartment being older than in the conventional compartment suggesting there was a slower speed of fruit ripening in the fan and duct system.

Higher CO_2 levels in the fan and duct greenhouse suggest that the increase in yield was due to higher fruit weight. The total yield in the fan and duct compartment was 52.4kg/m^2 compared to 48.7kg/m^2 in the conventional compartment (7.6% more).

Figure 12 – Weekly yield

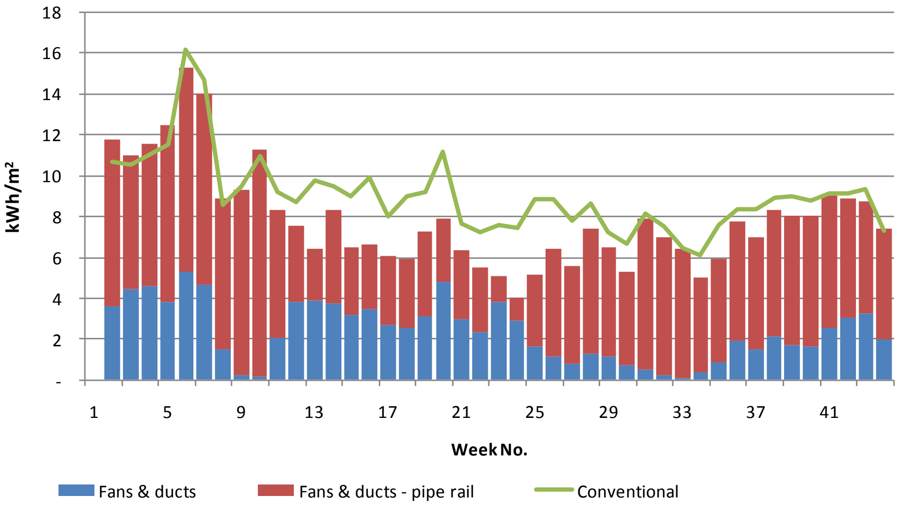


Disease assessments showed that there was less disease (principally Botrytis) in the fan and duct compartment. In the areas monitored there was a smaller number of girdling stem lesions in the fan and duct compartment (99 per 5 rows) than the conventional compartment (166 per 5 rows). The number of leaf Botrytis lesions and missing stem bases was also less and the number of surviving heads was greater.

Energy

Figure 13 shows the weekly heat energy use in each compartment and the contribution of the fan and duct system towards the total heat delivery.

Figure 13 – Weekly heat use



Up to week 10, when the heat demand was dominated by the need to maintain greenhouse temperature, the total amount of heat used in each greenhouse was similar. During this period the fan and duct system provided 26% of the total heat input to the compartment.

The fan and duct system was turned off half way through week 8 due to the temperature uniformity problems and turned on again in week 11.

Energy savings of 20-30% per week were made between weeks 11 and 30 as a result of the relaxation of humidity control set points in the fan and duct compartment. High disease pressure due to poor weather between weeks 30 and 32 required changes to set points which meant little energy was saved during this period. Total delivered heat in terms of gas consumptions (assuming 85% boiler efficiency) was:

- Conventional compartment 458kWh/m^2
- Fan and duct compartment 399kWh/m^2
- Saving 59kWh/m^2 (12.8%).

Further analysis of the data showed that 95% of the heat use in the fan and duct compartment was from water of 50°C or less. In the conventional compartment this proportion was only 60%. The remaining 5% of heat use for CMP 12 still only required a water temperature of less than 60°C. It is important to note that 40°C water satisfied 60% of the heat requirement in the fan and duct compartment.compared to 13% in the conventional compartment. This is of specific interest to those considering the use of low temperature heating systems, like heat pumps.

The fans used 11kWh/m^2 of electricity in 2009 which offsets a significant amount of the heat energy saving. However, it should be noted that the fans ran almost continuously throughout the year, mainly in an attempt to minimise the temperature uniformity problem. It is felt that there is much room for improvement in this area now that the temperature uniformity problem is thought to have been overcome. Reducing electricity consumption will be a major focus in 2010.

Financial benefits

Heat

Assuming the use of a gas fuelled boiler, the energy saving (59kWh/m^2 gas) is worth £1.00/m^2 at current gas prices (1.7p/kWh). Note that gas costs are low at present - 2008 gas costs were closer to 2.6p/kWh (76p/therm) making the energy saving worth £1.53/m^2. There is little doubt that the long term trend will be for higher gas costs.

A major component of this project was to expand the opportunities to use alternative heat sources by enabling lower temperature heating water to be used. With typical heating costs of £10.00/m^2 the value of this could be significant, especially where low-grade waste heat from other industries may be available.

Where CHP is available, as at Mill Nursery, low grade heat is often rejected to heat destroyers in the form of water at 40-45°C. This could be used by the fan and duct system. On the basis that this heat would normally be 'dumped' it could be regarded as free heat. There are also potential savings in electricity used by the fans on the heat destroyers. Subject to the running regime and size of the CHP it may be possible to satisfy up to 30% of the greenhouse heat demand from such sources giving a saving of up to £30,000/Ha.

Electricity

The fans used 11kWh/m^2 of electricity. At current mains electricity prices this would cost £0.77/m^2. Where a nursery has CHP the effective cost of electricity is much less than 'mains price' and is equivalent to the value of electricity sold to the grid at wholesale prices. This would reduce the cost of electricity to around £0.50/m^2.

For a nursery using gas boilers and mains electricity the net value of energy saving in 2009 would be £0.23/m^2.

Maintenance

Maintenance requirements and cost have been minor after the 'teething troubles' which occurred during the first year of commercial trials in 2008. Two fans failed - one required replacement bearings at minimal cost and the other required a motor re-wind. Both fans were on the same side of the greenhouse (CMP11) where there were problems with water ingress in 2008.

The only item that requires ongoing maintenance to date is air filters in the air handling units. Alternative filter media will be tested early in 2010 to try and identify the ones that are: cheaper; that can be cleaned and that do not significantly impede airflow.

Crop

A yield increase of 3.7kg/m^2 (7.6%) was achieved. This occurred from week 27 onwards and as such coincides with typically lower prices for the fruit. As the crop was the loose round variety Encore, additional yield in terms of kilos will deliver additional income.

The same may not be the case with tomatoes on the vine. However, if consistently overweight vines are produced there is the opportunity to either produce more vines by increasing the crop density or reduce levels of CO_2 enrichment and associated energy use.

Taking a notional value of £0.50/kg for the crop the extra yield could be worth £1.85/m^2.

Capital cost

The capital cost of the installation was £15.90/m^2. It should be remembered that this technology is very much in its early adoption stage and costs are expected to come down. Since this installation was completed in March 2008 several other suppliers have brought similar products to the market. Growers are therefore advised to obtain quotes for a fan and duct installation specific to their own circumstances as significant variance is expected.

Taking the specific example discussed above the total financial benefit (net energy saving plus yield increase) was worth £2.08/m^2. This gives a simple payback on investment of 7.6 years. However, if low grade heat from the CHP had been used, which is notionally free, the pay back on investment could be as low as 3 years.

Conclusions

It is commonly believed that any means of increasing air movement will improve the uniformity of the greenhouse environment. Interestingly, this project shows that this is not the case and work needs to be done on the design of forced air distribution systems to ensure that this is not a problem. However, in spite of the temperature uniformity problems encountered, fan and duct installations have been proven to deliver:

- Increased yield (7.6% in 2009) largely due to reduced venting for humidity control leading to higher CO_2 levels in the greenhouse.
- A saving of 59kWh/m^2 of gas used for heating (12.8%) - offset by high electricity use (11kWh/m^2).
- The ability to use low grade heat sources to satisfy the heating demand of greenhouses. With appropriate design it should be possible to heat a greenhouse with a maximum heating water temperature of 40^{o}C.
- Lower disease levels.
- Minimal impact on the way that the crop is managed.

Action points for growers

The results presented in this report are the findings from the first full year of commercial trials of the fan and duct system and this should be borne in mind when considering their possible commercial replication. Nevertheless, growers who have the potential to access sources of low grade heat may well consider this trial as ample evidence to justify adoption of this technology.

Potential adopters of the technology should:

- Determine the amount of heat that is available and the synergy between production and greenhouse heat demands.
- Explore the feasibility and cost of accessing the heat. This could be significant. For example, in the case of CHP this may require additional heat exchangers, pumps and control systems.
- Identify potential suppliers of fan and duct systems.
- Obtain quotes using the specification of the system installed for this project (2 air changes per hour, 450kW heating capacity/Ha).

Science Section

Introduction

High energy costs and greater awareness of climate change issues continue to threaten the viability of glasshouse horticultural production in the UK. As a result growers are constantly looking for methods to both reduce their dependence on fossil fuels and increase production relative to the energy used. Growers in the Netherlands are subject to these same business pressures and one of the outcomes of this has been extensive Dutch research and development into closed glasshouse systems. PC 256 (2007) investigated the potential for using closed glasshouse technology in the UK and concluded that the application of closed glasshouse concepts as a whole was not technically or financially viable. However, the project identified that ducted air heating and ventilation systems that are widely used in closed glasshouses may offer considerable benefits if applied to conventional glasshouses. Combined with the results of PC 226 (2005) and PC 47 (1994) the need to develop and test such a system on a commercial scale in the UK was viewed to be a high priority and, as a result, this project was commissioned.

Objectives

- The aim of the project is to investigate the ability of ducted air delivery systems to:
- Reduce energy use and cost in heated glasshouses.
- Reduce CO_2 emissions associated with glasshouse production.
- Expand the opportunities for glasshouse businesses to use alternative heat sources.
- Improve yield and quality.
- Reduce disease incidence and therefore the use of crop protection chemicals.

Materials and methods

The project comprises three parts:

- Research, development and design of a commercially acceptable ducted air heating and ventilation system for the trial greenhouse at a commercial nursery in the UK.
- Installation of the selected system at the trial site.
- Commercial trials to investigate system performance and crop response.

Previous reports, PC 278 Interim Report, September 2008 and PC 278 Annual Report April 2009 cover items 1, 2 and the first year of commercial trials in 2008. This report details the second year of commercial trials carried out in 2009.

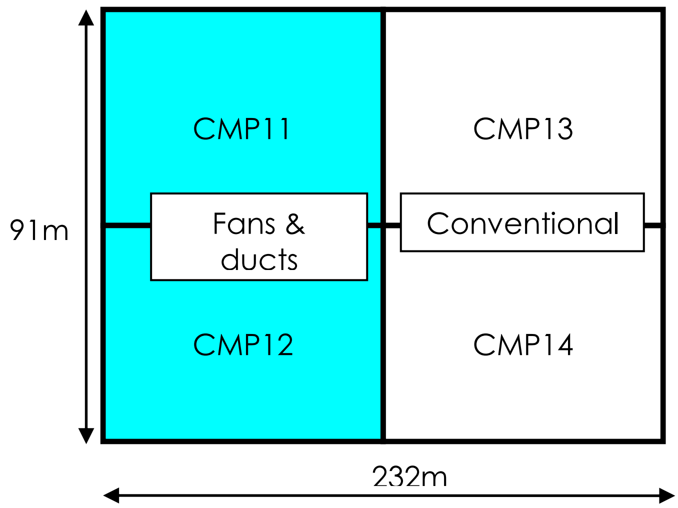
Trial site and equipment

The trial site, equipment and data collection procedures remain the same as in 2008. For ease of reference they are repeated below.

Site/greenhouse

The project is being carried out in a 2.1Ha greenhouse at Mill Nursery Ltd in East Yorkshire. A fan and duct system was installed in one half of the greenhouse in March 2008 and is being compared with the other half of the greenhouse which has a conventional heating and ventilation system. A temporary partition was installed to create two separate airspaces as shown in Figure 14.

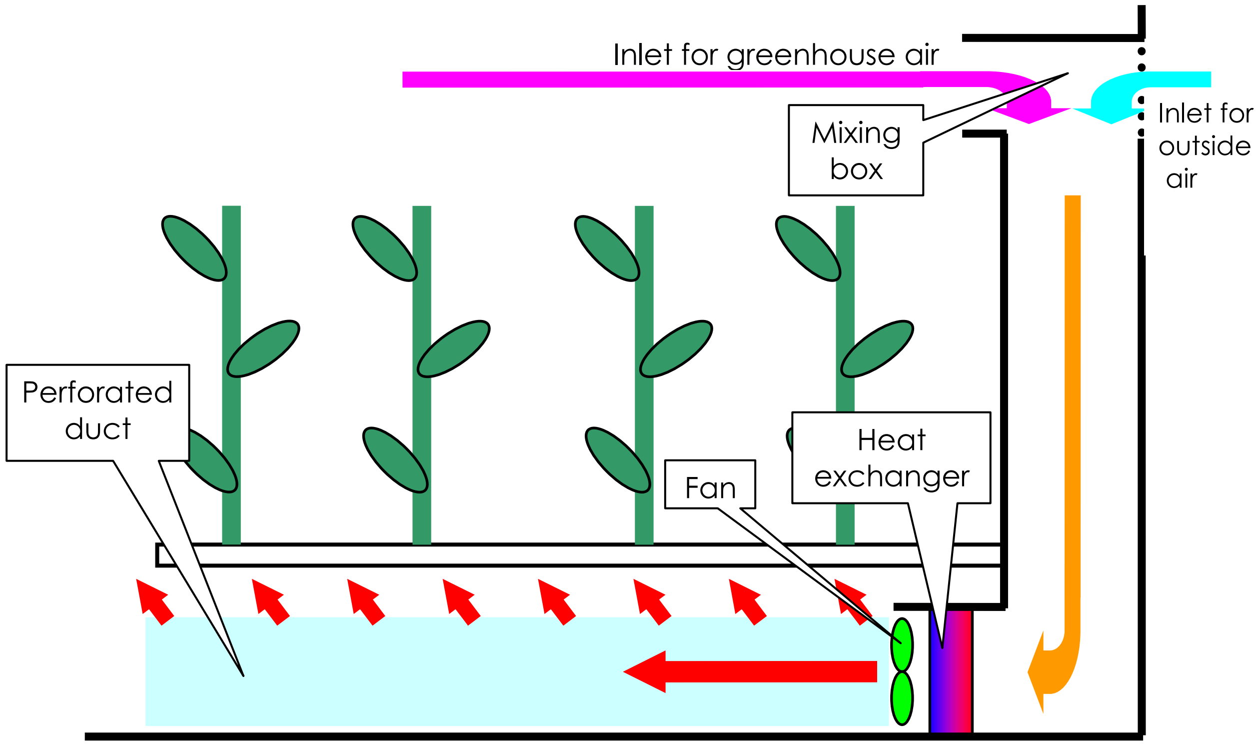
Figure 14 – Layout and dimensions of the trial greenhouse



Equipment

The installation comprises 18 air handling units (AHU). Figure 15 shows a single air handling unit of the type installed.

Figure 15 – Air handling unit schematic



The fan and duct installation has a heating capacity of 450kW/Ha and delivers an airflow of 108,000m^3/hr (2 air changes per hour). It should be noted that it is not capable of satisfying all the heating and ventilation needs of the greenhouse and the existing pipe rail heating system and roof vents continue to be used.

The design of the installation is provided in more detail in report PC 278 Interim report, September 2008.

Regular data collection

Greenhouse environment

The aerial environment within CMP12 (fans and ducts) and CMP14 (conventional) was recorded using the site climate control computer. Data was downloaded every week via broadband connection by FEC consultants. Table 1 below lists the measurements taken in each compartment.

Table 1 – Greenhouse aerial environment measurements

Location	Temperature °C	Humidity deficit g/m^3	Relative humidity %	Dew-point temperature °C	CO_2 concentration ppm
30-50cm above the growing media	✓	✓	✓	✓	
30-50cm below the growing point of the crop	✓	✓	✓	✓	✓

The following equipment status was recorded:

- Set points – heating and ventilation temperatures, minimum heating pipe temperature.
- Heating system – calculated and measured heating pipe temperature.
- Ventilation system – calculated and measured vent position.
- Thermal screen position.

