Project title:	The development and commercial demonstration of ducted air systems for glasshouse environmental control
Project number:	PC 278a
Project leader:	Tim Pratt, Farm Energy Centre
Report:	Final report
Previous report:	Annual report, April 2011
Key staff:	Andrew Kneeshaw, Farm Energy Centre Jon Swain, Farm Energy Centre Chris Plackett, Farm Energy Centre Tim O'Neill, ADAS UK Ltd
Location of project:	Farm Energy Centre, Warwickshire Mill Nurseries Ltd, East Yorkshire
Industry representatives:	Ian Ball, Humber VHB Gary Taylor, Valley Grown Nursery John Overvoorde, Delfland Nurseries Philip Pearson, A. Pearson & Sons Rob Bezemer, Jan Bezemer & Sons Fay Richardson, Coletta & Tyson
Date project commenced:	1st July 2007
Date project completed (or expected completion date):	31st April 2012

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

Farm Energy Centre

Signature .... Date ....

Report authorised by:

Report authorised by:

Andrew Kneeshaw

Managing Director

Farm Energy Centre

Signature .... Date ....

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GROWER SUMMARY

Headline

Four years of testing and development of a ducted air heating and ventilation system in a commercial tomato greenhouse in East Yorkshire have resulted in crop yield improvements, and heat energy saving.

Background

The fans and ducts system offers an alternative to conventional heating and ventilation in, what has become known as, the 'closed greenhouse'. Pioneered in the Netherlands, the system gives better control of air mixing and air infiltration in the greenhouse. It also presents the opportunity to deliver heat in a much more responsive way compared with the use of pipe rail systems, which are relatively slow to respond. Fans and ducts also offer the opportunity to the grower to use low-grade heat (water temperatures below 60˚C); a level which is commensurate with the low-grade heat delivery systems such as CHP, boiler condensers, ground source heat pumps or waste heat from other industries.

Project PC 256 reviewed the theoretical potential for the closed glasshouse concept for UK horticulture. This concluded that although the closed greenhouse concept as a whole was not viable, ducted air systems could offer significant advantages over conventional greenhouse design. These are:

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

With little practical experience in the UK, HDC decided to initiate this project to look at costs, benefits and practicalities of such systems.

Figure 1 overleaf shows the basic schematic layout of the fans and ducts system.

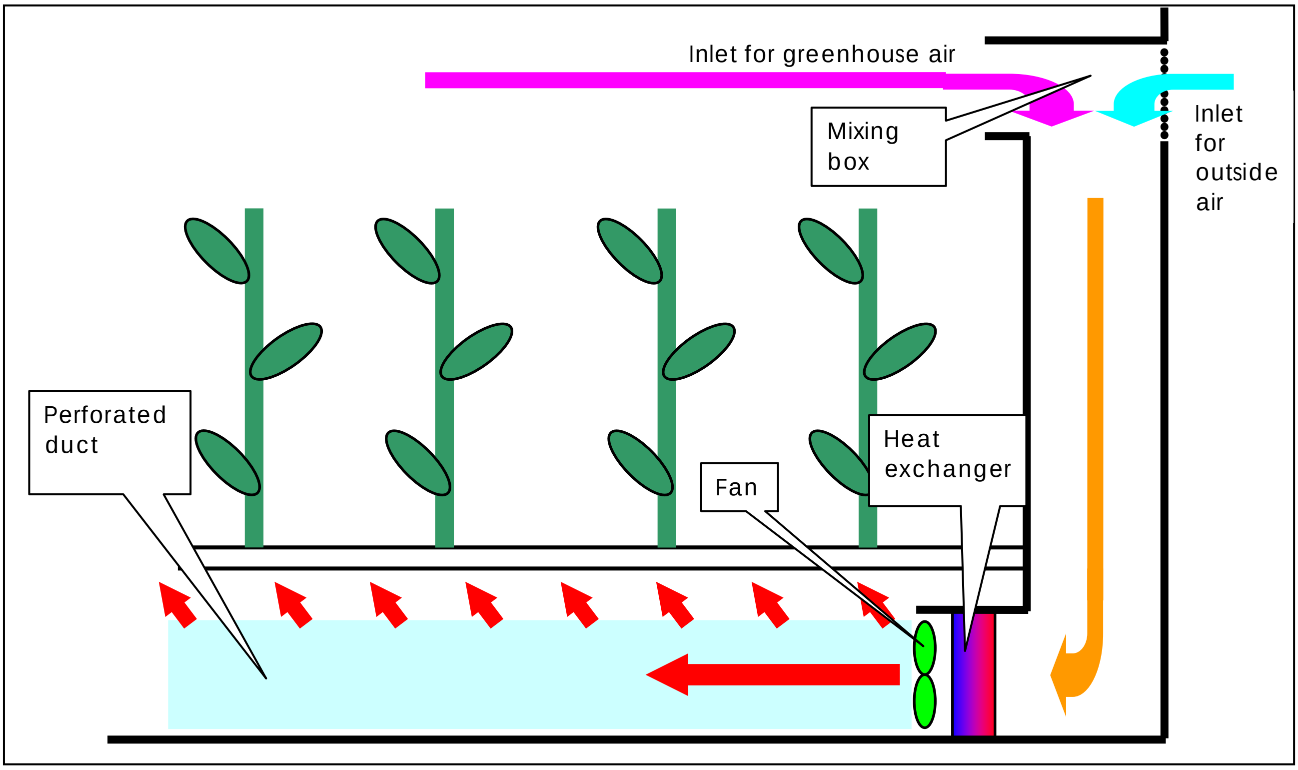


Figure 1 – Fans and ducts schematic (full system)

Summary of work over the four-year trial

The project started in 2008 with the design of a ducted air heating system to suit commercial conditions for a UK tomato grower. A supplier (Priva) was selected and an installation carried out at a commercial tomato grower in East Yorkshire over an area of 10,286 m^2 (two greenhouse compartments).

Initial trials began to characterise the system and allow the grower to become familiar with the operation of the new method of environmental control. For comparative purposes, control areas of a similar area were also monitored which used conventional heating, ventilation and environmental control.

Over the four years of the trial energy performance, crop yield, quality and disease were monitored. Refinements were made to reflect the practical and financial issues associated with the technique. Main modifications have been:

- Refinement of air delivery system to give better temperature uniformity.
- Alterations of air delivery rates and techniques to reduce the electrical running costs.

Figure 2 overleaf sets out the progress of the project over the last four years.

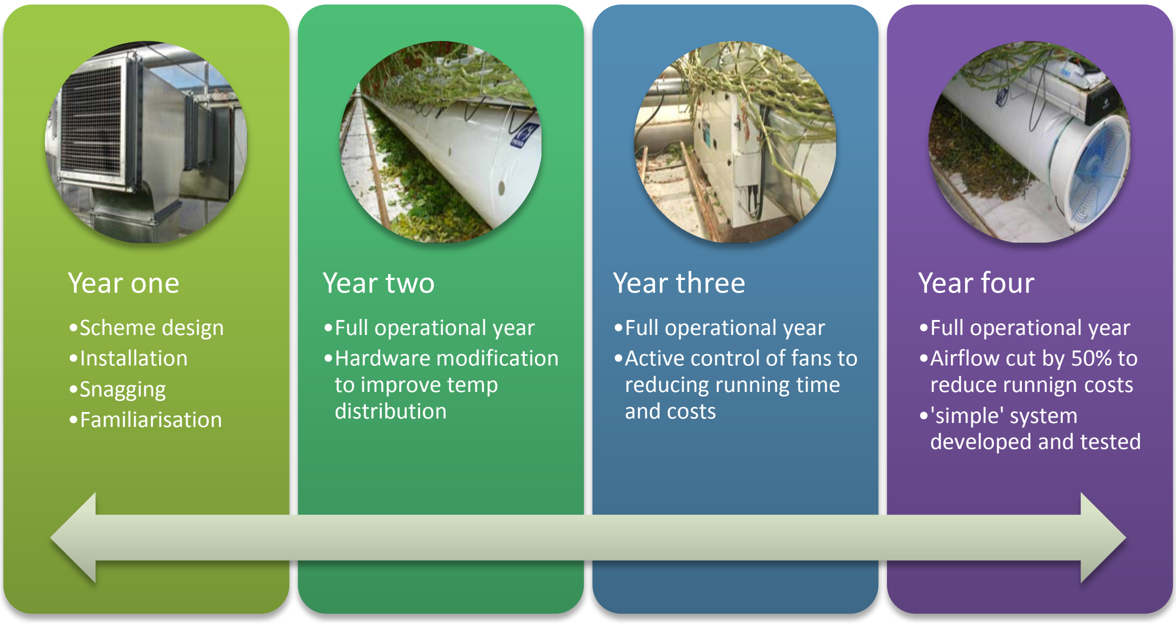


Figure 2 – Project timeline

In the final year (2011), a secondary 'simple' system was designed and tested in an effort to capture most of the practical benefits of the full fans and ducts system, but with lower capital and running costs. The simple system only employed the air recirculation element of the design. The heating function and ability to introduce outside air was forgone.