Irrigation

The water uptake by the plants in compartments 12 and 14 was calculated using grow-scale and drain measuring equipment, and with the Priva Integro which controls the irrigation system.

Energy use

Heat use was measured using non invasive ultrasonic flow meters connected to a heat meter integrator.

Electricity

The electricity used by the fans was measured by a meter built into the variable speed drive used to control them.

Crop data

Crop registration data formed the basis for numerical comparison of the development of the plants in each compartment. Measurements were taken every week by nursery staff and returned to FEC for analysis. The measurements taken included:

- Stem diameter
- Weekly and total growth
- Number of leaves per plant and leaf length
- Number of trusses formed and harvested
- Distance of the youngest truss from the growing point

Yield was recorded as the total kilos of fruit harvested each week.

Disease levels, principally Botrytis, were assessed in defined areas in two ways:

- Plants removed - recorded by nursery staff.
- Detailed assessment at key stages of the season

Results

Temperature uniformity within the greenhouse

Results from 2008 showed that the uniformity of temperature within the fan and duct compartment (CMP12) was broadly the same as in the conventional compartment albeit with slightly greater row to row variation. These measurements were taken during September and October when the vents tended to be open and the heat demand was low. As such, they were not a good indication of how the fan/duct system was performing in respect of temperature uniformity.

To explore the temperature uniformity further, especially during winter operation (no venting and high heat demand), fifteen temperature loggers were installed in each greenhouse compartment at a height of approximately 30cm above the hanging gutter. They were placed half way along each compartment in a grid pattern to enable any variation in temperature both across and along rows to be identified. Figures 16 and 17 show the average temperature recorded by each data logger between 07/01/2009 and 13/01/2009.

Figure 16 – Fan and duct compartment (CMP12)

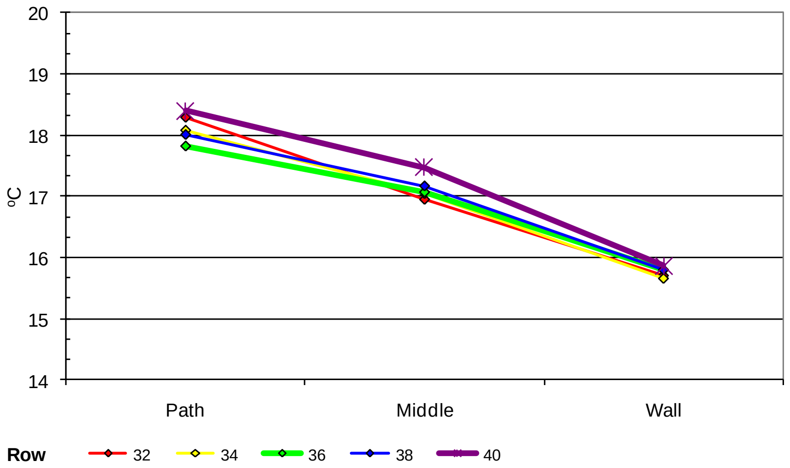
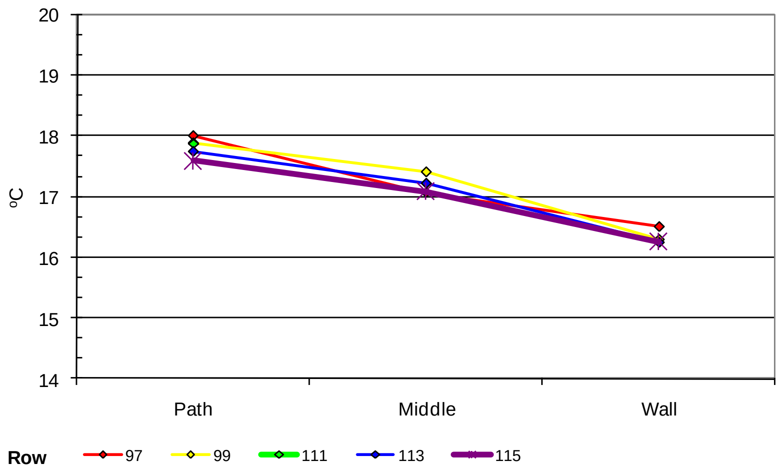


Figure 17 – Conventionally heated compartment (CMP14)



Both compartments were colder at the wall of the greenhouse than at the central path. However, the temperature differential in the case of the fan and duct compartment was 2.3^{o}C compared to 1.5^{o}C in the conventionally heated greenhouse. Continued monitoring showed that this trend was maintained whenever the greenhouse vents were closed.

The ducting installed at this stage had holes equally spaced along its length and measurements taken in 2008 and again in 2009 showed that 15-20% more air exited the outlets at the path end of the duct than at the wall end of the duct. Heated air exiting the duct was also colder at the path end of the duct. The combination of higher airflow and warmer air implied that more heat was being delivered at the wall end of the duct - opposite to that suggested by the temperature uniformity data.

Various modifications were tested on three ducts in the middle of the greenhouse representing an area of 44m x 38.4m (1,689m^2) to prove / disprove theories and test possible solutions. Each modification and its effect are detailed below.

Modification 1

Progressively more duct outlets were blocked towards the path end in an attempt to increase the proportion of heat delivered close to the greenhouse wall. Monitoring showed that this had no effect on the temperature uniformity achieved.

Modification 2

The duct blocking was increased with two out of every three outlets closed at the path end, with gradually less blocked until all were left fully open at the wall. Monitoring showed that this also had no effect on the temperature uniformity achieved.

Modification 3

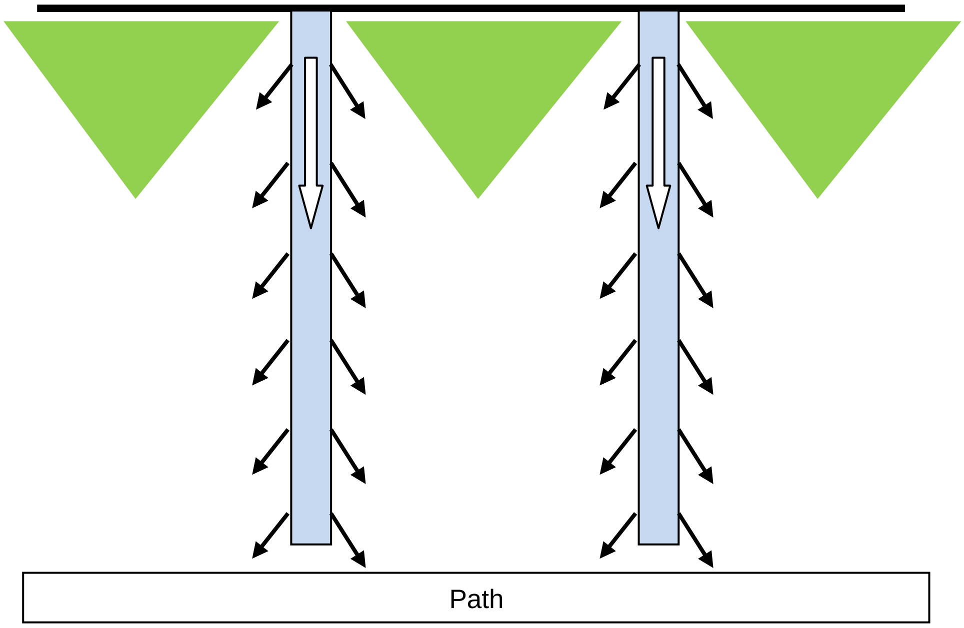
At this point (mid-February) plant development at the wall end of the rows in the fan and duct compartments was visibly behind the path end of the rows. This was significantly worse than in the conventional greenhouse. As a result, although the fans continued to run, the fan and duct installation was not allowed to add any heat. It was believed that this would continue to deliver the benefits of air movement whilst delivering the same heating uniformity (via the pipe rail system) in both the conventional and fan and duct compartments.

Ongoing monitoring showed that, even in this mode of operation, the temperature close to the wall in the fan and duct compartment remained significantly lower than at the path and worse than in the conventional compartment. As a result, the fan and duct installation was shut down for two weeks to allow the crop to recover before resuming testing. It was concluded that the underlying cause of poor temperature uniformity was related to air circulation patterns rather than heat distribution.

Modification 4

Figure 18 is a plan view of two ducts and shows the direction of the air leaving the duct outlets. As the outlets are in the form of a plain circular hole and the air within the duct is travelling towards the path, the air does not leave the outlets at 90^o to the duct. This leaves a dead-zone (green triangles) that was largely unaffected by any of the modifications made up to this point. It was postulated that if the air was made to leave the ducts at 90^0 to the duct direction this would aid even temperature distribution.

Figure 18 – Plan view of airflow from the ducts



To address this, nozzles were fitted to each outlet to force the air to exit at 90^{o} to the duct (Figure 19).

Figure 19 – Nozzles installed in the duct

However, this still had no affect on the temperature uniformity achieved.

Modification 5
At this point it was believed that, even though the modifications to date affected 1,689m^2, they were being overpowered by the air movement patterns created in the greenhouse as a whole. Combined with the experience gained up to this point Priva NL installed additional fans and ducts (no heating or air mixing facility) in the whole of CMP11 to blow air back towards the greenhouse wall (Figures 20 and 21).

Figure 20 – Layout of additional fans installed in CMP11

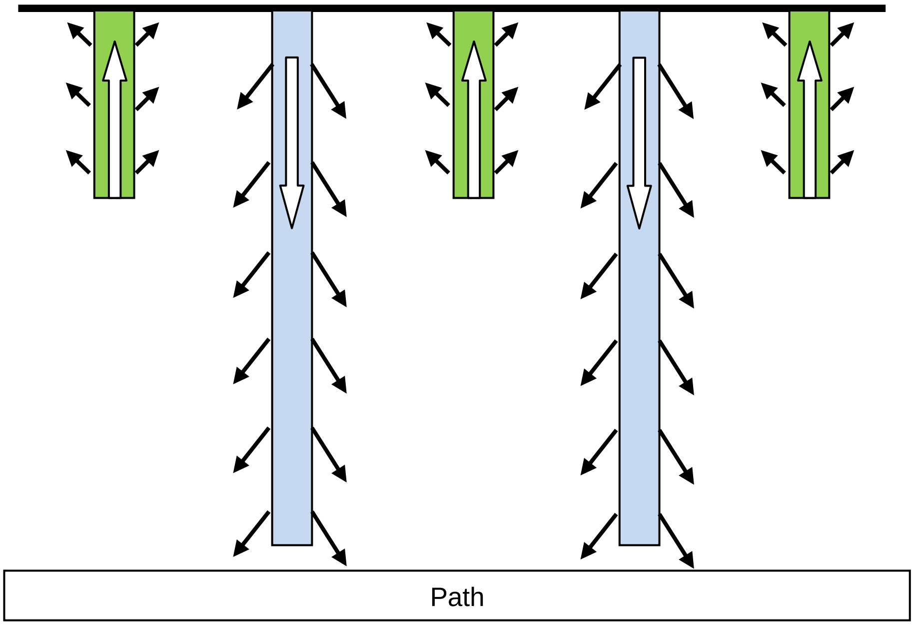


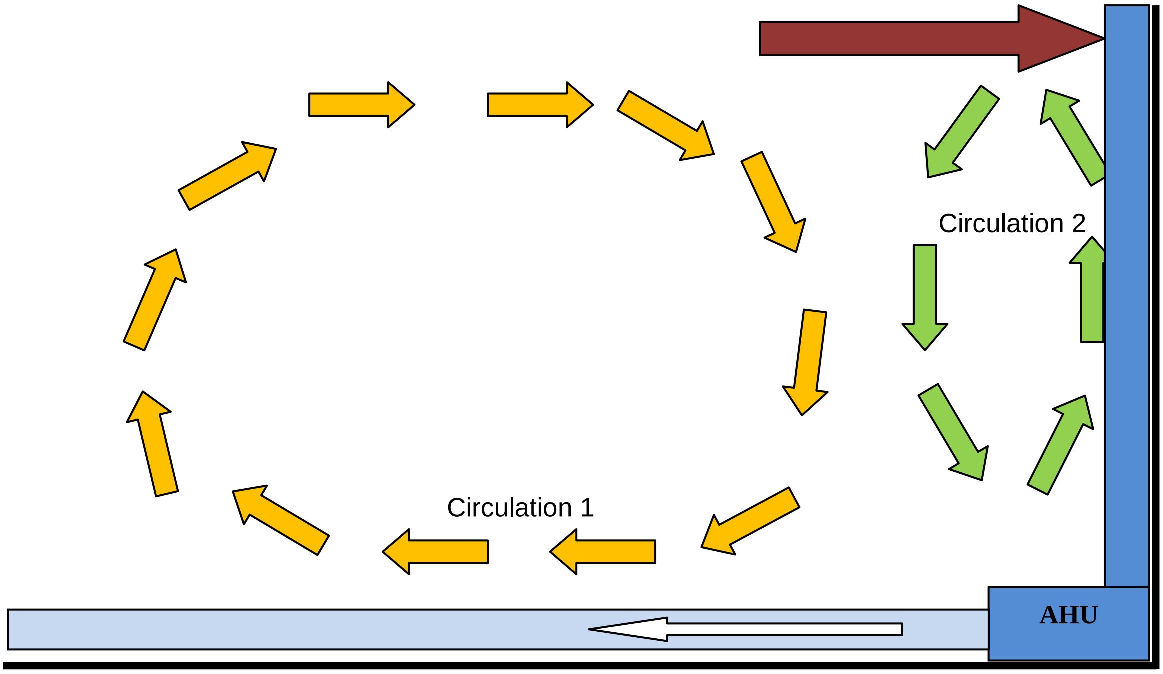
Figure 21 – Photograph of extra fans installed in CMP11

In this instance the temperature uniformity achieved in CMP11 (original fan and duct installation plus extra fans) was compared with CMP12 (original fan and duct installation). Once again the modifications had no affect on the temperature uniformity achieved. However, testing was extremely limited due to higher outside temperatures at this stage.

At this stage (late April 2009) weather conditions were such that there were few opportunities to test further modifications until much later in the year.

Modification 6
Further smoke tests confirmed that there were two air circulation patterns in the greenhouse which could be the root cause of the poor temperature uniformity (Figure 22).

Figure 22 – Original air circulation patterns



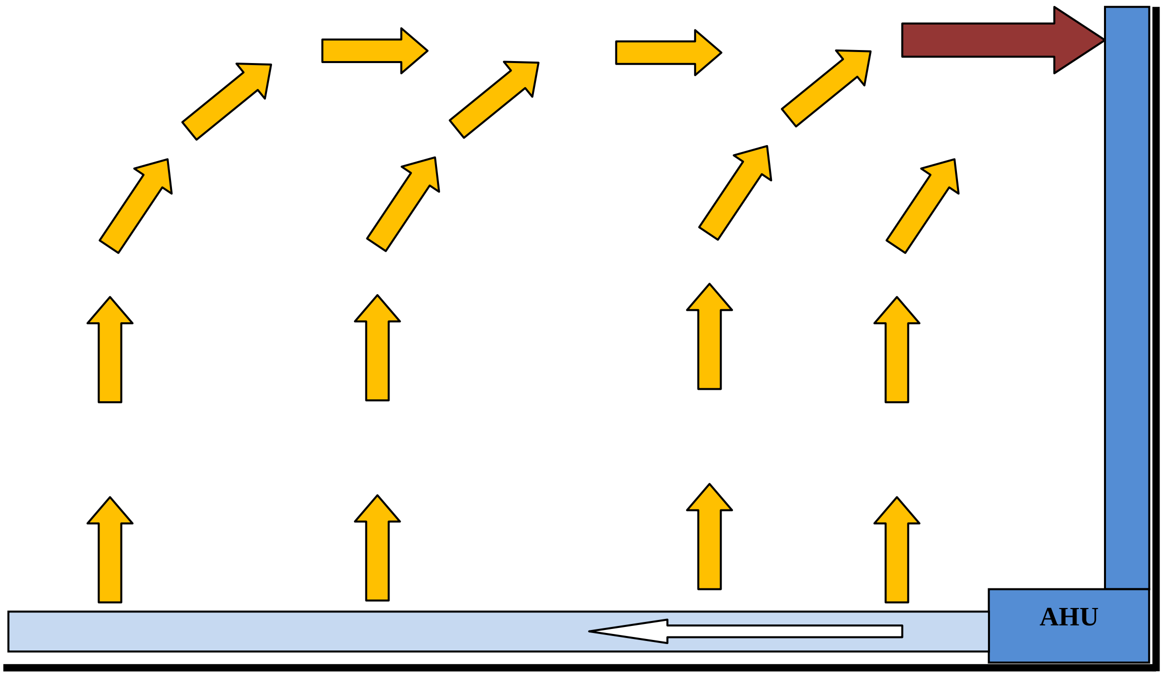
The power of circulation pattern 1 was exaggerated by the air exiting the duct with some residual forwards velocity. To reduce the power of this air circulation patter the air should exit the duct at 90o. However, this alone was not expected to eliminate circulation pattern 2.

Circulation pattern 2 was driven by the heating effect of the hot water distribution pipes along the wall. With air being driven forwards by the duct, there was no forced air to break this pattern.

Figure 23 shows the air circulation pattern required. To achieve this it would be desirable for:

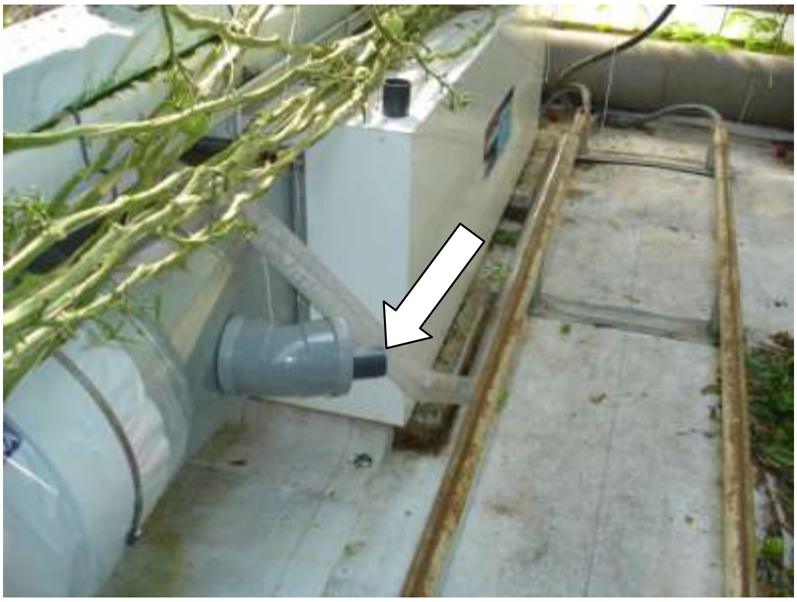
- Air to leave the outlets at 90° to the duct.
- Additional ducting or outlets to be installed to break up the secondary air circulation near the AHU.

Figure 23 – Desired air circulation pattern



Ensuring the air exited at 90° to the duct could have been achieved by installing nozzles as tested in modification 4. However, this would have required over 2,000 nozzles. The solution (proposed by Priva) was to fit a second larger diameter perforated duct over the existing ducts thereby isolating the final air outlets from the air travelling along the inner duct. The secondary air circulation near the AHU was modified by installing nozzles to blow a small amount of air back towards the wall (Figure 24).

Figure 24 – Nozzle blowing air towards the greenhouse wall



These modifications were made in the whole of the fan and duct greenhouse (CMP11+12) during August 2009.

Due to a lack of cold weather before the crop was pulled out in early November it was not possible to fully prove the effect of these modifications. Figures 25 and 26 show the temperature uniformity achieved between 00:00 and 07:00 on 02/11/2009.

Figure 25 – Fan and duct compartment (CMP12)

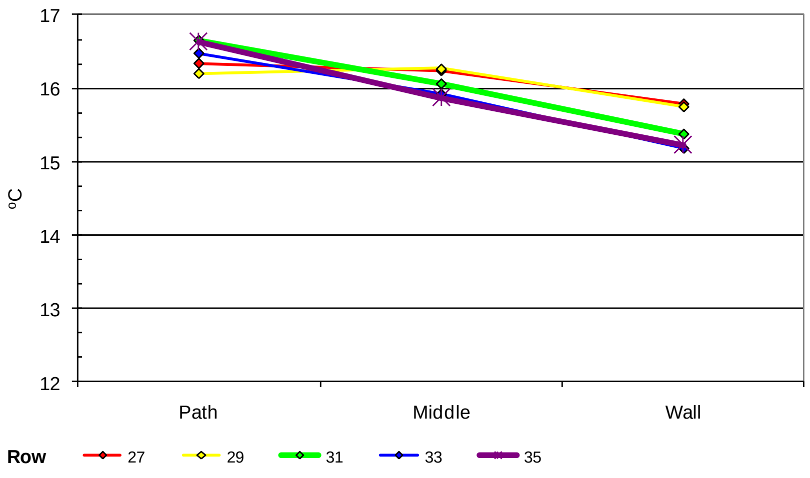
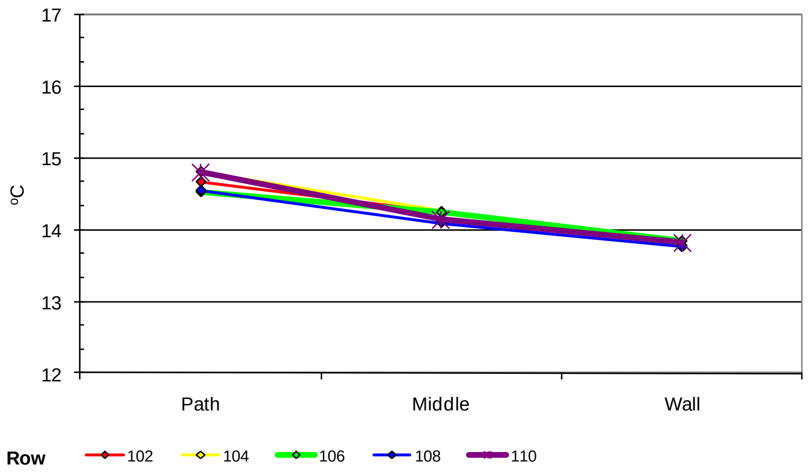


Figure 26 – Conventionally heated compartment (CMP14)



Once again both compartments were colder at the wall of the greenhouse than at the central path. However, the difference between the path and wall in each of the compartments was almost the same; 1.0°C in the fan and duct compartment compared to 0.9°C in the conventionally heated greenhouse. There was however slightly greater row to row variation in the fan and duct compartment.

The greenhouse environment and climate control strategy

The 2009 strategy was broadly similar to that used in 2008. The greenhouse climate in each compartment was managed according to the needs of the crop in all cases. This meant there were times when the greenhouse temperatures in particular were different. In general, a lower humidity deficit (HD) was targeted in the fan and duct compartment.

Temperature

The grower felt that the fan and duct crop was more generative than the conventional crop for the majority of the year. Greenhouse temperature (24-hour average, day-night difference) continued to be the main tool used to manage plant development in both greenhouse compartments. During February in particular, frequent changes to set points were implemented by the grower in response to small changes in crop development. The temperature could vary by as much as 2°C between compartments albeit for periods of only a few days. From April onwards the target greenhouse temperature was the same in both compartments the majority of the time.

It was possible to apply separate heating and ventilation temperature set points to the fan and duct system, pipe rail heating and greenhouse ventilators. The basic approach was to use the fan and duct system as the first stage of heating:

- The pipe rail heating temperature in the fan and duct compartment was set 0.2^{o}C lower than the fan and duct heating set point.
- The fan and duct cooling temperature was set the same as the lee side ventilation temperature in the conventional greenhouse.
- The lee side ventilation temperature in the fan and duct compartment was set 0.5^{o}C higher than the lee side ventilation temperature in the conventional compartment.

In addition, minimum pipe temperature set points were applied to the pipe rail heating to satisfy the base load heating demand. These were typically between 30-40^{o}C depending on the time of year and time of day and were usually 10^{o}C less in the fan and duct compartment.

Humidity
The target HD in the fan and duct compartment was lower due to the reduced disease risk and increased plant activity expected as a result of improved air movement.

As a general rule, a minimum pipe rail temperature of 30^{o}C was set in the fan and duct compartment whenever the HD was at or below target. During the night time any further humidity adjustments were led by to the fan and duct system i.e. there was no further increase in minimum pipe rail temperature. During the daytime, if the humidity deficit was less than 2.5g/m^3 the minimum pipe rail temperature was increased to 40^{o}C. In the conventional compartment, humidity influences increased the minimum pipe temperature to a maximum of 55^{o}C.

At ‘tier 1’ level, humidity control set points for the fan and duct installation were relatively simple. It was possible to set a target humidity deficit for different times of the day in the same way as heating temperature. The control software then calculated the correct mix of greenhouse to outside air and how much heat was required to achieve satisfactory humidity control. In practice, although better than in 2008, the outcome was often unsatisfactory, requiring constant attention to ‘tier 2’ and ‘tier 3’ set points. A useful addition in 2009 at a user level was the ability to set a minimum duct air temperature. This was provided following experience in the 2008 season when chilling of the stems and fruit was suspected. The minimum duct air temperature was typically equal to the greenhouse heating temperature apart from during the early evening / pre-night period when it was 1^{o}C less. The latter provided greater cooling capacity when the risk of condensation was low.

Temperature
Figure 27 shows the weekly average temperature measured at the top of the crop. This is the only temperature measured by most growers. For the sake of consistency the temperature and humidity at this point was used by the climate control computer on both greenhouses.

Figure 27 – Weekly average temperature at the top of the crop

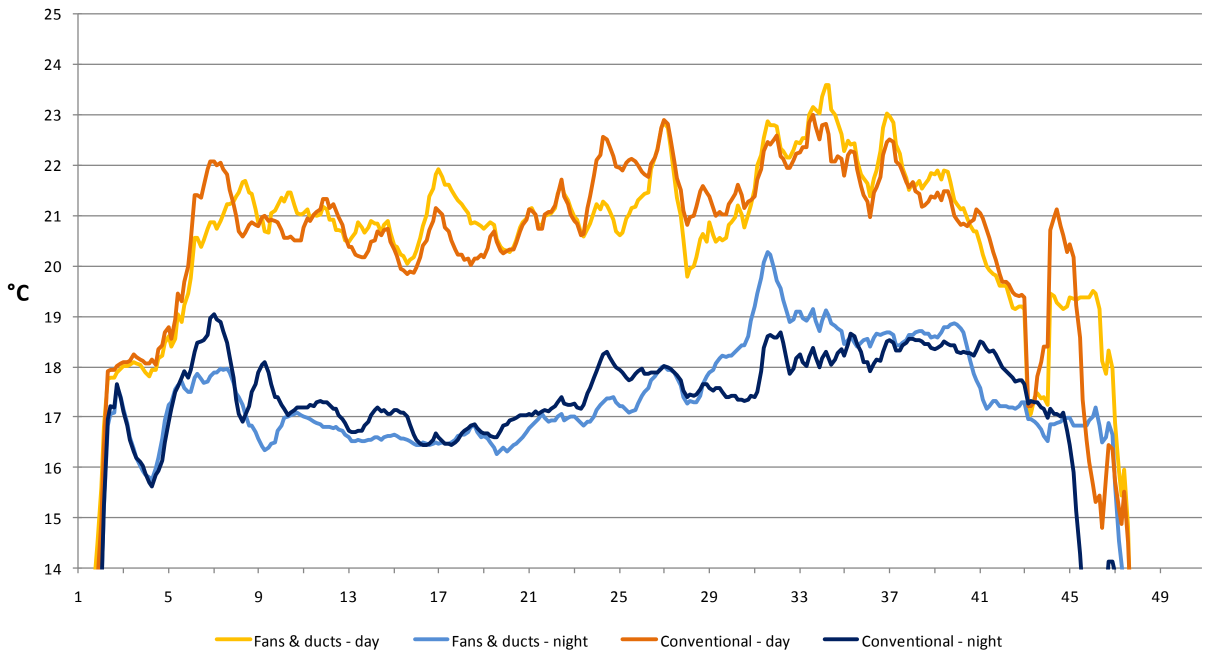
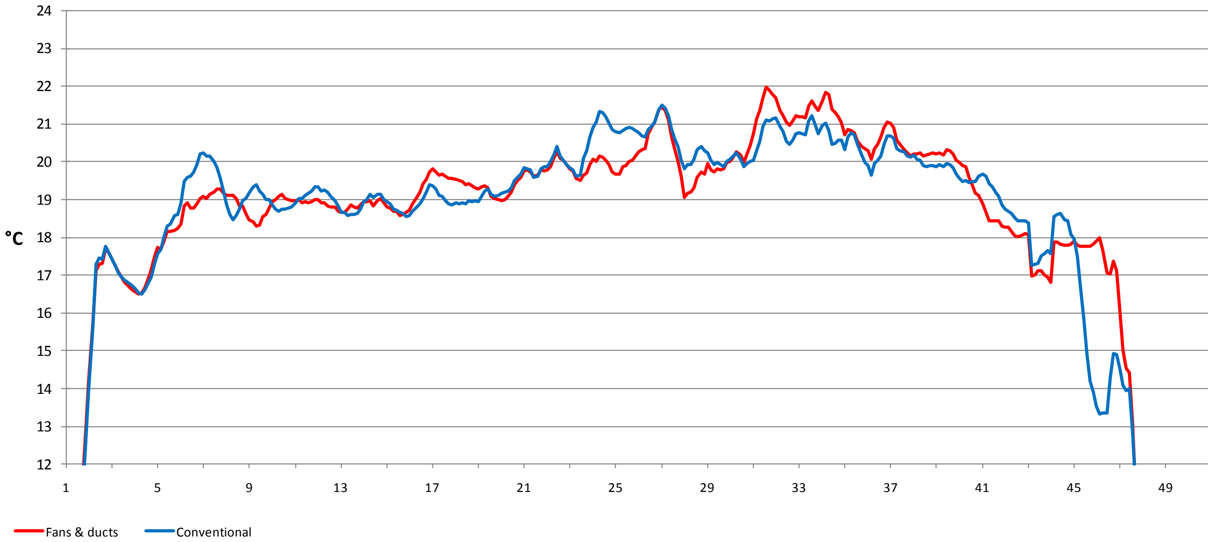


Figure 28 – Weekly 24-hour average temperature at the top of the crop



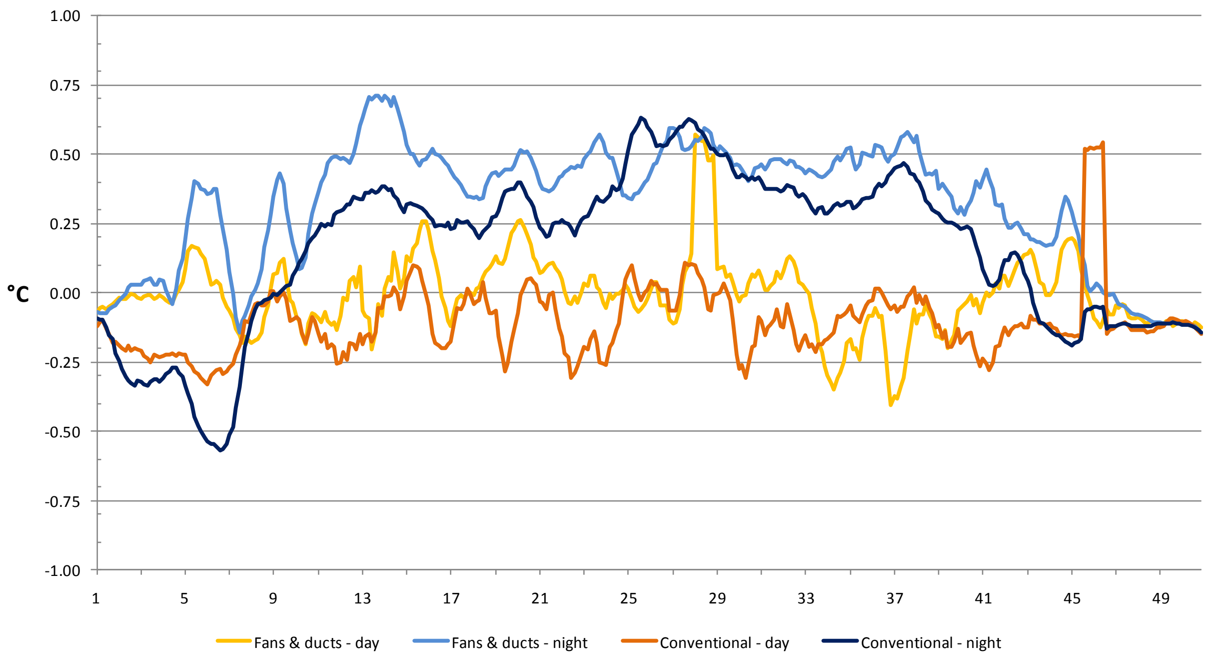
Several points of particular interest are noted on the graph:

- Virtually identical temperatures in both compartments during the first month.
- Week 7. The balance of the fan and duct crop was thought to be good whereas the conventional crop was felt to be too strong. A period of higher temperatures was therefore required.
- Weeks 11 to 29. As weather conditions improved the ability to achieve lower night time temperatures became more difficult especially when heat was used to control humidity. As a lower humidity deficit was tolerated in the fan and duct compartment less heat was used and lower night time temperatures were achieved.
- Week 32. The fan and duct crop was thought to be too generative. Therefore the day – night temperature difference was reduced to stimulate vegetative growth.