Financial benefits

Performance and financial results are set out in the following table. As the design, hardware, control and management of the system has been experimental and has continuously evolved – results may well be better for a more refined commercial system.

However, they do give a broad indication as to the potential of the system.

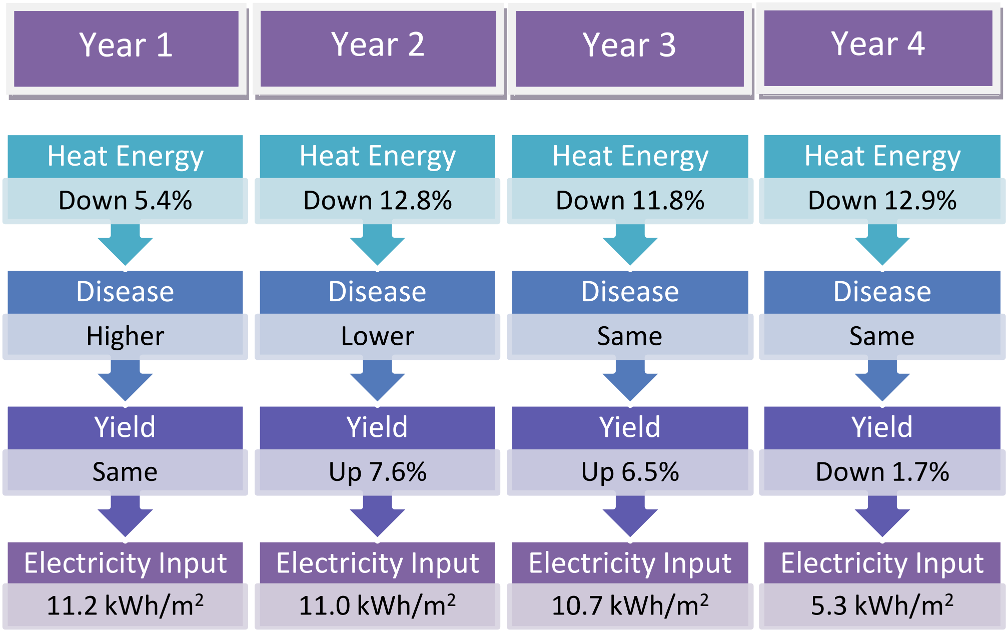


Figure 3 – Summary of results

The capital cost of the full system (as installed) was £15.90 per m^2. The value of additional yield, lower heating cost minus the cost of electricity used has averaged £2.06 per m^2 giving a simple payback of 7.7 years. The capital cost of a new, better-designed system is likely to be less – especially if it is integrated within a new-build greenhouse.

Simple system

Following two years of evaluation of a full fans and ducts system, it became clear that, as the major financial benefit came from enhancement in crop performance from better control of humidity and air mixing, then it might be possible to improve financial viability by forgoing some of the less critical features of the system.

A simple system was designed and installed with reduced capital and operation costs. Capital costs at £2 per m^2 were dramatically less than the full fans and ducts system (£15.90 per m^2).

Results showed modest heat energy savings of 16 kWh per m^2 using the simple system. This was in the face of some unexpected and un-associated management and disease difficulties, which, if put aside, might well have pushed heating energy saving to 22 kWh/m^2 or 5%. The simple system used 3 kWh/m^2 of electricity. However, savings in electricity from not having to run the normal roof fans should be allowed for (estimated to be 1.5 kWh/m^2).

Yield performance was disappointing with, in fact, a slight reduction (1.1%) over the control area.

On this evidence alone, payback would be over six years for on capital employed. It is however felt that, with more experience and fewer problems with extraneous disease events, this could be brought down dramatically.

Overall summary

On average, over the three years of full cropping trials the full fans and ducts system as opposed to traditional heating pipes and ventilation:

- Reduced energy costs by £0.39 per m^2.
- Increased average yield by 4.1%%.
- Enabled 95% of total greenhouse heat demand to be satisfied by water at 50°C or less (compared to 60% of heat demand with a conventional heating system).

However, experience from the project suggests that better performance than this can be achieved.

The one-year test (2011) of the ‘simple’ system was compromised by poor quality crop work in the trial area. However, indications were positive and experience with the full system suggests that a payback on investment should be possible within three years.

Action points for growers

The fans and ducts technique has greatest immediate potential where it can enable lower grade heat sources to be utilised.

Growers with a potential source of low-grade heat 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 fans and ducts systems. There were at least six exhibiting at the Hortifair 2010.

Growers planning to build a new greenhouse without a low-grade heat source should:

- Investigate the ability to integrate the ‘full system’ concept using alternative (lower cost) designs that are only possible with a new-build greenhouse.

Growers with existing greenhouses who do not have access to lower cost heat sources should consider the benefits of a simple system.

SCIENCE SECTION

Introduction

Heating and ventilation of glasshouses in the UK is dominated by a traditional configuration, which comprises:

Heat provided by a centralised boiler and delivered by low-pressure hot water piping, which provides an extensive network of convecting / radiating surface area around the crop growing area.

Ventilation provided by opening and shutting for roof vents to allow natural convection.

Most systems are controlled using a 'climate control computer', which has a network of sensors measuring internal and external climatic conditions (temperature / humidity / air speed / solar radiation). Boiler, pump and vent operation is co-ordinated to achieve required internal growing conditions.

This heating and ventilation configuration has certain advantages and disadvantages, which are set out below.

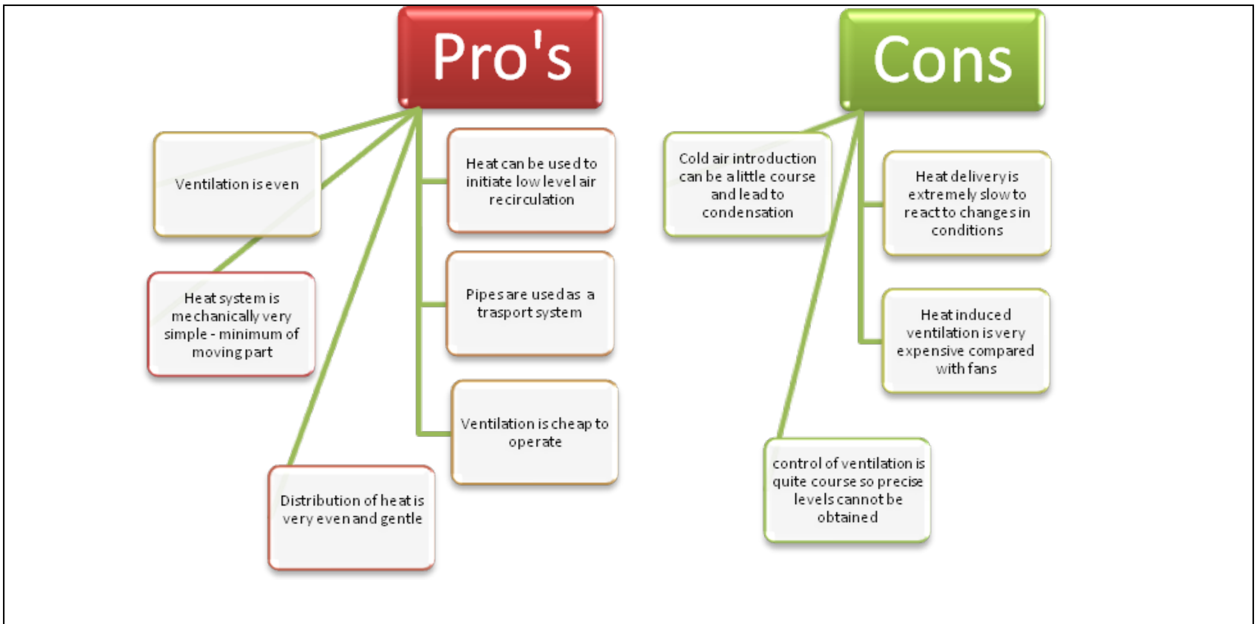


Figure 4 – Conventional heating and ventilation: pros and cons

The main issues with traditional heating and ventilation are controllability and reaction time. When these issues pose practical operational problems, growers tend to operate conservative control set points, which give them a degree of security, but higher heating costs than should be strictly necessary to achieve good growing conditions

Traditional systems rely on heating pipes to provide low levels of air recirculation which, although effective, are expensive to provide – particularly when the heat is not required to support general air temperature.