The air blown into the bottom of the crop by the fan and duct installation can range from:
100% outside air with no heat added – as cold as 10^{o}C.
100% recirculated greenhouse air with heat added – as warm as 35^{o}C.

This can affect the vertical temperature differences in the fan and duct greenhouse and therefore plant development. Figure 29 shows the difference between the temperature measured at the top and bottom of the crop in both greenhouses.

Figure 29 – Weekly average vertical temperature difference (bottom minus top)



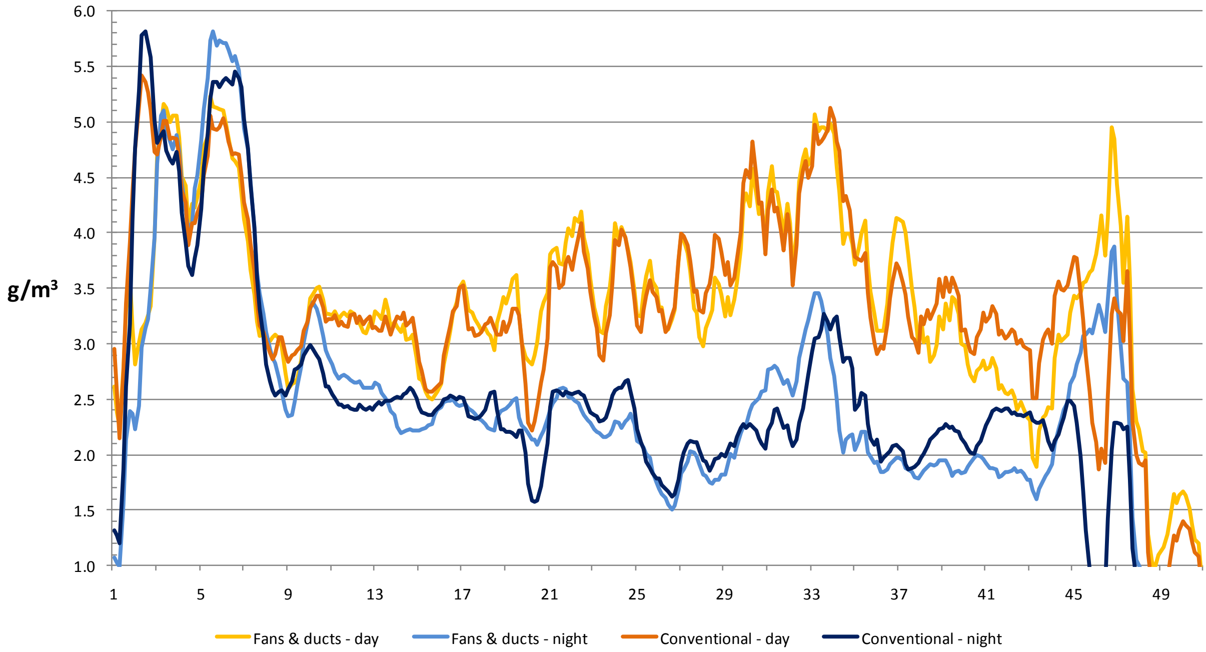
Key points are:

- Up to the end of February when the crop was small, slight variation in plant growth determined whether the top measuring box was effectively within the crop or suspended in free air. Therefore comparisons up to this point are likely to be inaccurate.
- During the night time it was warmer at the bottom of the crop in both compartments. However, the difference was approximately 0.2^{o}C greater in the fan and duct compartment than in the conventional compartment.
- During the daytime there was a slight tendency for it to be cooler at the bottom of the crop in the conventional compartment (0.1^{o}C over the whole year). Whereas in the fan and duct compartment there was virtually no difference (0.01^{o}C colder over the whole year).

Humidity deficit

Figure 30 shows the average humidity deficit (HD) measured at the top of the crop.

Figure 30 – Weekly average HD at the top of the crop



The target HD during the daytime was 3.0g/m^3 in the conventional compartment (CMP14) and 2.8g/m^3 in CMP12. During the night time it was 2.5g/m^3 in the conventional compartment but a lower level (2.2g/m^3) was targeted in the fan and duct compartment. Such differences are difficult to see in averaged data. From the point of view of disease it is the amount of time spent at low HD (high RH) that is important. Figures 31-32 compare the number of hours per week that the HD was below 2.5g/m^3 during the night in each compartment both at the top and bottom of the crop.

Figure 31 – Top of crop HD hours per week below 2.5g/m^3

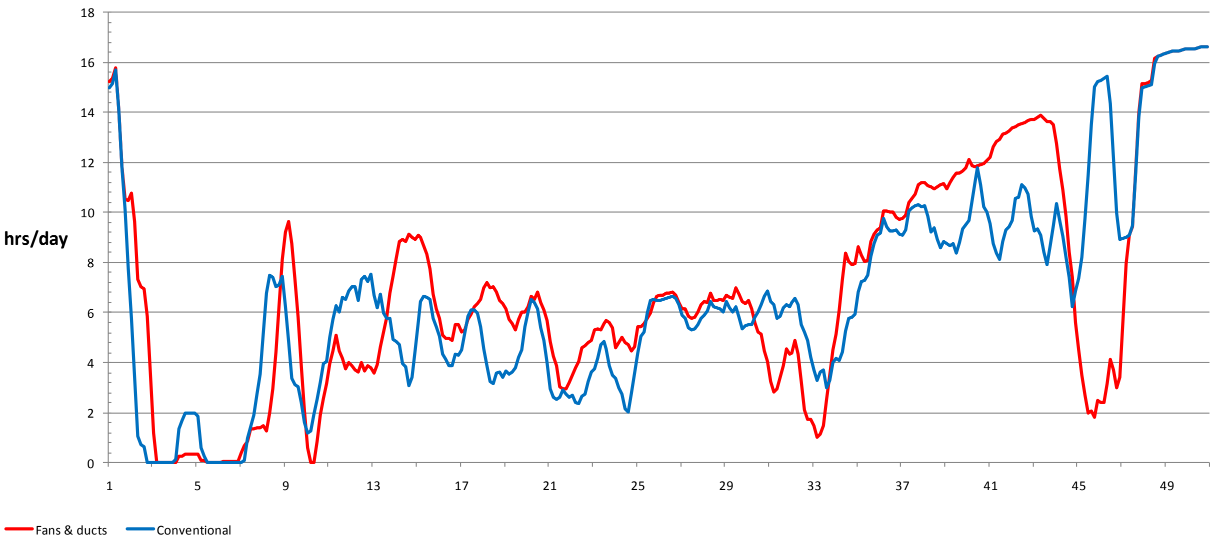
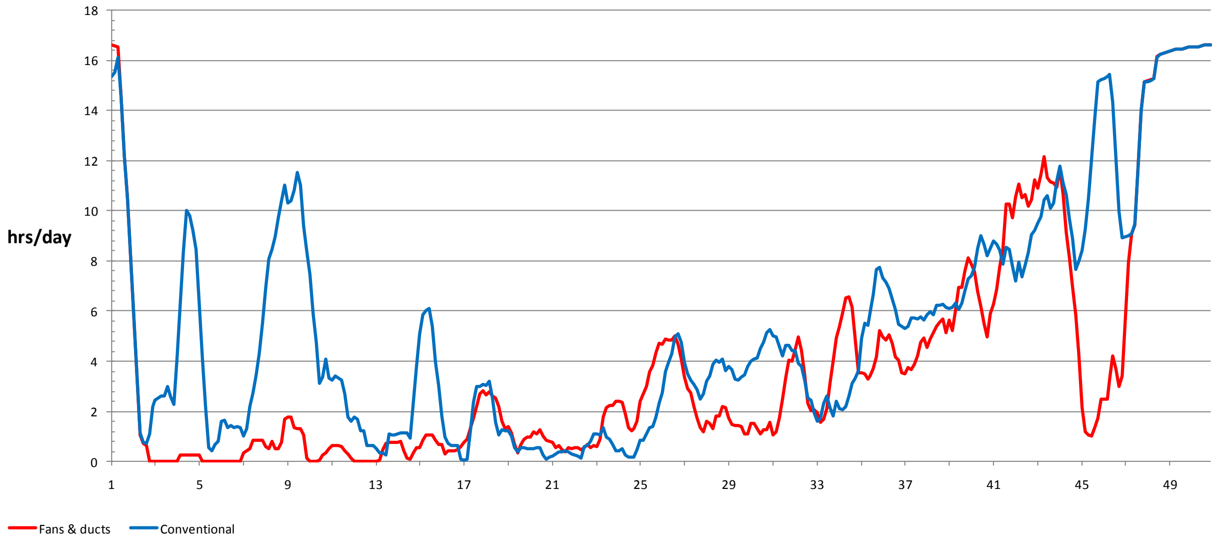


Figure 32 – Bottom of crop HD; hours per week below 2.5g/m³

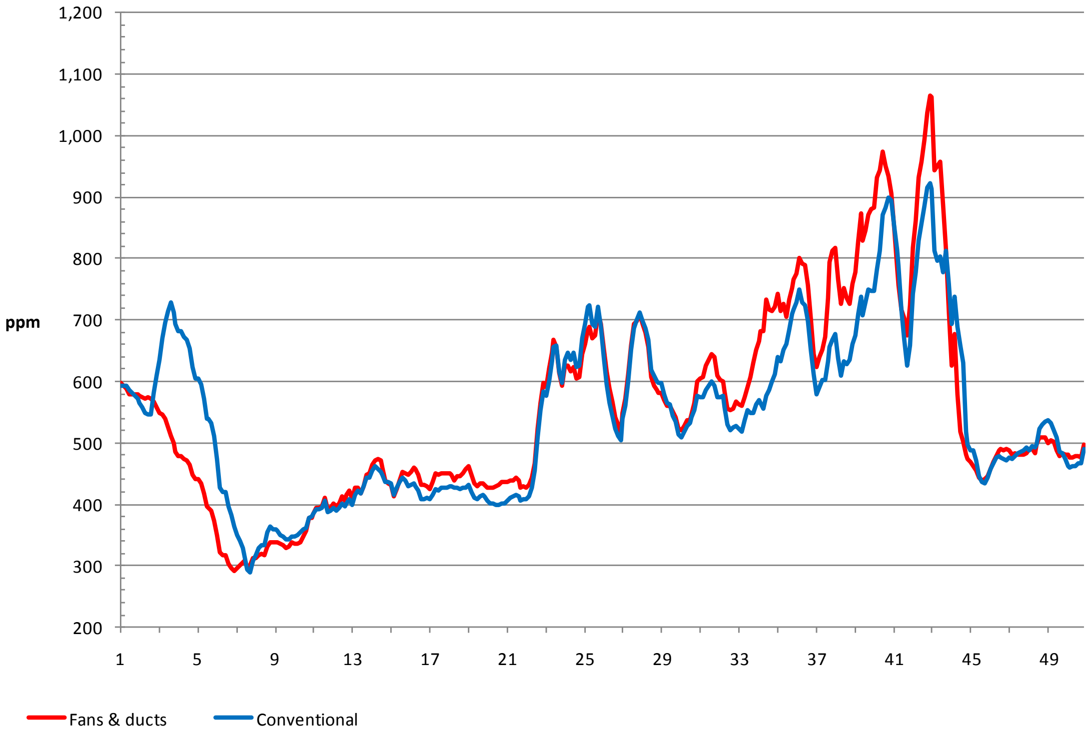


The period of greatest interest is from mid-March to the end of September - normally recognised as a difficult period to control night time humidity in a conventional system with a well developed crop canopy. As a generally lower HD was accepted in the fan and duct compartment, and the top of crop measurement was used for control; the lower HD recorded in the fan and duct compartment was therefore not unexpected. Despite this, it is notable that the HD at the bottom of the crop was below 2.5g/m^3 for less time in the fan and duct compartment than in the conventional compartment. This is because, with the ducted system, drier outside air is introduced directly into the bottom of the crop rather than, with the conventional system, being brought in through the vents where it is allowed to mix with wetter air before reaching the bottom of the crop.

CO_2 enrichment

Both compartments are served by a single CO_2 enrichment system that is controlled according to the highest of two measurements, one taken in each of the compartments. Note that up to the end of February the CO_2 measurement in CMP14 was faulty. Also availability of CO_2 was extremely limited until the end of May due to CHP problems on the nursery.

Figure 33 – Daytime CO_2 concentration



Key points are:

- Slightly higher CO_2 levels in the fan and duct compartment during April and May.
- Higher CO_2 levels in the fan and duct compartment from August to September. This is expected to be as result of a reduced need for venting at each end of the day due to lower HD's being accepted.

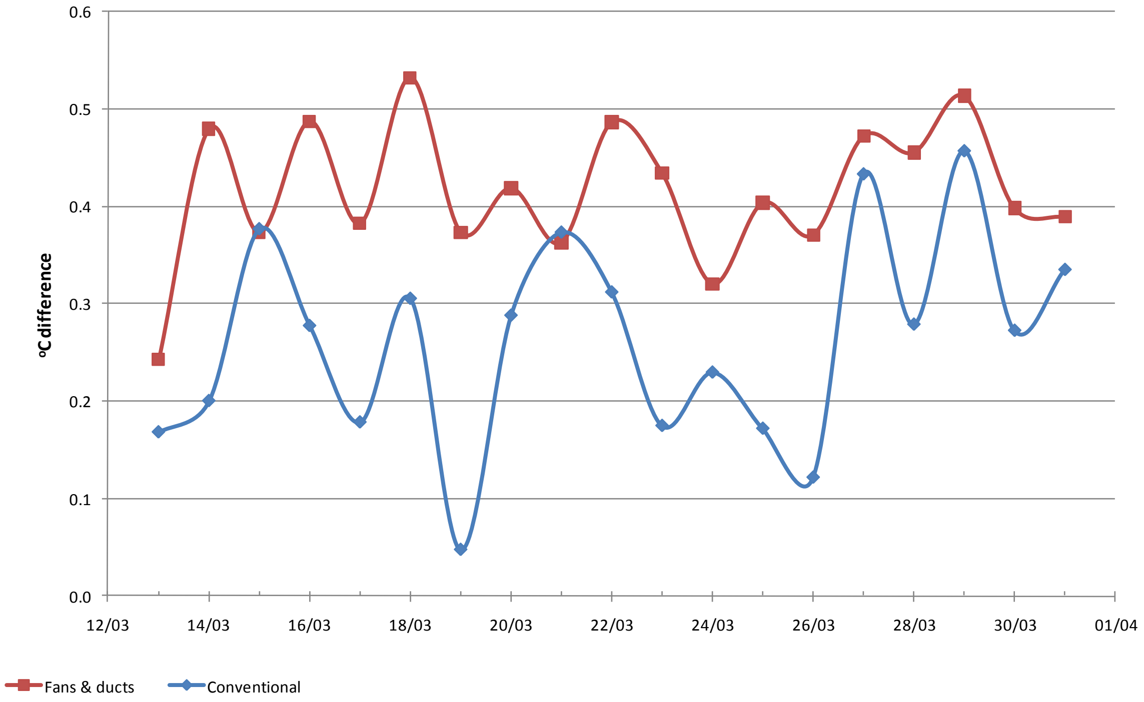
Fruit temperature

In 2008 there was a significant delay in the first fruit being picked from the fan and duct compartment. At this time it was not possible to set a minimum duct air temperature. This was thought to have caused lower fruit temperatures. A reduction in radiant heat from the pipe rail was also suggested as a possible cause.