A fans and duct system uses mechanical ventilation as opposed to unforced natural ventilation and convection. It overcomes most of the problems associated with traditional vent and heat systems, albeit presenting some new challenges of its own.

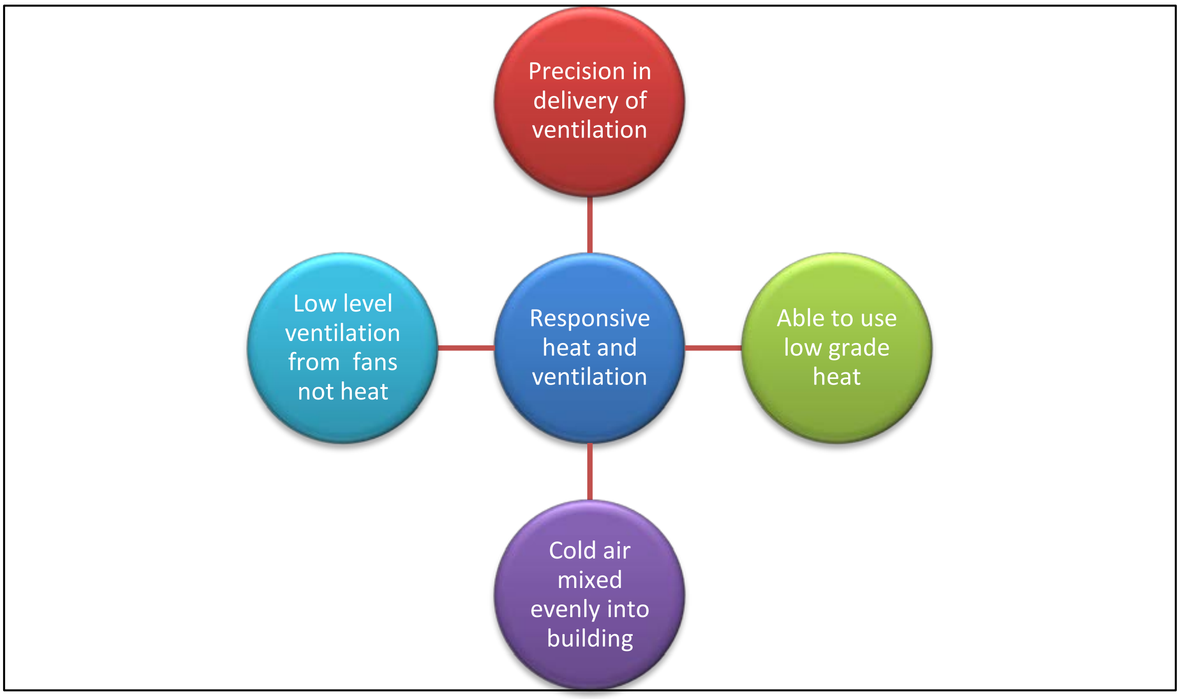


Figure 5 – Fans and ducts: benefits

The central physical aim of a developed fans and ducts system is to provide a responsive heating and ventilation system. The routes to this are shown above.

From a wider perspective, the objective of the project was to:

Reduce energy use and costs 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.

The project was carried out in a 2.1 Ha greenhouse at Mill Nurseries Ltd in East Yorkshire. A fans and ducts system was installed in one half of the greenhouse in March 2008 and was compared with the other half of the greenhouse, which had a conventional heating and ventilation system. A temporary partition was installed to create two separate airspaces.

Materials and methods

An illustration of the components of an Air Handling Unit (AHU), the heart of the full 'fans and ducts' system, is shown in the following diagram.

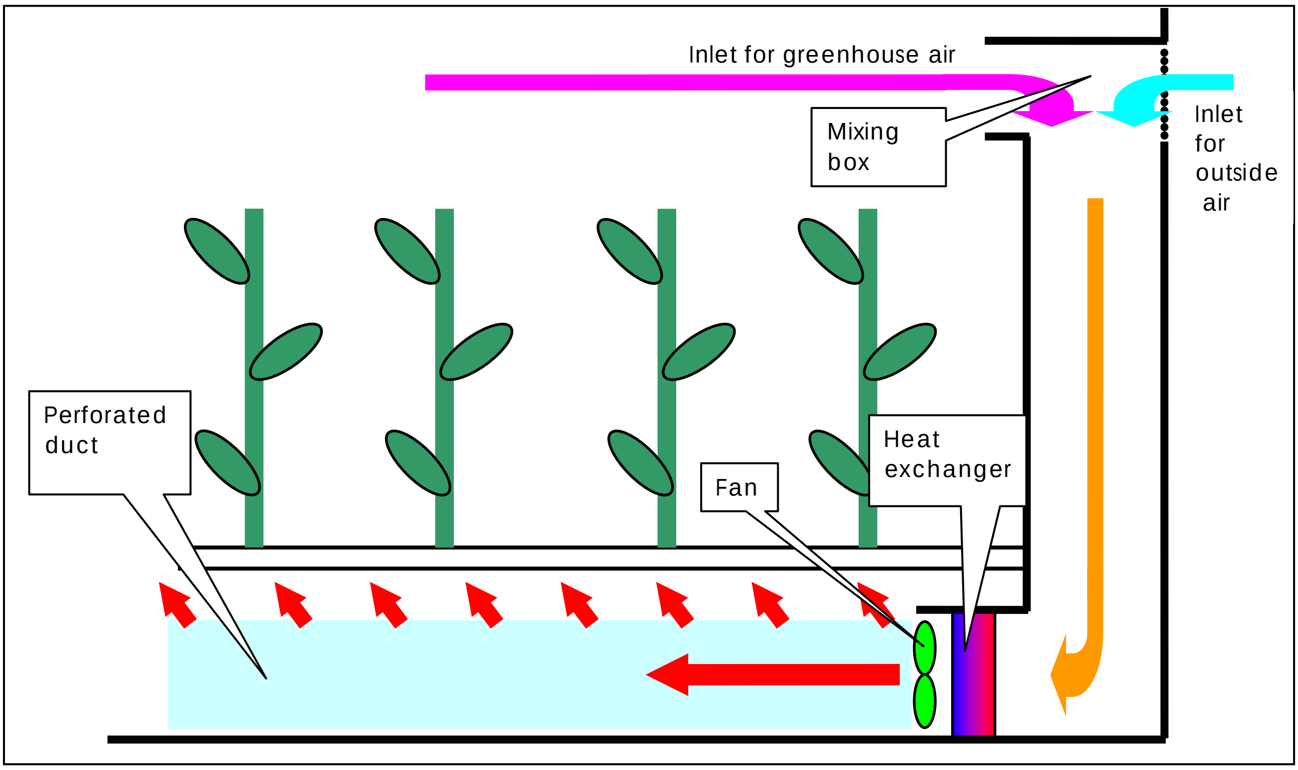


Figure 6 – Fans and ducts schematic (full system)

The project was set up in two adjacent 1 Ha greenhouse compartments. A fans and ducts system was installed in one compartment and compared with an adjacent and otherwise identical compartment with a conventional heating and ventilation system.

The installation used 18 AHUs arranged as shown in Figure 7. Each unit had an air handling capacity of 6,000 m^3/hr with a 25 kW heat exchanger fitted.

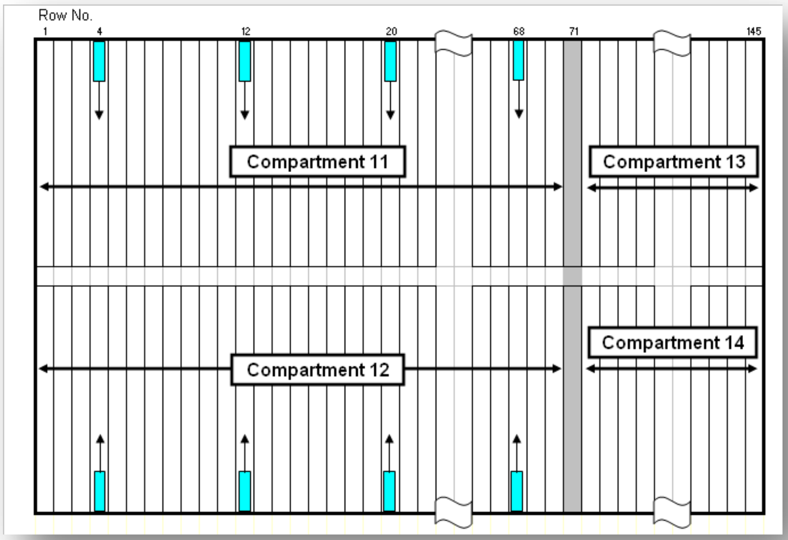


Figure 7 – AHU layout

Total heating capacity was 450 kW/Ha with air delivery of 108,000 m^3/hr (two air changes per hour). The fans and ducts installation was not capable of satisfying all the heating and ventilation needs of the greenhouse and the existing pipe rail heating system and roof vents continued to be used to supplement heating and ventilation.

Data monitoring

Greenhouse environment

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

Table 1 – Greenhouse aerial environment measurements

Location	Temp ˚C	Humidity deficit g/m^3	Relative humidity %	Dew-point temperature ˚C	CO_2 concentration ppm
30-50 cm above the growing media	✓	✓	✓	✓	
30-50 cm 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.

Energy use

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

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

Yield

This was recorded by the nursery as total kilos of fruit harvested each week in each area.

Disease

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 – carried out by Dr Tim O'Neill, ADAS UK Ltd.

Temperature uniformity

This was assessed using compact data loggers placed in a grid pattern within each greenhouse compartment. The data loggers were mounted approximately 30 cm above the growing media.

Results

A summary of each year of the project plus a full report on the 2011 trials follow. For more detailed information on earlier years, refer to the following reports:

HDC Project PC 278; Interim Report (2008).
HDC Project PC 278; Annual Report (2009).
HDC Project PC 278; Annual Report (2010).
HDC Project PC 278; Annual Report (2011).

Growing year 2008

This was very much a year of establishment for the project, where details like duct air temperature and control were settled. One thing that became evident quite quickly was that the distribution of air and temperature uniformity was likely to be a challenge with the system, compared with conventional venting.

Familiarisation and establishing confidence in the abilities of the system were also going to be a big factor if savings were to be achieved.

One example of the difference between the traditional and fans and ducts system was in responsiveness to external weather change. Speed of response tests showed that the fans and ducts system could go from zero to maximum heat output at the farthest point of the greenhouse in six minutes. This compared to 17.5 minutes for the pipe rail heating system. This clearly illustrated that temperature and humidity management needed a different approach.

Energy performance for fans and ducts was not consistently better throughout the season and overall the costs of running the ventilation fans outweighed the value of gas saved.

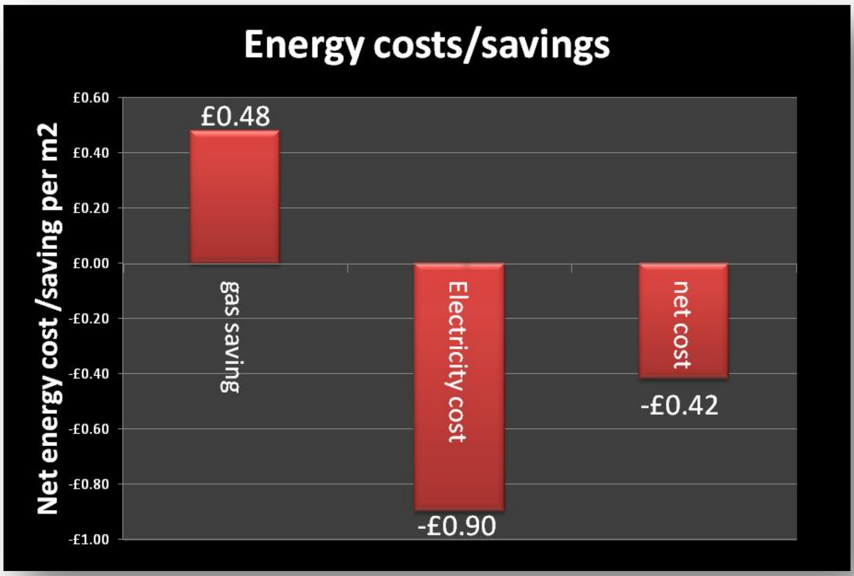


Figure 8 – 2008 energy costs / savings

Crop yields were similar with both treatments and disease was slightly worse for the fans and ducts crop.

This initial lack lustre performance was put down largely to inexperience and some teething problems.

Growing year 2009 (full report published April 2010)

This was the first full year where operators of the systems were starting to benefit from their knowledge and experience of the new growing system.

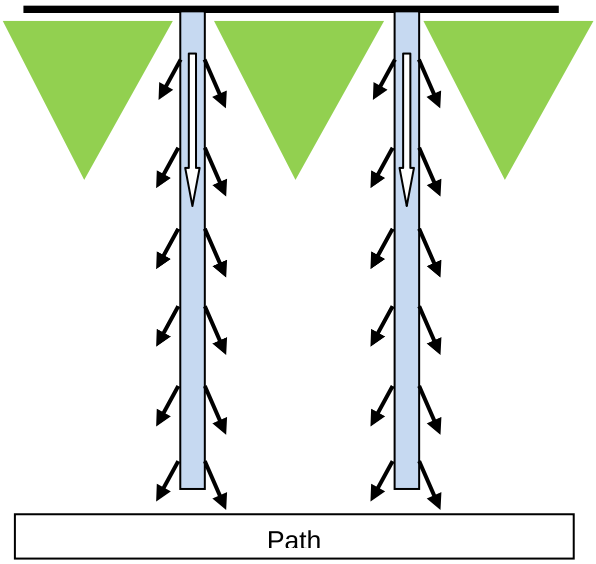


Figure 9 – Airflow dead-spots

From an engineering perspective, some work was done this year in trying to sort out temperature uniformity in the glasshouse. Temperatures near to the wall of the greenhouse on the side of the structure where the AHUs were positioned were consistently low in comparison to similar positions in the control building. Studies on the air distribution from the AHUs indicated that a 'dead spot' may be occurring in this area.

Some modifications were made to recirculate more air in this area in an effort to even out temperatures.

During the season, tighter control of ventilation with fans and ducts led to higher levels of CO_2 retention and therefore higher crop yields.

Lower energy uses were also achieved in the fans and ducts compartment.

Overall cost balance achieved is shown in the following graph. It is worth noting the dominant effect of crop yield in the economic balance. Clearly, crop yield needs to be maintained or improved if the fans and ducts system is to be viable.

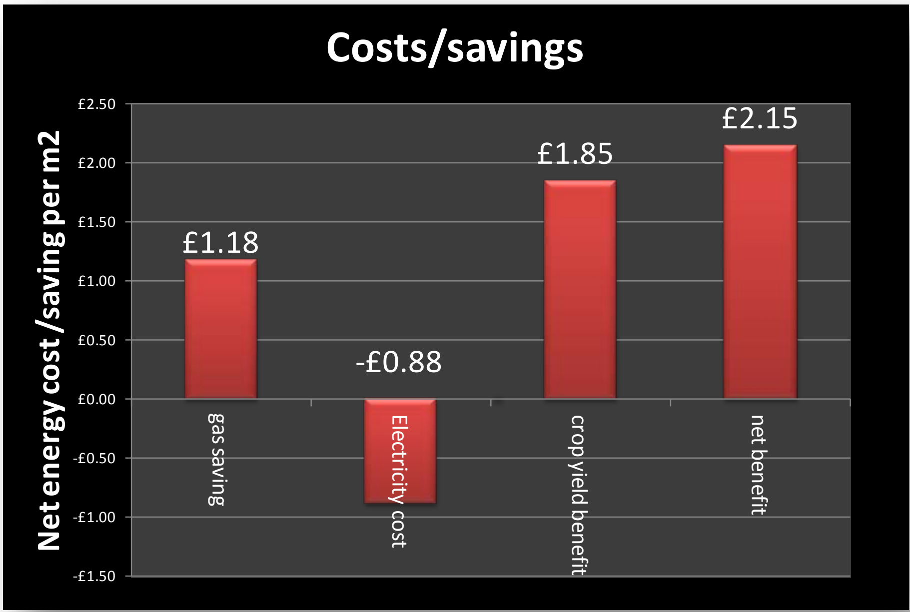


Figure 10 – 2009: financial results

Growing year 2010 (full report published April 2011)

Now in the second year of full operation, and with growing confidence that the fans and ducts system could deliver closer control of humidity, more adventurous set points were tried in an attempt to achieve lower energy use. The consequences were lower average HDs at night-time with the fans and ducts system and generally higher CO_2 levels.