This was investigated by inserting sensors into fruit close to the de-leafing line during March 2009 when the effect was expected to be greatest. It should be noted that it was possible to set a minimum duct air temperature in 2009 and that it was typically set to be the same as the greenhouse heating temperature. The fruit temperatures were compared with:

- The air temperature at the bottom of the crop – as differences between compartments would suggest a radiant heating effect.
- The air temperature at the top of the crop – as this is the measurement used by the majority of growers for control.

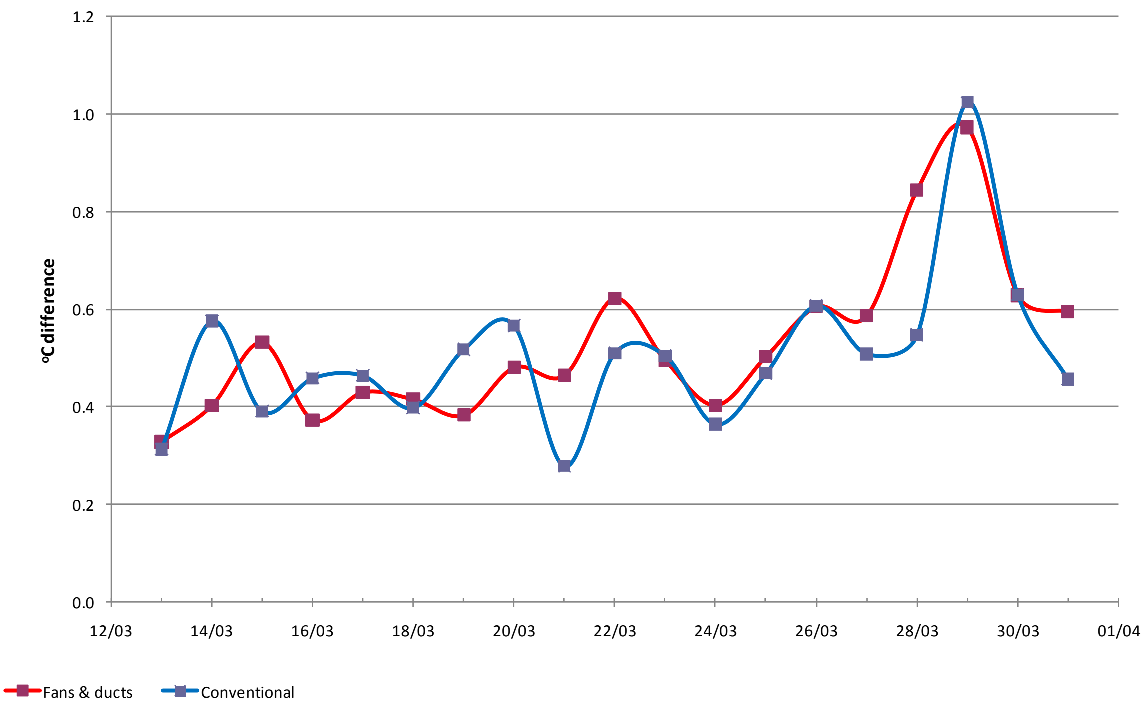
Figure 34 – Fruit temperature minus the temperature at the bottom of the crop



During the period monitored the fruit temperature in the fan and duct compartment was, on average, 0.42°C higher than the air temperature at the bottom of the crop compared to 0.26°C in the conventional compartment. The difference, albeit small, does not support the hypothesis that lower pipe rail temperatures (reduced radiant heating effect) will lead to lower fruit temperatures.

Comparing the fruit temperature with the air temperature at the top of the crop (Figure 35) it was, on average, 0.53°C higher in the fan and duct compartment and 0.50°C higher in the conventional compartment. Therefore, under the control regime applied in 2009, comparing the air temperature at the top of the crop in each compartment gives a reasonable indication of any difference in fruit temperature and therefore fruit ripening speed.

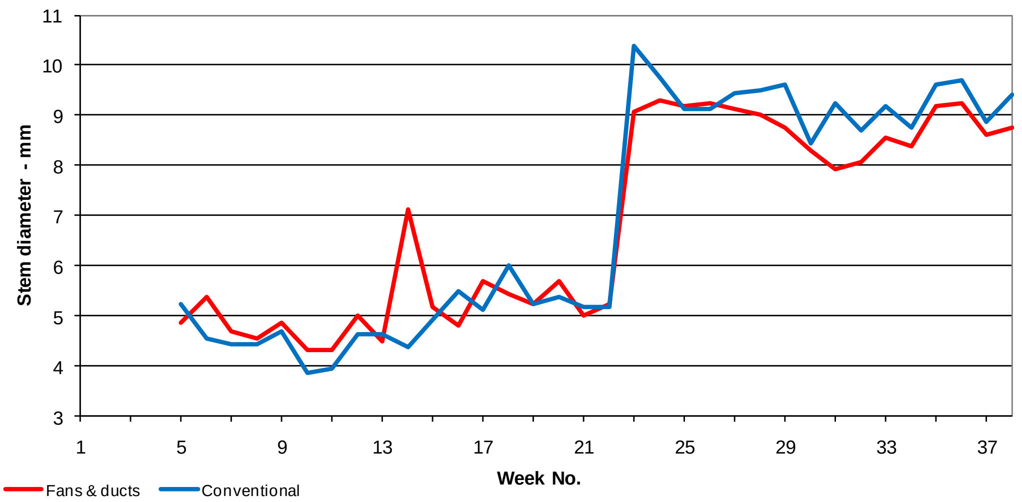
Figure 35 – Fruit temperature minus the temperature at the top of the crop



Crop data

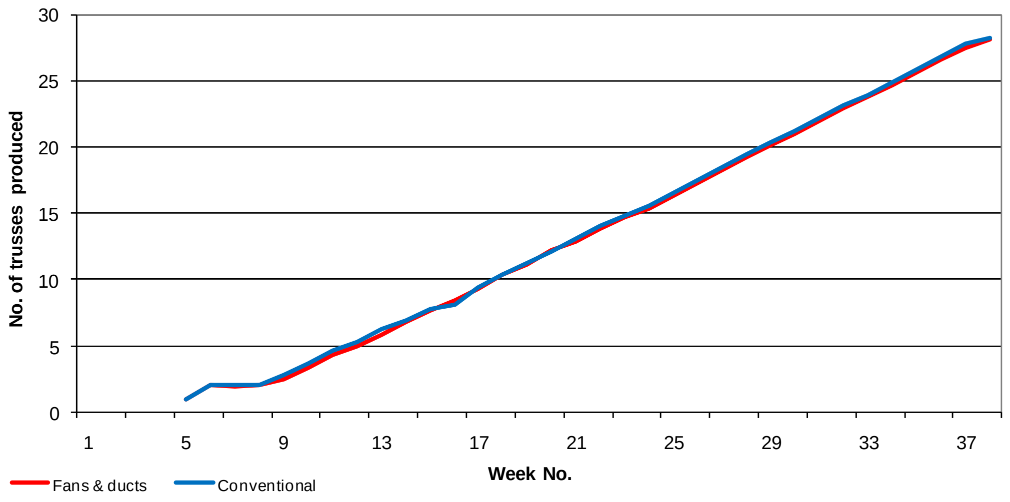
Crop registration data

Figure 36 – Stem diameter



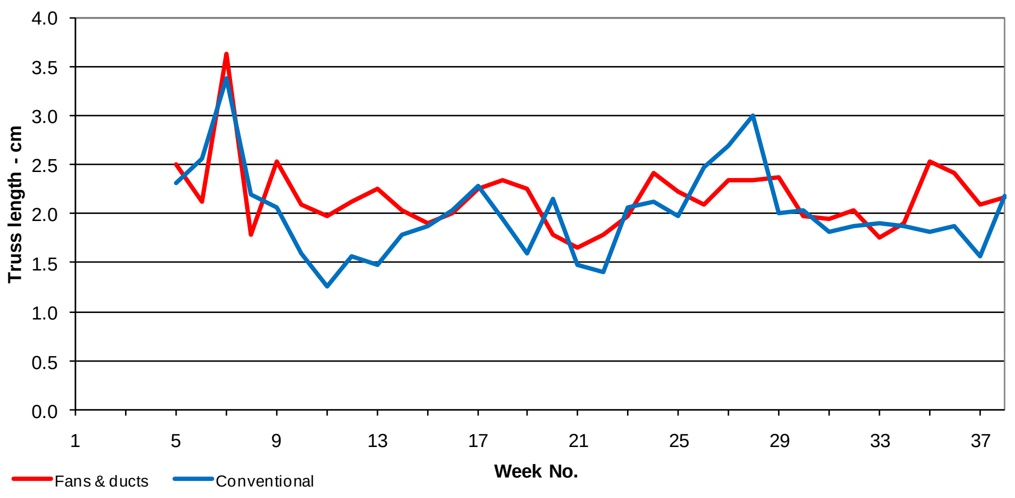
The position on the plant at which this measurement was taken changed in week 23. Data obtained up to this point is therefore not comparable. From week 27 onwards the stem diameter in the fan and duct compartment was consistently lower than in the conventional compartment. During the same period the average temperature in the fan and duct compartment was slightly higher; this is therefore the likely cause of the difference in stem diameter.

Figure 37 – Trusses produced



There was a slight tendency for the fan and duct crop to produce less trusses. However, over the whole season the difference was only 0.07 trusses per plant.

Figure 38 – Truss length



The truss length was longer in the fan and duct compartment between weeks 9 and 13 in particular. At the same time the height of the flowering truss was also greater in the fan and duct compartment. This suggests that the fan and duct crop was less generative during this period. However, the grower believed the opposite was true.

Figure 39 – Height of the flowering truss

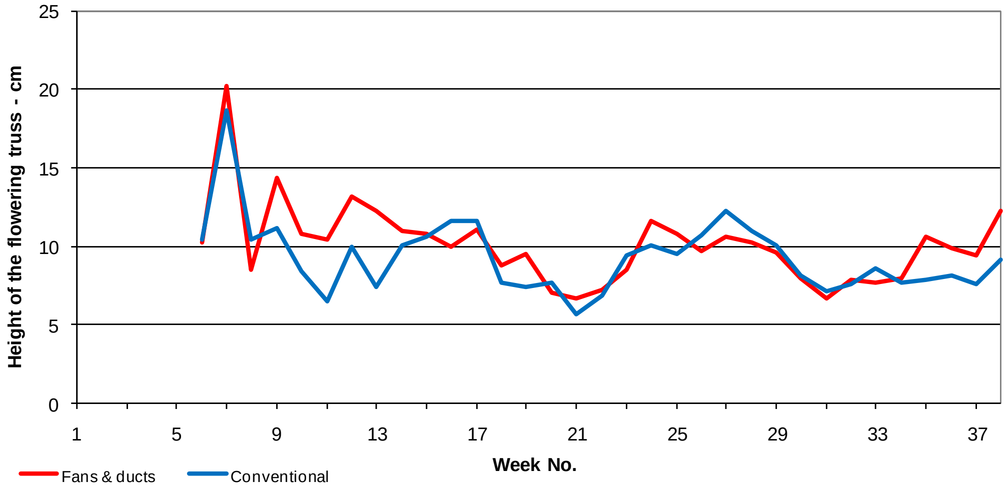
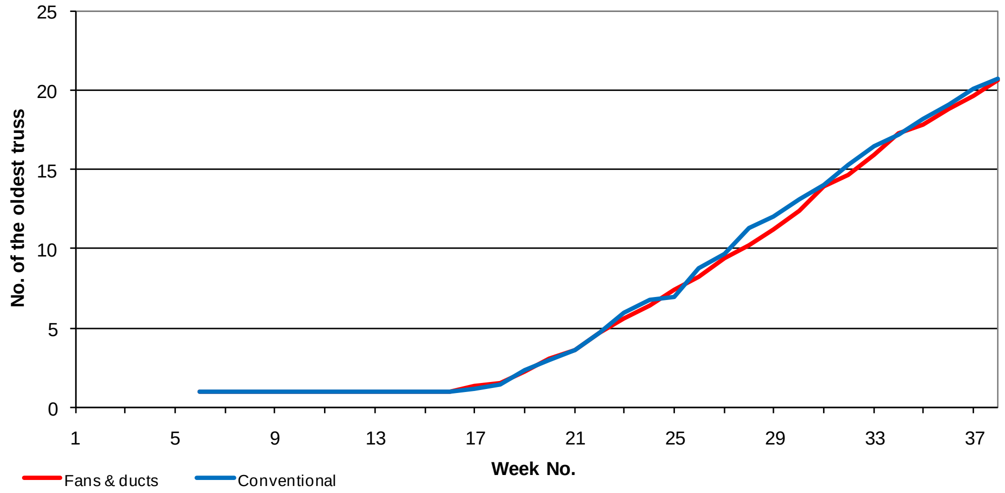


Figure 40 – Oldest truss on the plant

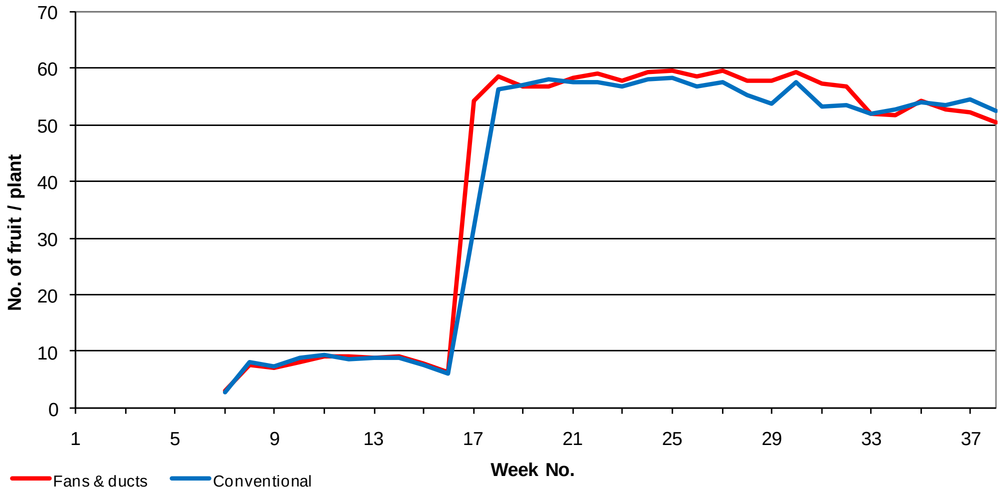


From week 25 onwards, the oldest truss on the plants in the fan and duct compartment tended to be older than in the conventional compartment. During the same period the number of fruit on the plants in the fan and duct compartment (Figure 41) increased relative to the conventional compartment. As there was no difference in the speed of truss production (Figure 37) this suggests that the fruit was ripening faster in the conventional compartment and was therefore being harvested earlier. However, around this time there was little difference in the greenhouse temperatures - this being a typical reason for differences in ripening speed. In addition, from week 27 onwards the weekly yield from the fan and duct compartment was consistently higher. The only obvious explanations for this are:

- Higher fruit weight
- More fruit set.