Anecdotal observation was that transpiration levels could be maintained at lower HDs with the fans and duct system.

Overall cost balance achieved is shown in the following graph:

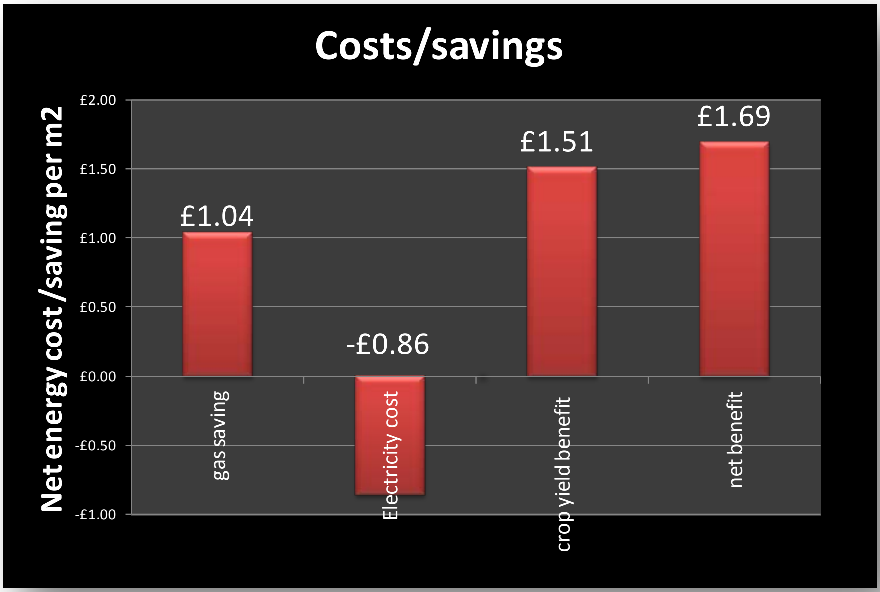


Figure 11 – 2010: financial results

Information was derived on the use of lower grade heat through the heat exchangers. Figure 12 below shows that 95% of the energy delivered could come from heating water of 50°C or below and 60% of the heat delivered could be satisfied with water of 40°C or below; this last figure contrasts with only 13% for a conventionally heated area. This is of particular interest when considering the use of low temperature heating systems such as heat pumps or waste heat sources.

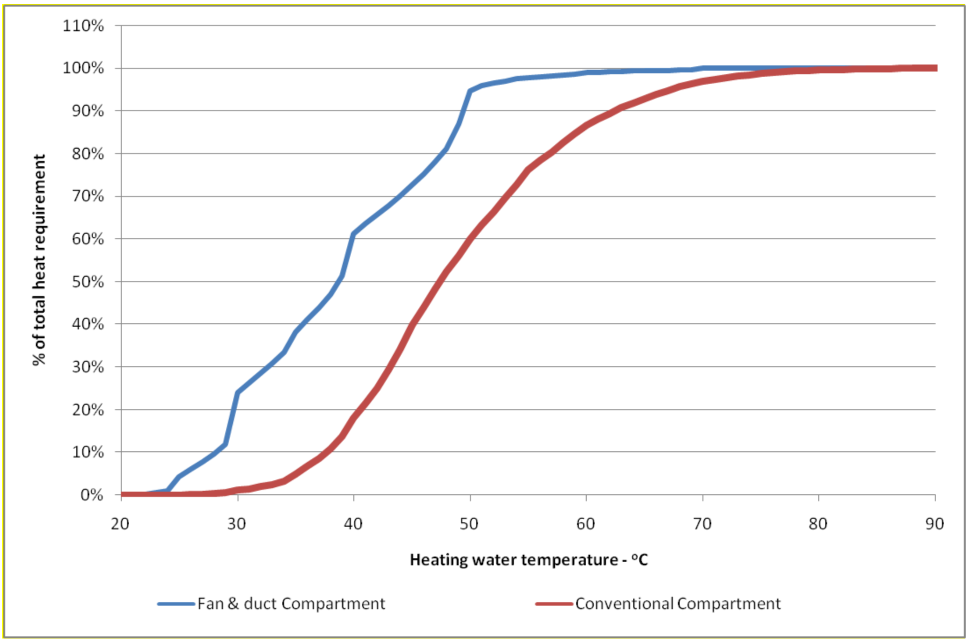


Figure 12 – Heat use profile

Growing year 2011

Overview

This year was the last year of operation and the following section represents the full report for this year.

The main focus of this year was to work on the running cost of the ventilation system and also consider if it might be possible to engineer a simple version of the fans and ducts system to reduce capital costs whilst taking advantage of its major operational benefits.

One external issue was a change in management on the site, which led to more conservative operation of the system compared with previous years. This probably had a detrimental effect on overall energy savings achieved.

Main fans and ducts system

Background for this year

Testing was continued on the main fans and ducts system, which was originally installed in 2008. Since that time, efforts had been made to reduce electrical running costs and this was taken a stage further this year by **a reduction in the air delivery rate using variable fan speed controls**. The move to do this was supported by more recent commercial practice in the Netherlands, where it has become more common to use lower air delivery systems, and also through the findings from this project over the previous two years, which indicated that there was potential for using low airflow delivery without undue risk of significant performance reduction.

System overview

The layout of the fans and ducts systems is represented in the following diagrams:

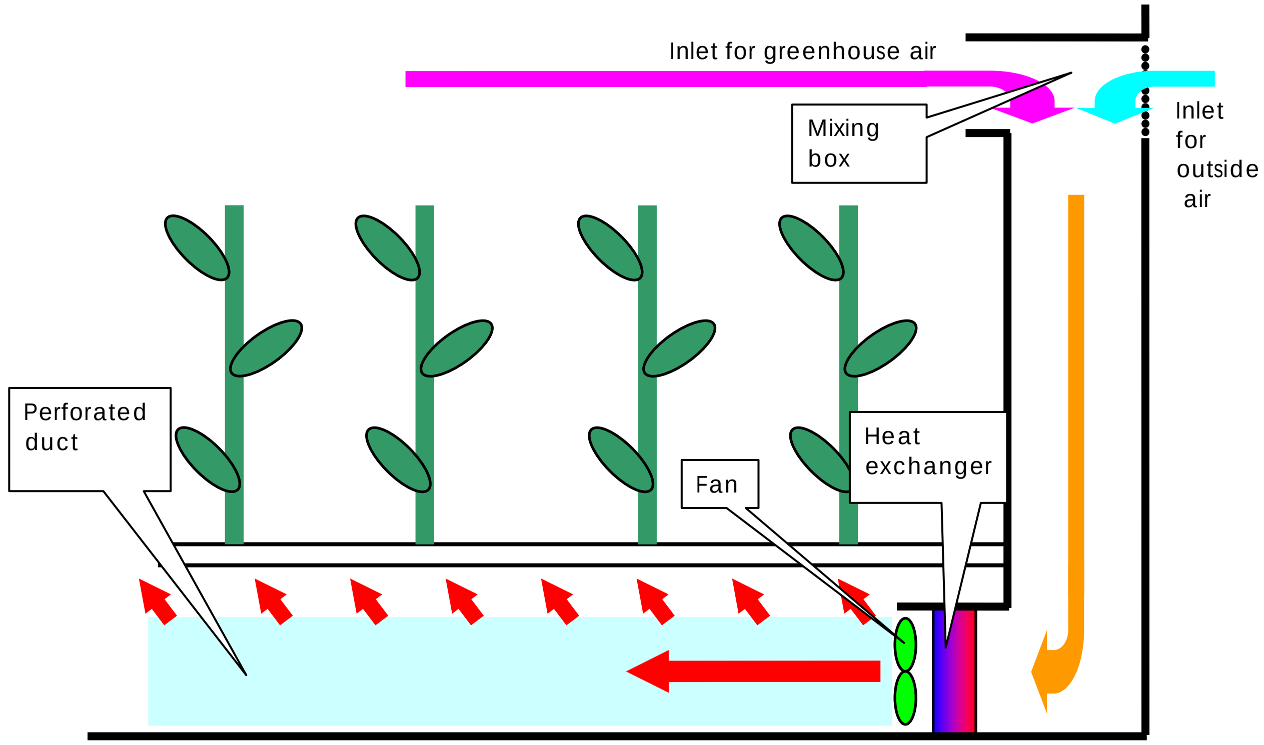


Figure 13 – Fans and ducts schematic (full system)