Neither of these factors were recorded in 2009. However, higher CO_2 levels were recorded; while the greatest affect of CO_2 concentration is on fruit size, it can also affect fruit set.

Figure 41 – Number of fruit per plant



Note – up to week 16 the number of fruit set on the most recently formed truss was recorded. This was similar in both compartments adding confidence to the earlier conclusion that fruit weight was the most likely cause of higher yields.

Yield

Figure 42 – Weekly yield

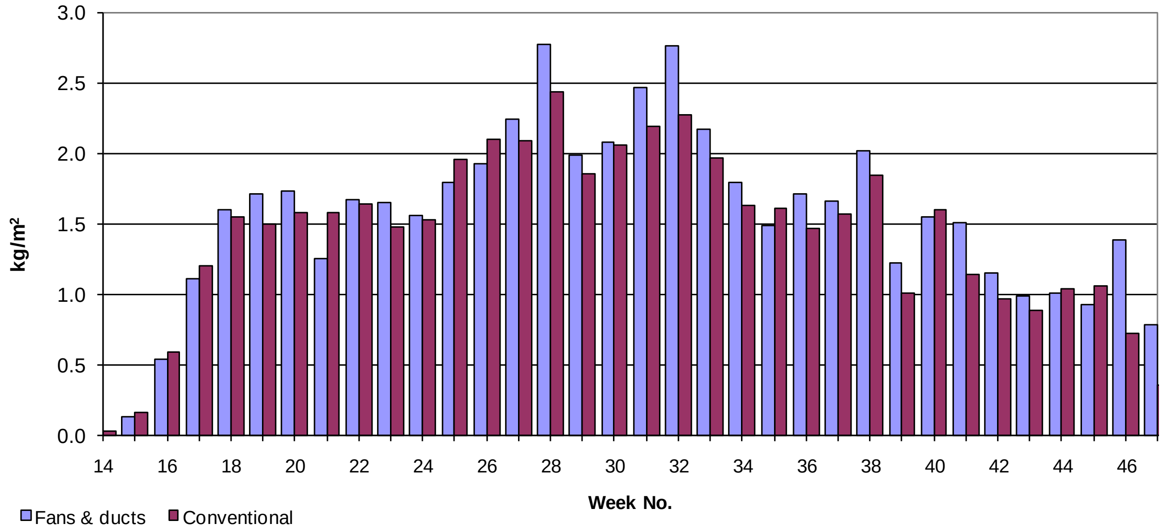
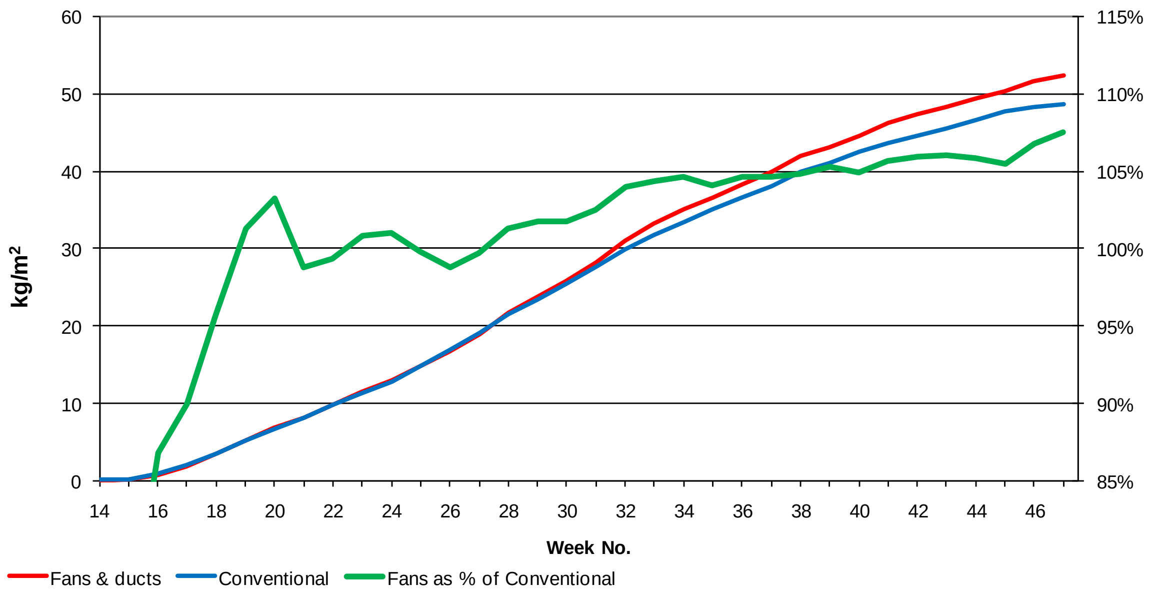


Figure 43 – Total yield



There was a delay of 2-3 days in picking the first fruit in the fan and duct compartment. However, prior to the installation of fans and ducts the delay was sometimes up to 7 days in this compartment. This meant that the yield from the fan and duct compartment was less until week 19 and although significant in percentage terms, the difference in kg/m^2 was small. The total yield was broadly the same up to week 28 after which the fan and duct compartment consistently yielded more. At the end of the season the fan and duct compartment produced 3.7kg/m^2 more fruit (7.6%). Although individual fruit weight was not recorded, CO_2 and crop registration data suggests that higher fruit weight as a result of higher CO_2 levels was responsible for the majority of the yield increase.

Disease

The crops were assessed for Botrytis on 30 March, 8 July and 2 October 2009. Plants were examined for missing stem bases (i.e. where a dead plant had been removed), missing stem tops (i.e. where a broken or dead top had been removed), Botrytis stem lesions and Botrytis petiole lesions. Botrytis stem lesions were assigned to one of three severity grades: limited – confined to a leaf node; spreading – extending up and down the stem; girdling – extending all the way around the stem and causing softening. A stem Botrytis severity index was calculated using a weighted score as follows: severity index = sum of (limited lesions x 1) + (spreading lesions x 2) + (girdling lesions x 3).

Assessments were done on five rows of crop in each greenhouse compartment. This allowed examination of the effect of air management versus no air management, distance from the ducted row, distance along the row from the central path and face of the row. A record of the total numbers of plants and heads removed each week was also maintained by nursery staff in the monitored areas. Full details can be found in Appendix 1.

March
No Botrytis was found.

July
Botrytis stem lesions were evident and appeared to originate primarily from leaf petiole lesions.

The total number of stem Botrytis lesions in the assessed areas was similar in the compartment with fans and ducts (19 per 5 rows) and the control compartment (22 per 5 rows). Missing stem bases (plants) and tops can occur due to Botrytis or to stem breakage during crop work. When combined, the number of missing stem bases and tops was similar in the two houses (26 and 30 per 5 rows).

The distribution of missing stem bases and missing tops and Botrytis girdling lesions and stem Botrytis severity index did not differ significantly between or within houses.

October

The number of stem and leaf Botrytis lesions had increased greatly over those recorded in July. The major lesion type was girdling stem lesions. There was a smaller number of girdling stem lesions in the five rows of the house with fans and ducts (99 per 5 rows) than the control house (166 per 5 rows). The number of leaf Botrytis lesions and missing stem bases was also less. The number of surviving heads was greater in the house with fans and ducts (1,178) than in the control house (1,016).

Examination of the various factors (greenhouse compartment, distance from duct, distance along row) showed that the number of surviving heads was affected by compartment and no other factor.

The number of girdling stem Botrytis lesions was affected by house, face of row, and fan x distance interactions. In the fans and ducts house, the incidence of girdling Botrytis stem lesions decreased from the fan row (3.2 lesions per quarter row face) to the row mid-way between fans (1.3 lesions per quarter row face). In the control house, the incidence of girdling stem Botrytis lesions was higher in the middle row of the monitored area. The reason for a greater incidence of girdling stem Botrytis lesions on one row face than another is unknown. This effect was not observed with numbers of leaf lesions or live heads remaining.

In both houses, the incidence of leaf Botrytis was lowest near the central path and greatest at the glass wall. As this effect was observed in both houses, it cannot be concluded it was due to the presence of fans and ducts; possibly this difference may be associated with differences in temperature and/or leaf wetness duration across the houses. This is borne out by the greenhouse temperature uniformity data which showed the wall area to be colder in both compartments.

The number of missing stem bases was affected only by house, the greater number being in the control house (82) than the fans and ducts house (53).

Nursery records of the number of plant heads and whole plants removed from 15 rows in the area with the air optimiser system and from equivalent rows in the control area also revealed a higher incidence of stem death in the control than the fans and ducts house.

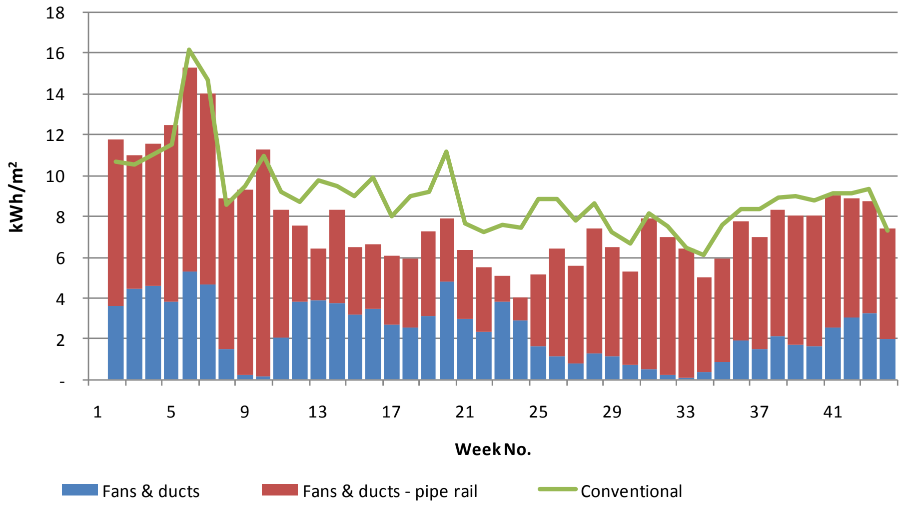
Other than a low level of powdery mildew, no other diseases were recorded on crops.

In conclusion, differences in levels of leaf and stem Botrytis, and numbers of missing plants/surviving heads, were evident between the two houses. Botrytis incidence was generally greater in the control house than in the fans and ducts house. These differences developed between July and October. Due to the nature of such trials it is possible that the difference was due to other factors such as the quality of crop work.

Energy data

Heat

Figure 44 – Weekly heat use

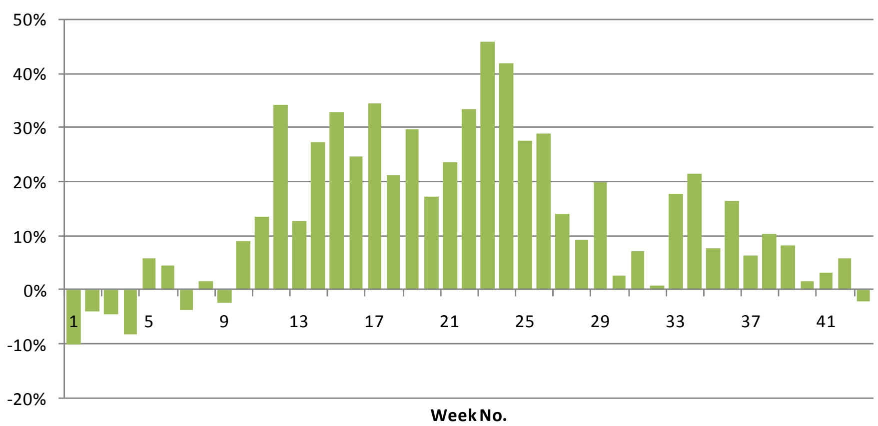


Up to week 10 the total amount of heat used in each greenhouse was similar. This was expected as similar greenhouse temperatures were achieved and no humidity control was required. The total amount of heat used during this period was 106kWh/m^2 in the fan and duct compartment compared to 104kWh/m^2 in the conventional compartment. During the same period the fan and duct system used 1.8kWh/m^2 of electricity which ultimately converts into heat. Therefore the total energy input to the greenhouses during this period was virtually identical and no correction has been applied to the energy data to take account of an inherent difference between them. The fan and duct system provided 26% of the total heat input during this period.

Note - the fan and duct system was turned off half way through week 8 due to temperature uniformity problems and turned on again in week 11.

Significant energy savings were made between weeks 11 and 30 (typically 20-30%). Savings of over 40% in weeks 23 and 24 were considered to be too high and therefore too risky at this stage in the project and set points were adjusted accordingly. High disease pressure due to poor weather between weeks 30 and 32 required changes to set points which meant little energy was saved.

Figure 45 – Weekly heat saving



The total amount of heat used in the fan and duct compartment from week 1 to week 44 inclusive was 339kWh/m^2 compared to 389kWh/m^2 in the conventional compartment; a saving of 50kWh/m^2 (12.8%). Converted into mains gas (assumed boiler efficiency of 85%) this is equal to:

- CMP12 - 399kWh/m^2
- CMP14 - 458kWh/m^2
- Saving - 59kWh/m^2.

Electricity

In striving to get best temperature uniformity and to overcome other control related problems, the fans ran continuously throughout the year. This meant that the amount of electricity consumed by the fans was higher than might be necessary (11kWh/m^2) in fully developed commercial practice.

Brief periods where the fans were turned off, when the humidity was good and the vents were open, demonstrated the potential to reduce electricity consumption. This approach will be developed further in 2010.

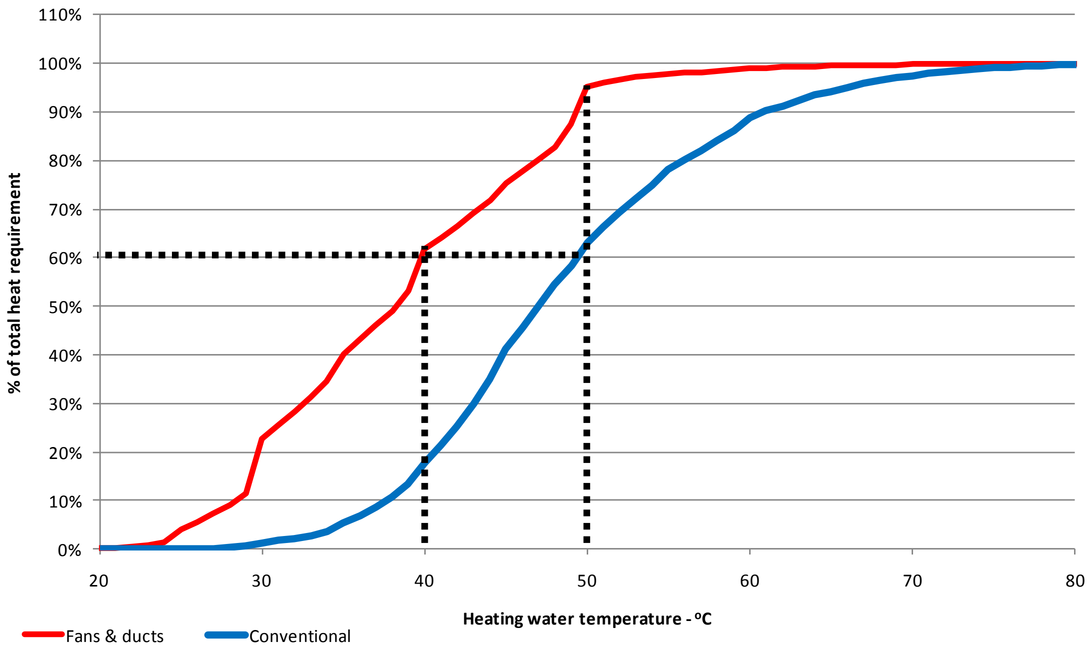
Using low grade heat

Figure 46 shows that 95% of the heat used in the fan and duct compartment was from water that was below 50^{o}C. This compares to only 60% in CMP 14. The remaining 5% of energy for the fan and duct compartment still only required a maximum water temperature of 60^{o}C. The use of this small amount of higher temperature water could have been avoided if slightly less than ideal growing temperatures had been tolerated for brief periods.