Positioning for each of these units in relation to the plant rows is shown below:

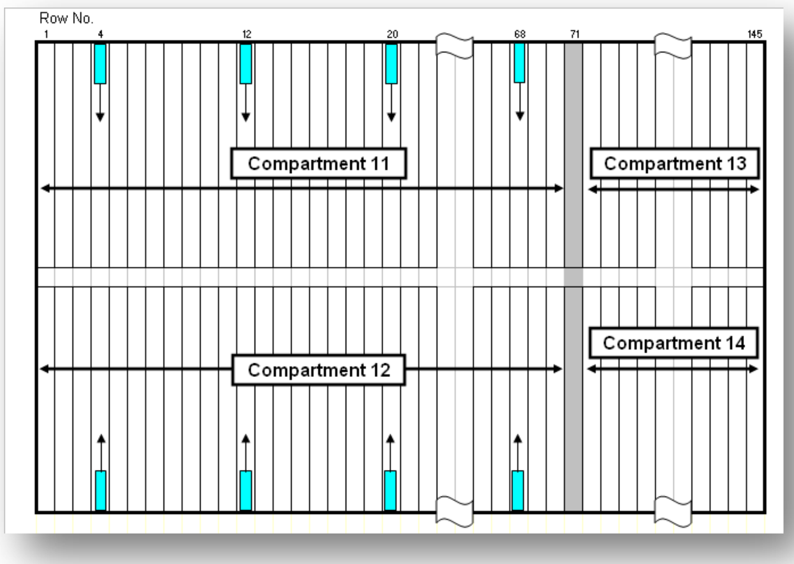


Figure 14 – AHU layout

Reduction in airflow

The main modification for the 2011 trials was to lower the airflow rate delivered by the system. Anecdotal evidence from commercial units in the Netherlands indicated that the lower airflow ratings would work successfully. An airflow figure of one air change per hour (about half of that used for the trial to date) appeared to be a reasonable target.

System airflow was reduced by lowering the speed of the fans with variable speed drives (VSDs). To maintain the same air velocity through the duct delivery holes and hence maintain the lateral throw of the air across the greenhouse, 50% of the holes in the duct were blocked.

The power consumed by the fans reduced from 18 kW/Ha to 9 kW/Ha as a result.

Fans and ducts (simple)

With most of the financial benefits of the fans and ducts systems coming from better crop performance and this, in turn, being driven by more even temperatures and humidity, it was rational to examine the hardware with a view to cutting out expenditure on components and features which only contributed marginal financial benefits. The key economic and practical factors driving the development of a simple system are illustrated in the diagram below.

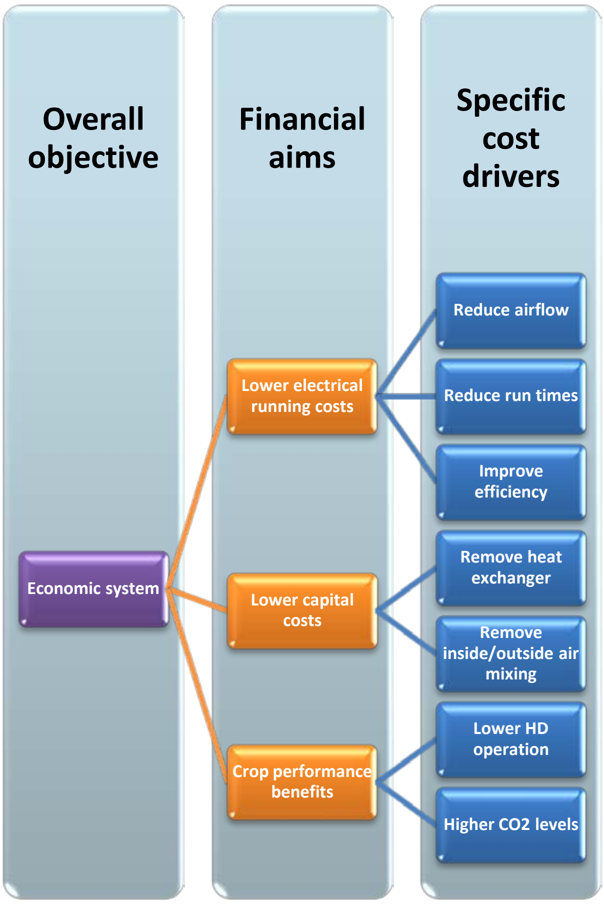


Figure 15 – Simple fans and ducts: economic and practical drivers

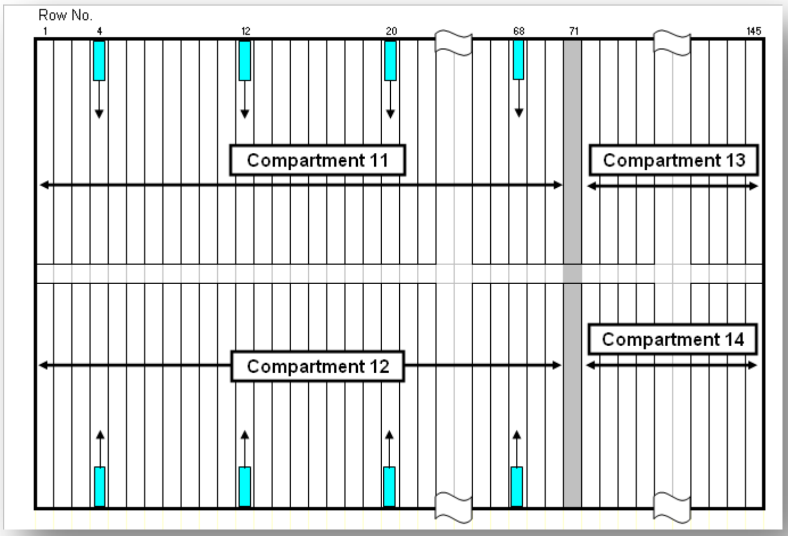


Figure 16 – Simple fans and ducts: fan layout

On the basis that the greatest potential for performance returns were associated with better yield and not in energy savings, the first areas to explore were what elements within the hardware could be abandoned whilst still maintaining the crop performance benefits.

The essential characteristic of the fans and duct system impacting directly on the crop was the ability of the system to effectively provide air recirculation. On that basis, the outside air mixing system and heat exchanger were abandoned to produce a simplified solution. In most greenhouses ventilation is provided for by opening vents and heating comes from using a pipe rail system.

Capital costs of the resulting simple system were around £2 per m^2, some 87% less than full fans and ducts.

Test area for simple system

Compartments 15 and 16 were used to house the simple system and compartments 17 and 18 provided the experimental control area. The greenhouse was originally built in 2000 with a standard construction – being 5 m to the gutter with hanging gutters for the plants and a thermal screen.

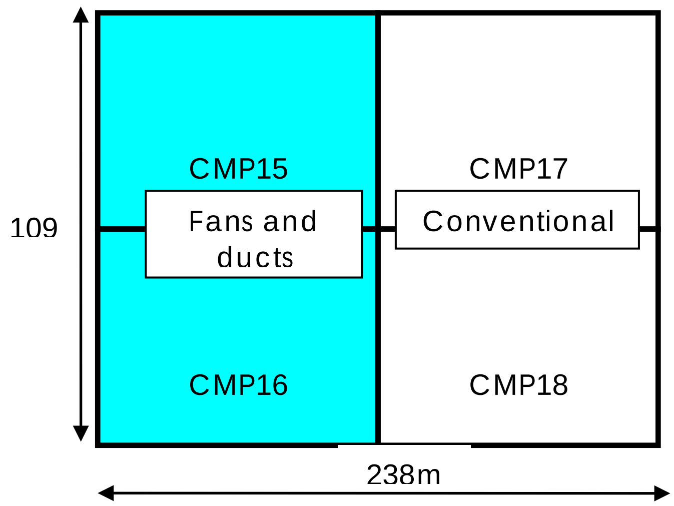


Figure 17 – Simple fans and ducts: trial compartments

Components of the system

On every fifth row, a single propeller fan and plastic duct was suspended under the hanging gutter. Ducts were 53 m in length. Each fan was rated at 160 W electrical input and provided an airflow of 4,550 m^3/hr. Total airflow for the compartment gave an equivalent air mixing rate of 2.1 air changes per hour.