Of specific interest in relation to heat pumps is that 40^{o}C water was able to satisfy 60% of the heat requirement in the fan and duct compartment compared to just 16% in the conventional compartment.

The heating capacity of the fan and duct installation in this project was limited to some extent by capital cost and the specific needs of the site / project. However, where a sufficiently cheap heat source is available, it should be possible to satisfy all the heating needs of a greenhouse with 40^{o}C heating water.

Figure 46 – Heating water temperature profile



Financial
Energy

Heat

The amount of heat saved in 2009 was 50kWh/m^2. Although Mill Nursery have CHP the majority of growers still rely on mains gas fuelled boilers. Assuming the latter, 50kWh/m^2 of heat is equal to 59kWh/m^2 of gas. The value of this is obviously dictated by the cost of gas which continues to be volatile.

At the time of writing this report gas costs for a 12-month contract are around 1.7p/kWh (50p/therm). The heat saving is therefore worth £1.00/m^2. However, it is worth noting that in 2008 gas costs were closer to 2.6p/kWh (76p/therm) making the saving worth £1.53/m^2. There is little doubt that the long term trend will be for higher gas costs.

A major component of this project was to expand the opportunities to use alternative heat sources by enabling lower temperature heating water to be used. With typical heating costs of £10.00/m^2 the value of this could be significant, especially where waste heat from other industries can be used.

Where CHP is available (as at Mill Nursery) low grade heat is often rejected to heat destroyers. This water, which is typically 40-45^{o}C, can be used by the fan and duct system. Heat sources of this type can be regarded as zero cost (excluding capital). There are even additional potential savings from avoiding the use of fans on the heat destroyers. Subject to the running regime of the CHP it could be possible to satisfy 30% of the greenhouse heat demand from such sources giving a saving of £30,000/Ha. The fan and duct installation has not yet been connected to this heat source at Mill Nursery.

Electricity

The fans used 11kWh/m^2 of electricity. At current mains electricity prices this cost is £0.77/m^2. Where a nursery has CHP the cost of electricity used by the fans is much less as it is in effect the value of electricity that would have been sold to the grid at wholesale price. This would reduce the cost of electricity to around £0.50/m^2.

As previously discussed, the cost of electricity consumed by the fans is significant and a key part of the economic viability of fan and duct installations is to reduce the amount of electricity consumed. The importance of this reinforced by the fact that electricity prices are expected to increase at a greater rate than gas.

For the trial site the net energy saving was £0.50/m^2 in 2009.

Maintenance

During the first year of commercial trials (2008) there were some problems with reliability. However, these were solved by re-engineering the system or replacement with higher quality components. As such it would be unfair to consider them as an ongoing maintenance cost for a new installation. More recently two fans have failed, one required replacement bearings at minimal cost, the other required a motor re-wind. Both fans were on the same side of the greenhouse (CMP11) where there were problems with water ingress in 2008. Whereas, following initial ‘teething troubles’ in CMP12 there have been no fan failures.

The only item that has proven to be an ongoing maintenance item to date is air filters in the air handling units. Alternative filter media will be tested early in 2010 to try and identify ones which are cheaper, can be cleaned and do not significantly impede airflow.

Crop

A yield increase of 3.7kg/m^2 (7.6%) was achieved. This occurred from week 27 onwards and as such coincides with typically lower prices for the fruit. As the crop was the loose round variety Encore, additional yield in terms of kilos will deliver additional income. The same may not be the case with tomatoes on the vine. However, if consistently overweight vines are produced, this would provide the opportunity to produce more vines by increasing the crop density or to reduce levels of CO_2 enrichment and associated energy use.

Assuming a value of £0.50/kg, the extra yield could be worth £1.85/m^2.

Capital cost

The capital cost of the installation was £15.90/m^2. It should be remembered that this technology is very much in its early adoption stage and costs are expected to come down. Since this installation was completed (March 2008) several other suppliers have brought similar products to the market, growers are therefore advised to obtain quotes for a fan and duct installation specific to their own circumstances as significant variance is expected.

Taking the specific example discussed above, the total financial benefit (net energy saving plus yield increase) was worth £2.08/m^2. This gives a simple payback on investment of 7.6 years. However, if low grade heat from the CHP had been used, which is notionally free, the pay back on investment could be as low as 3 years.

Discussion

Temperature uniformity

Poor uniformity of temperature in the fan and duct compartment was the biggest challenge in 2009. It compromised the development of the crop in the fan and duct compartment early in the year and required the attention of the project team at the expense of fine tuning in other areas. Time for extensive testing was restricted by a lack of cold weather towards the end of the 2009 growing season. However, a slight improvement was seen and further tests in early 2010 are expected to confirm that a solution has been found.

Energy

The saving in heat energy used was significant (12.8%). However, the electricity used by the fans offset a large part of this. Simple strategies to reduce electricity use by turning the fans off under certain conditions are expected to reduce this but were not used to their full extent during 2009 due to their potential effect on temperature uniformity.

The total air movement capacity of the installation is also a key factor when considering electricity use. This is currently equal to two air changes per hour. However, reducing the airflow will also reduce the heating and dehumidification capacity of such installations. Therefore the effect of this, especially in relation to the use of low grade heat, would require detailed investigation.

Climate control / crop management

A significant change to growing methods, particularly temperature regimes was expected. However, only slight differences were required and these were largely during the first 16 weeks of the year. The same ‘rules’ of tomato growing were employed, so adopting this technology should not present significant crop management challenges to growers. The climate control computer software and set points associated with the fan and duct installation are complex and require considerable attention to detail. However, these are subject to continued development by the supplier (Priva).

Yield and disease

Data suggests that the increase in yield is the result of higher CO_2 levels, due to less venting for humidity control, leading to higher fruit weight. Unfortunately it is not practical to record fruit weight on the nursery with any degree of statistical confidence / accuracy. The crop registration data collected in 2010 will be reviewed to provide greater confidence in this conclusion.

Disease levels (principally Botrytis) were lower in the fan and duct compartment. Although this is not statistically proven, anecdotal evidence from the grower suggests that prior to the fan and duct installation, there was little difference between the compartments. In both compartments disease levels were higher close to the greenhouse wall. This is where lower temperatures were recorded. Any improvement in temperature uniformity is therefore expected to deliver an improvement in disease levels.

Conclusions

It is commonly believed that any means of increasing air movement will improve the uniformity of the greenhouse environment. This has been shown not to be the case. In spite of the temperature uniformity problems encountered, fan and duct installations have already been able to deliver:

- Increased yield (7.6% in 2009) due largely to reduced venting for humidity control leading to higher CO_2 levels in the greenhouse.
- A saving of 59kWh/m^2 (12.8%) of gas used for heating. This was however offset by high electricity use (11kWh/m^2).
- The ability to use low grade heat sources to satisfy the heating demand of greenhouses. With appropriate design it should be possible to heat a greenhouse with a maximum heating water temperature of 40^{o}C.

Technology transfer

The following technology transfer activities were carried out:

- HDC News – February 2009
- TGA Conference – September 2009
- Project steering group meeting – September 2009
- BPOA Technical Committee – September 2009
- Pepper Experience open day – September 2009
- TGA Technical Committee – December 2009.

Glossary

Air handling unit (AHU)
The combination of fan, heat exchanger and mixing box that delivers conditioned air to the greenhouse.

Air changes per hour
The airflow delivered per hour divided by the total volume of air held within the greenhouse structure.

Combined heat and power (CHP)
Typically, a gas fuelled reciprocating engine that is used to generate electricity for export to the national grid. The heat produced (engine cooling water and exhaust gases) is captured and used to heat the greenhouse.

Mixing box
A chamber, typically including two automatically controlled louvers that allow varying proportions of outside air and greenhouse air to be mixed and delivered to the greenhouse.

Heat exchanger
In relation to this project it is a means of transferring heat from the hot water supply to air that is drawn through it by the fan.

Variable speed drive (VSD)
An electronic device that allows the speed of 3-phase motors to be varied.

Humidity deficit (HD)
The amount of additional water that air is able to hold before reaching saturation. Typically measured in g/m^3.

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Appendix 1

Summary

The effect of increased air movement using a Priva air optimiser system on tomato grey mould (*Botrytis cinerea*) was monitored in a crop of cv. Encore in Yorkshire. It was not possible to randomise replicates as the system used to modify the aerial environment was installed in one glasshouse only, with an equivalent area in the adjacent house.

No Botrytis was observed in the trial areas on 30 March 2009. By 8 July, stem Botrytis was present in both areas at a similar level (around 4 lesions/row). Towards the end of the season (12 October), the incidence of stem Botrytis had increased greatly. The mean number of girdling stem Botrytis lesions was less in the house with fans and ducts (40/row) than in the house without them (66/row). The mean number of missing stem bases per row was less in the house with fans and ducts (10.6) than the control house (16.4). These differences may have been due to effects on Botrytis caused by: a) a difference in the aerial environment resulting from the fans and ducts; b) inherent differences in the aerial environment of the two houses; c) differences in quality of crop work; d) a combination of these factors; e) an unidentified factor.

The distribution of leaf and/or stem Botrytis lesions varied with row face, distance from fan row and distance from the central pathway in the fans and ducts house and also in the control house. This suggests these differences were not due to the presence of fans and ducts. The incidence of leaf Botrytis was noticeably greater near the glass wall than at the central pathway in both houses; possibly this may be associated with lower temperatures recorded near the walls.

Introduction

The use of a ducted air system suspended beneath hanging gutters is currently being examined as a method for energy saving in tomato crops through greater uniformity of air temperature and the use of lower grade heat. The objective of this study was to examine the effect of a climate management system (Priva air optimiser) which increases air movement by fans and ducts and controls air temperature and humidity, on tomato grey mould (*Botrytis cinerea*). The trial ran from planting to the end of cropping. Full details of the system are given elsewhere in this report.

In 2008, when the system was being installed and optimised, severe leaf and stem Botrytis occurred in both the crop area with the air optimiser units and in the control area (see Annual Report, April 2009). At the end of the season, the number of live heads remaining in the monitored rows was 29% fewer (i.e. Botrytis was probably greater) in the area with the air optimiser units than in the control area. This study in 2009 examined the effect of the optimised ducted air system on leaf and stem Botrytis over a full cropping season.

Methods

<u>Crop production</u>

Crops of tomato cv. Encore were grown on rockwool slabs on hanging gutters. There were two propagation cubes per slab and two plants per cube. Usually each plant had two heads. No fungicides with activity against *B. cinerea* were applied to the monitored areas except for Switch (cyprodinil + fludioxonil) on 16 March 2009 to all the monitored rows. The remainder of the crop in both houses was treated with Switch on 25 February followed by Rovral WG (5 May, 3 July, 6 August and 26 September). Leaf trimmings were left on the floor beneath the hanging gutters.

Air handling units (AHUs) were located every eighth row on both sides of the central pathway in one half of the house (compartments 11 and 12). Air was drawn in from outside the glasshouse at the ends of rows, temperature and humidity were adjusted by the climate optimiser, and the adjusted air was blown out under the crop as described above. The units were in operation continuously from week 1. Pipe heating was also used, with the maximum pipe temperature limited to 50^{o}C.

There were no climate optimiser units in the control area, compartments 13 and 14.
The control area was heated by a conventional pipe heating system with a maximum pipe temperature of 80^{o}C, though this was rarely required.

Disease assessments

Crops were assessed for Botrytis on 30 March, 8 July and 2 October 2009. Plants were examined for missing stem bases (i.e. where a dead plant had been removed), missing stem tops (i.e. where a broken or dead top had been removed), Botrytis stem lesions and Botrytis petiole lesions. Botrytis stem lesions were assigned to one of three severity grades: limited – confined to a leaf node; spreading – extending up and down the stem; girdling – extending all the way around the stem and causing softening. Dead leaves were only considered due to Botrytis when sporulating *B. cinerea* was visible on the leaf or petiole. A stem Botrytis severity index was calculated using a weighted score as follows: severity index = sum of (limited lesions x 1) + (spreading lesions x 2) + (girdling lesions x 3).

Assessments were done on five rows of crop in the area with AHUs, comprising alternate rows from one ducted row to the next ducted row (Fig 1). This resulted in assessment of two ducted rows, one row mid-way between two ducted rows, and two rows a quarter-way from the nearest ducted row. A set of rows located in the equivalent area in the adjacent glasshouse compartment, without AHUs, was also assessed. This systematic monitoring allowed examination of the effect of air management versus no air management, distance from the ducted row, distance along the row from the central path (quarter 1), and face of the row.

At the July assessment, there was rarely more than one leaf petiole and/or stem lesion per plant. A total maximum Botrytis score was therefore calculated by summing missing stems (assuming these were removed due to Botrytis), stem tops missing or affected with Botrytis, stem lesions and leaf petiole Botrytis. Other diseases were noted.

At the October assessment, the number of surviving heads was counted. Shoots more than around 1 m long were considered as separate heads. Botrytis stem lesions were assessed on green stems only, examining both the bundle of layered stems and the upright stems.

A record of the total numbers of plants and heads removed each week was also maintained by nursery staff in the monitored areas (rows 31-45 and 101-115).

Experiment design and analysis

A randomised design was not possible because there was no replication of houses containing fans and ducts. Assuming that the crops and glasshouse environment of cv. Encore in different halves of the same house were identical except for the AHUs, different rows and parts of rows in the same house were treated as pseudo-replicates. A total of 144 plants per row were examined, comprising 72 on either face and 36 per quarter length of row. Data were examined by analysis of variance using a factorial design. There were four factors (area of crop, position of row, face of row and quadrant along the row from the central pathway) at 2, 3, 2 and 4 levels respectively.

Results and discussion

No Botrytis was found at the first assessment in March. By 8 July, Botrytis stem lesions were evident and appeared to originate primarily from leaf petiole lesions.

The total number of stem Botrytis lesions in the assessed areas was similar in the house with AHUs (19 per 5 rows) and the control house (22 per 5 rows) (Table 1). Missing stem bases (plants) and tops can occur due to Botrytis or to stem breakage during crop work. When combined, the number of missing stem bases and tops was similar in the two houses (26 and 30 per 5 rows).

The distribution of stem Botrytis lesions and 'total' Botrytis (i.e. missing bases, dead tops, stem Botrytis and leaf Botrytis lesions) was examined (Table 2). There was a significant effect ($p < 0.05$) on both variables with distance from the fan row. The number of Botrytis stem lesions was greater in the fan row than in rows a quarter or half-way between fan rows (Table 3). However, as the same pattern occurred in the control house, one cannot conclude that this pattern was due to the presence of fans and ducts. No other factor affected Botrytis distribution (Table 2).

The distribution of missing stem bases and missing tops (Table 1) and Botrytis girdling lesions and stem Botrytis severity index (data not shown) did not differ significantly between or within houses.

By 13 October, the number of stem and leaf Botrytis lesions had increased greatly over those recorded in July. The major lesion type was girdling stem lesions. There was a smaller number of girdling stem lesions in the five rows of the house with AHUs (99 per 5 rows) than the control house (166 per 5 rows) (Table 4). The number of leaf Botrytis lesions and missing stem bases was also less (Tables 4 and 5). The number of surviving heads was greater in the house with AHUs (1,178) than in the control house (1,016).

The effect of main factors (fans vs no fans; distance from fan row; face of row and quarter of row) and two-way interactions on occurrence of Botrytis and healthy plants in October was examined (Table 6). Disease was affected by the presence of fans and ducts, face of row, quarter of path and various interactions. Key results are detailed in Tables 7-9 and discussed below.

The number of surviving heads (live tops) was affected by house, as detailed above, and no other factor (Table 7).

The number of girdling stem Botrytis lesions was affected by house, face of row, and fan x distance interactions. In the fans and ducts house, the incidence of girdling Botrytis stem lesions decreased from the fan row (3.2 lesions per quarter row face) to the row mid-way between fans (1.3 lesions per quarter row face) (Table 8). In the control house, the incidence of girdling stem Botrytis lesions increased from the fan row (3.2 lesions per quarter row face) to the row mid-way between fans (5.5 lesions per quarter row face) The reason for a greater incidence of girdling stem Botrytis lesions on one row face than another is unknown. This effect was not observed with numbers of leaf lesions or live heads remaining.