Figure 18 – Simple fans and ducts installation

In order to provide even air movement the direction of each fans and ducts, air delivery was alternated (see diagram below).

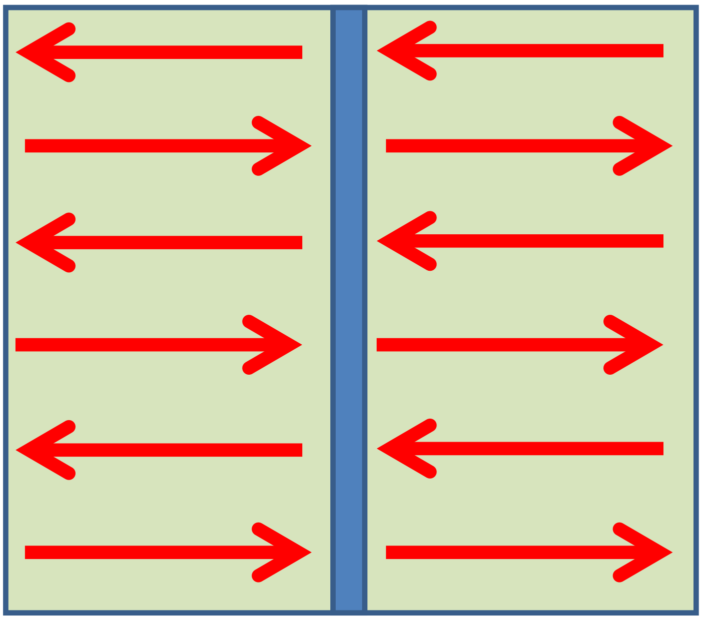


Figure 19 – Simple fans and ducts layout

Control

Control of the fans was either on or off (no speed control) and the controlling parameters were humidity deficit and Lee side vent position. Criteria for control were:

Table 2 – Simple fans and ducts: control strategy

		Humidity Deficit	
		(HD) below 3.5 g/m^3	above 3.5 g/m^3
Lee side vent position	Open more than 15%	Fans on	Fans off
	Open less than 15%	Fans on	Fans on

Data collection (both systems)

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 Farm Energy Centre consultants. Table 3 below lists the measurements taken in each compartment.

Table 3 – Greenhouse aerial environment measurements

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

Energy use

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

The electricity used by the fans was recorded using a combination of run-time and spot measurements of kW drawn.

Yield

This was recorded by the nursery as total kilos of fruit harvested each week in each area.

Disease

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

- Plants removed – these were recorded by nursery staff.
- Detailed assessment at key stages of the season – carried out by Dr. Tim O'Neill, ADAS UK Ltd.

Temperature uniformity

This was assessed by placing compact data loggers on a grid pattern within each greenhouse compartment. The data loggers were mounted approximately 30 cm above the growing media.

Results (full system)

Temperature uniformity

Compared to previous years, there was no obvious effect from lowering the airflow of the fans and ducts system. A cold corner, which was not evident in previous years, was evident around at the end wall where CMP11 met CMP13. This was thought to be due to leakage of cold / outside air into the mixing box where the louver was exposed to wind pressure. In previous years all inlet louvers had been covered in plastic sheet during the winter, but in 2011 this was not used.

Greenhouse climate

Temperature patterns were similar to previous years:

Daytime temperatures in both fans and ducts compartment and the control compartment were virtually the same throughout the year. Nighttime temperatures were similar during periods when humidity control was not required (up to Week 15). From Week 15 onwards, when good air movement in the fan compartment allowed less heat to be used for humidity control, the nighttime temperature was consistently lower in the fans and ducts compartment by about 0.5–0.8°C.

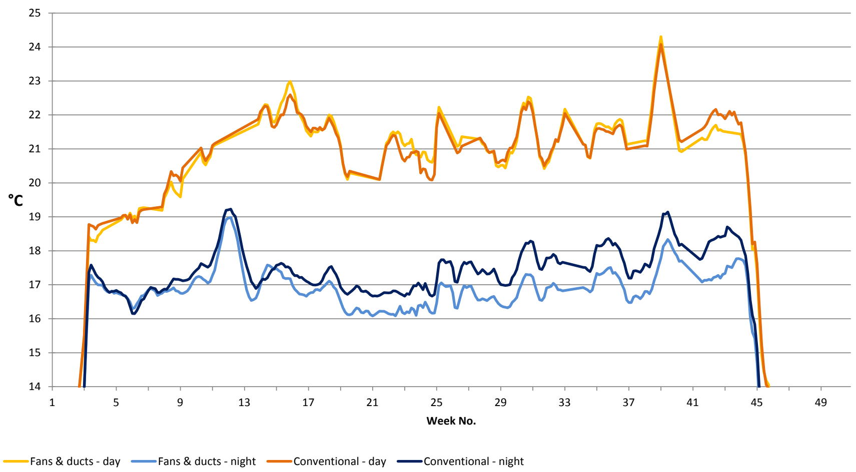


Figure 20 – Greenhouse temperature (full system)

Daytime HDs in the fan and control compartments were virtually identical over the season. In previous years, a lower HD had been achieved mostly by virtue of the confidence and experience achieved by the grower. With a new grower taking an understandably more conservative approach, HDs were kept higher.

The new grower was successful however in achieving lower night-time HDs and associated energy savings were evident.

The following graph shows average night-time HDs over the season for the two compartments. Problems were experienced with the site controller (Priva) around Weeks 15 and 21. This had an adverse effect on energy use during these periods.

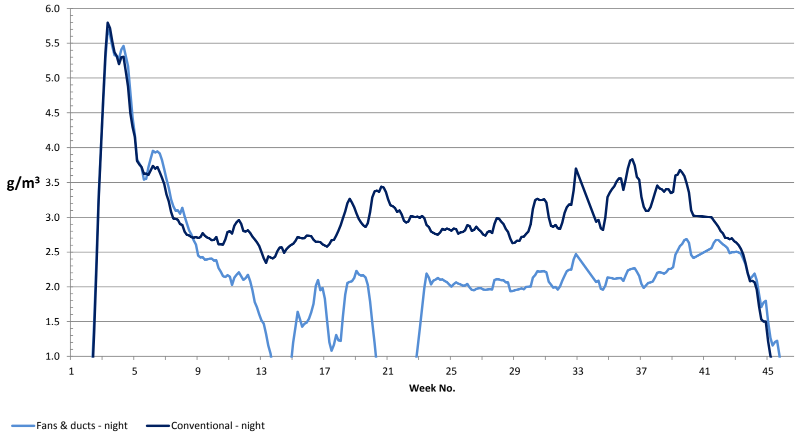


Figure 21 – Greenhouse humidity (full system)

CO_2

CO_2 levels were slightly lower compared with previous years and very similar to the control compartment, mainly due to the wish of the grower to sustain similar HDs in both compartments and hence ventilation rates. As CO_2 is the main driver to yield there was, predictably, no yield increase over and above the control compartment.

Heat energy

Figure 22 below shows the percentage energy saving (heat) in the fan compartment compared with the control compartment. Note a negative result means more energy was used.