The number of leaf Botrytis lesions in October was affected by house, quarter from the central path and fan x distance, distance x face and fan x quarter interactions. The effects are shown in Table 9. The total number of leaf Botrytis lesions was greater in the control house (126) than the fan and duct house (72) (Table 4).

In both houses, the incidence of leaf Botrytis was lowest near the central path and greatest at the glass wall. As this effect was observed in both houses, it cannot be concluded it was due to the presence of fans and ducts; possibly this difference may be associated with differences in temperature and/or leaf wetness duration across the houses.

The number of missing stem bases was affected only by house, the greater number being in the control house (82) than the fans and ducts house (53).

The mean stem Botrytis index was affected by factors as described for girdling stem Botrytis lesions, and additionally a fan x face interaction.

Nursery records of the number of plant heads and whole plants removed from 15 rows in the area with the air optimiser system and from equivalent rows in the control area also revealed a higher incidence of stem death in the control than the fans and ducts house (Table 10).

Other than a low level of powdery mildew, no other diseases were recorded on crops.

In conclusion, differences in levels of leaf and stem Botrytis, and numbers of missing plants/surviving heads, were evident between the two houses. Botrytis incidence was generally greater in the control house than in the fans and ducts house. These differences developed between July and October. From discussion with the nursery manager, it was evident that the quality of crop work can have a major effect on the level of Botrytis in a particular row. Crop work in the two monitored areas was done by different staff. Differences between the two houses, and between different rows, may therefore have been caused by differences in quality of crop work rather than any differences in air movement/stem wetness duration resulting from the presence of fans and ducts. Additionally, as it was not possible to randomise replicate rows where fans and ducts were located to different houses, observed differences may have been due to inherent differences in the environment between the two houses.

In summary, it can be reported that at the end of the season the level of Botrytis was less in the house with fans and ducts than in the adjacent house without them. This difference may have been due to effects on Botrytis caused by: a) a difference in the aerial environment resulting from the fans and ducts; b) inherent differences in the aerial environment of the two houses; c) differences in quality of crop work; d) a combination of these factors; e) an unidentified factor.

Table 1: Effect of air optimiser on occurrence of Botrytis in tomato cv. Encore – 8 July 2009

Treatment and row number	Number of missing [a]: Stem bases	Tops	Number of Botrytis lesions on: Stems	Leaf petioles
AHUs present				
35/36 (AHU row)	4	0	10	0
37/38 (quarter-way)	0	3	3	1
39/40 (mid-AHUs	2	5	3	0
41/42 (quarter-way)	1	3	1	0
43/44 (AHU row)	1	7	2	0
Total	8	18	19	1
No AHUs				
101/2 (control row)	11	3	9	1
103/4 (quarter-way)	3	2	4	0
105/6 (mid-way)	2	0	2	0
107/8 (quarter-way)	3	2	2	0
109/10 (control row)	1	3	5	0
Total	20	10	22	1

[a] 144 plants assessed per row.

Table 2: Analysis of variance tables for selected symptoms on cv. Encore, July 2009

Symptom and sources of variation[a]	Df	F pr
Total number of stem lesions		
Fan (fan vs no fan area)	1	0.689
Face of row (north or south)	1	0.894
Distance (from fan row)	2	**0.043**
Quarter of row	3	0.887
Fan x face	1	0.505
Fan x distance	2	0.865
Face x distance	2	0.964
Fan x quarter	3	0.784
Face x quarter	3	0.951
Distance x quarter	6	0.815
Residual	32	
Total	79	
Total Botrytis[b]		
Fan	1	0.280
Face of row	1	0.223
Distance	2	**0.036**
Quarter of row	3	0.349
Fan x face	1	0.863
Fan x distance	2	0.359
Face x distance	2	0.427
Fan x quarter	3	0.642
Face x quarter	3	0.653
Distance x quarter	6	0.330
Residual	32	
Total	79	

[a] Three factor interactions not shown; no significant effects.
[b] Sum of missing bases, dead tops, stem lesions and leaf lesions.

Table 3: Effect of distance from fans and duct row on total number of Botrytis stem lesion - July 2009

Glasshouse with:	Fan row	Quarter way	Half way
Fans	0.75	0.25	0.38
No fans	0.88	0.38	0.25
Mean	0.81	0.31	0.31

Table 4: Effect of air optimiser on occurrence of live tops and stem and leaf Botrytis in tomato cv. Encore – 12 October 2009

Treatment and row number	Number of live tops[a]	Number of Botrytis stem lesions			Number leaf lesions
		Limited	Spreading	Girdling	
AHUs present					
35/36 (AHU row)	220	0	1	28	20
37/38 (Quarter way)	236	0	2	19	15
39/40 (Mid way)	231	0	3	10	15
41/42 (Quarter way)	248	0	7	19	3
43/44 (AHU row)	243	0	7	23	19
Total	1,178	0	20	99	72
AHUs present					
101/2 (AHU row)	204	0	3	24	20
103/4 (Quarter way)	186	2	6	41	24
105/6 (Mid way)	203	2	2	44	24
107/8 (Quarter way)	218	2	3	30	39
109/10 (AHU row)	205	2	6	27	19
Total	1,016	8	20	166	126

[a] 144 plants/row at planting

Table 5: Effect of air optimiser on occurrence of missing stem bases and missing tops – 12 October 2009

Treatment and row Number	Number of missing Stem bases	Tops	Mean stem Botrytis severity[a]
AHUs present			
35/36 (AHU row)	16	3	86
37/38 (Quarter way)	9	1	61
39/40 (Mid way)	12	1	36
41/42 (Quarter way)	7	0	71
43/44 (AHU row)	9	0	83
Total	53	5	337
AHUs present			
101/2 (Control row)	25	1	78
103/4 (Quarter way)	17	0	137
105/6 (Mid way)	18	1	138
107/8 (Quarter way)	10	2	98
109/10 (Control row)	12	1	92
Total	82	5	543

[a] Sum of (limited lesions x 1) + (spreading lesions x 2) + (girdling lesions x 3)

Table 6: Effect of fans and ducts on plant health – 12 October 2009 – Significance of main factors and two way interactions

Factor	F probability				
	Mean number of				
	Live tops	Girdling stem Botrytis lesions	Leaf Botrytis lesions	Stem bases missing	Mean stem Botrytis severity index (0-3)
Fan or no fan	**<0.001**	**<0.001**	**0.001**	**0.020**	**<0.001**
Distance from fan row	0.812	0.800	0.970	0.182	0.767
Face of row	0.384	**0.005**	0.894	0.677	**0.007**
Quarter from path	0.241	0.632	**<0.001**	0.133	0.371
Fan x Distance	0.689	**<0.001**	**0.008**	0.995	**<0.001**
Fan x Face	0.414	0.055	0.151	0.802	**0.028**
Distance x Face	0.562	0.070	**0.022**	0.687	0.075
Fan x Quarter	0.667	0.108	**<0.001**	0.474	0.077
Distance x Quarter	0.554	0.167	0.311	0.748	0.248
Face x Quarter	0.791	0.235	0.721	0.649	0.329

Three-way interactions are not detailed. Significant effects are shown in bold.

Table 7: Effect of fans and ducts on number of live tops remaining per quarter row face (36 stem bases) – 12 October 2009

Factor						
House and row	Face	Quarter from central path				Mean
		1	2	3	4	
Fan and duct house						
Fan row	1	28.0	29.5	27.5	27.0	28.0
	2	31.0	32.5	29.0	27.0	29.9
Quarter way	1	30.5	32.0	31.0	33.0	31.6
	2	30.5	29.0	26.5	30.0	29.0
Mid Way	1	34.0	32.0	26.0	36.0	32.0
	2	23.0	25.0	30.0	25.0	25.8
Mean		29.5	30.0	28.3	29.7	
Control house						
Fan row	1	29.5	24.5	24.5	28.0	26.6
	2	26.0	26.0	21.0	24.5	24.4
Quarter way	1	22.5	27.5	22.0	25.5	24.4
	2	27.0	26.0	23.0	28.5	26.1
Mid Way	1	27.0	21.0	26.0	26.0	25.0
	2	34.0	21.0	26.0	22.0	25.6
Mean		27.7	24.3	23.8	25.8	

Summary of overall significant effects	Significance level
1. Mean number of surviving heads per quarter row face was greater in the fan and duct house (29.5) than the control house (25.4).	<0.001

Table 8: Effect of fans and ducts on number of girdling stem Botrytis lesions per quarter row face (36 stems) – 12 October 2009)

Factor						
House and row	Face	Quarter from central path				Mean
		1	2	3	4	
Fan and duct house						
Fan row	1	4.5	1.5	2.0	0.0	1.9
	2	6.0	2.5	5.5	3.5	4.6
Quarter way	1	0.0	2.0	1.5	3.5	1.8
	2	2.0	3.5	4.0	2.5	3.0
Mid way	1	1.0	1.0	0.0	0.0	0.5
	2	2.0	2.0	2.0	2.0	2.0
Mean		3.9	2.1	2.5	1.9	
Control house						
Fan row	1	1.0	4.0	2.5	2.0	2.4
	2	4.0	2.5	3.5	5.5	3.9
Quarter way	1	2.5	4.0	3.5	10.0	5.0
	2	4.5	4.5	5.0	1.5	3.9
Mid way	1	5.0	3.0	7.0	5.0	5.0
	2	3.0	8.0	6.0	7.0	6.0
Mean		3.3	4.3	4.6	5.2	

Summary of overall significant effects	Significance level
1. More lesions in control house (4.12) than fan and duct house (2.47)	<0.001
2. More lesions on face 2 (3.83) than 1 (2.78).	0.005
3. Fan presence x row distance interaction: in the fan and duct house, Botrytis incidence decreases from fan row (3.19) to mid-way (1.25); in the control house, Botrytis incidence increases (3.12 to 5.50).	<0.001

Table 9: Effect of fans and ducts on number of leaf Botrytis lesions per quarter row face – 12 October 2009)

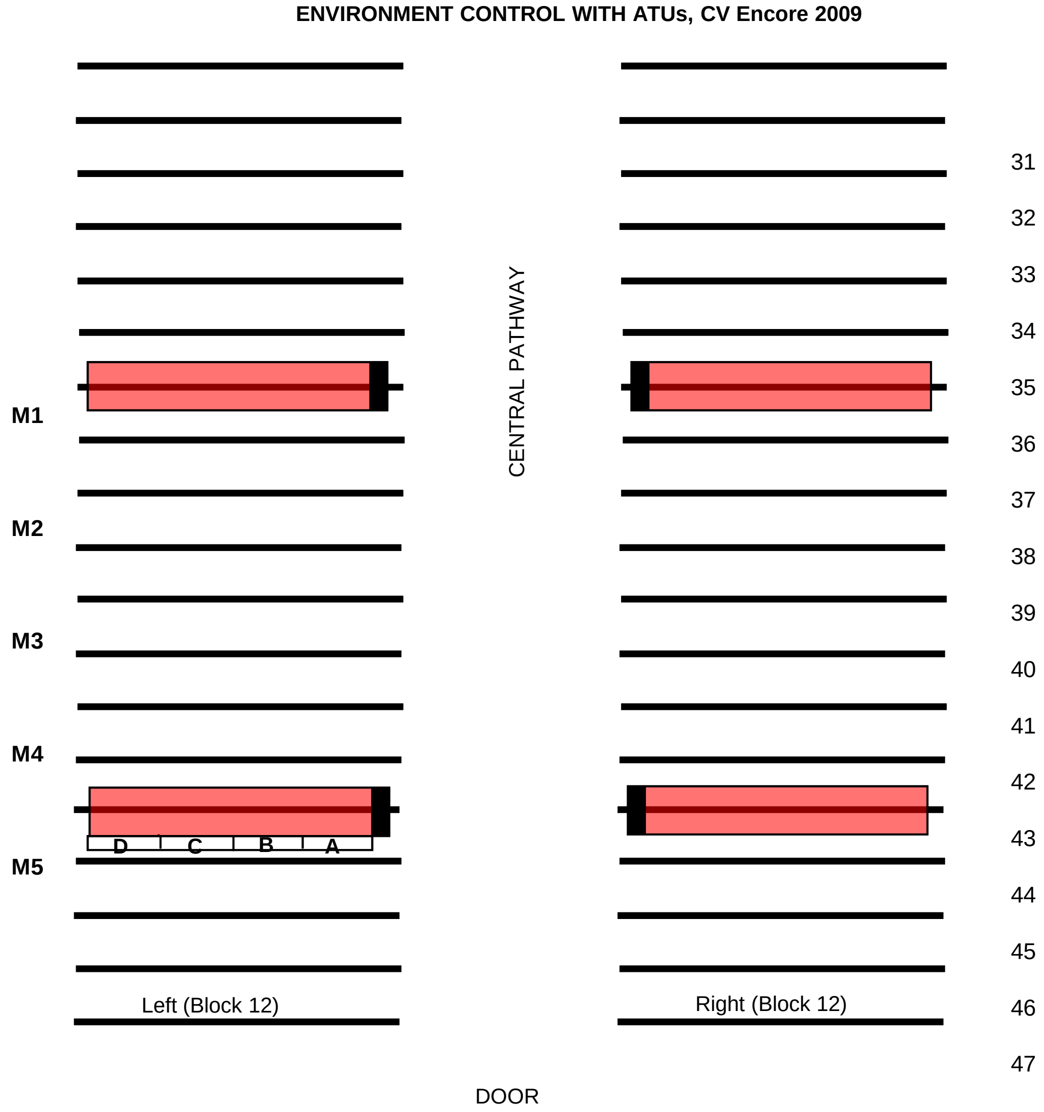
Factor						
House and row	Face	Quarter from central path				Mean
		1	2	3	4	
Fan and duct house						
Fan row	1	0.5	2.0	4.5	6.0	3.3
	2	0	1.0	2.5	3.0	1.6
Quarter way	1	0.5	2.5	0.5	2.0	1.3
	2	0.5	0.5	1.5	1.0	0.9
Mid way	1	1.0	2.0	1.0	1.0	1.3
	2	2.0	1.0	1.0	6.0	2.5
Mean		0.8	1.5	1.8	3.2	
Control house						
Fan row	1	0.0	0.0	1.5	9.5	2.8
	2	1.0	1.0	0.0	6.5	2.1
Quarter way	1	0.0	1.0	5.0	8.5	3.6
	2	2.0	2.0	4.5	8.5	4.3
Mid way	1	1.0	0	3.0	3.0	1.8
	2	1.0	3.0	7.0	6.0	4.3
Mean		0.8	1.2	3.5	7.0	

Summary of overall main factor significant effects	Significance level
1. More leaf lesions in the control house (3.15) than in the fan and duct house (1.80)	0.001
2. More leaf lesions near the glass side wall (5.30) than the central pathway (0.70)	<0.001

Table 10: Numbers of dead heads removed per week by nursery staff in nine paths (1,728 plants) from the fans and ducts area (paths 37-45) and the control area (path 103-111) – 2009

Week	Number of dead heads removed:		
number	Fans and ducts	Control	Total
14	0	4	4
15	0	0	0
16	-	5	5
17	0	0	0
18	0	2	2
19	1	0	1
20	1	14	15
21	0	21	21
22	3	18	21
23	5	34	39
24	5	19	24
25	5	18	23
26	-	16	16
27	14	9	23
28	7	-	7
29	16	-	16
30	19	33	52
31	27	14	41
32	-	18	18
33	39	18	57
34	37	33	70
35	25	19	44
36	15	16	31
37	12	16	28
38	10	8	18
39	17	26	42
Total	278 (16.1%)	328 (19.0%)	

Fig 1. Detail of rows monitored for disease (M1-M5) in relation to fans and ducts



Monitered rows = **M**
Both sides of each row were examined. One quarter row contains 9 slabs x 2 plants x 2 heads
No fungicides applied to rows 31 - 45 (ATU house) or 101 - 115 (Control house)