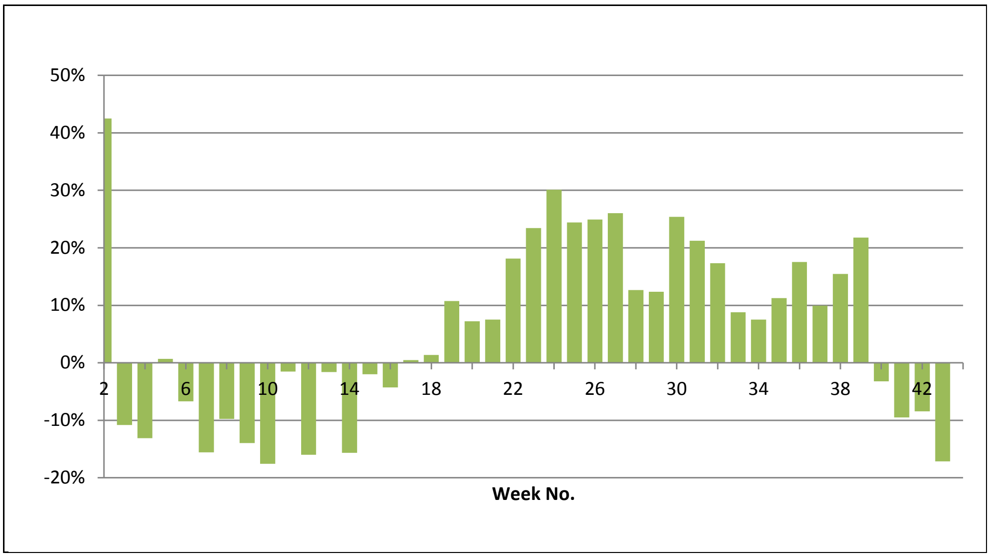


Figure 22 – Weekly heat saving (full system)

Up to Week 11, the fan compartment used more energy that the control. As this happened in previous years (even when fans were turned off for short periods) – this was deemed to be a compartment effect and not associated with the performance of the fans and ducts system.

Between Weeks 11–21, measuring box problems led to some erroneous readings for HD leading to heat to be used unnecessarily.

From Week 22 to 39, systems were working as required and good energy savings were being made.

After Week 40, the crop in the fans compartment was pushed through higher temperatures to give a faster finish. This is not an effect associated with the use of the fans and ducts system.

Looking at the period between Week 22 and Week 39 (stable, uncompromised results) and comparing against a similar period for the previous season, energy savings were 25.6 kWh/m^2 (gas boiler, 2010) as against 31.1 kWh/m^2 (gas boiler, 2011).

Extrapolation of savings over the weeks when the control system was not functioning correctly would give an equivalent season saving of 57.0 kWh/m^2 (average of 56.0 kWh/m^2 in previous years).

Electricity consumption

The reduction in airflow (50%) through the fans units produced a similar proportional effect on the amount of electricity used. This reduced to 5.3 kWh/m^2 (10.7 kWh in 2010).

Yield / crop

The yield in the fans compartment was 55.3 kg/m^2 compared with 56.24 kg/m^2 for the control (1.7% reduction). This compares with an increase averaging 6.5% in previous years. The reasons for this were:

There was no net CO_2 increase in the fans compartment over the control compartment this year, as the daytime HD and consequently vent rates were not reduced.

A bigger likely impact was the incidence of Pythium (root disease) in the fans crop in April. Although its impact was managed / controlled its effect was sustained throughout the year and as such there is little doubt the yield will have suffered.

Disease

Apart from the root disease which was not linked to the use of the fan system there was no discernible difference between the experimental and control compartments. A full disease analysis is included in Appendix 1.

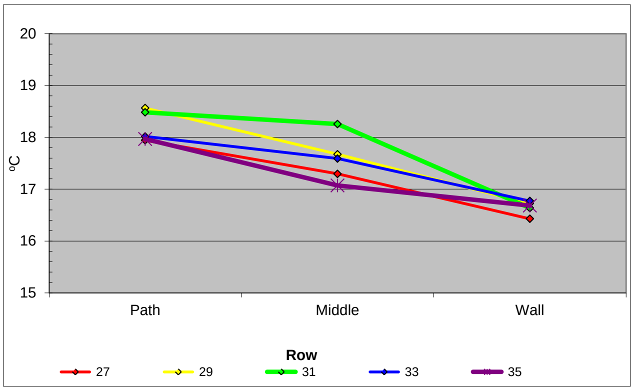
Results (simple fan system)

Temperature uniformity

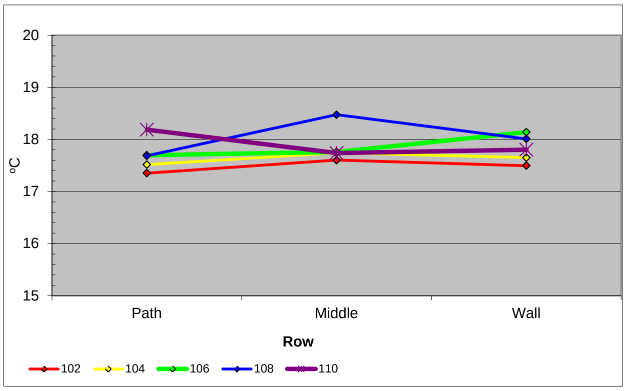
Initially temperature uniformity was notably worse in the fan ventilated area that the control, even though the layout of the fan operation followed the recommendations of the supplier and followed a 'snake' air delivery pattern (see Figure 19).

The graphs below show how operation of the fans made the wall side of the compartment cooler.

Fan compartment (CMP16) – fans on



Control compartment (CMP18)



Fan compartment (CMP16) – fans off

Control compartment (CMP18)

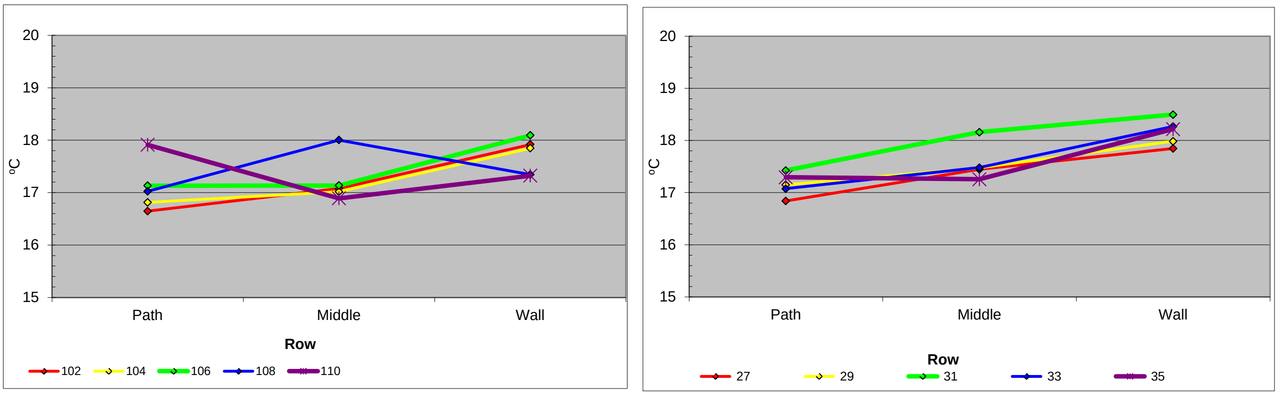


Figure 23 – Temperature uniformity (simple system)

An intuitive solution to the distribution problem was to configure the ducts so that they all pushed air away from the central passage and to the walls. This solution was finally proven to work in the latter part of the season when heat demand increased and the vents were closed (October).

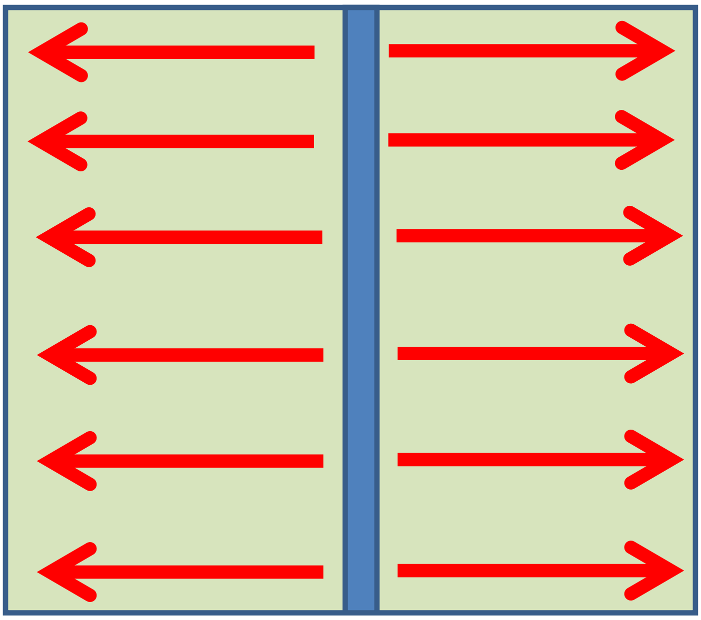


Figure 24 – Simple system: modified layout

Fan compartment (CMP16) – fans on

Control compartment (CMP18)

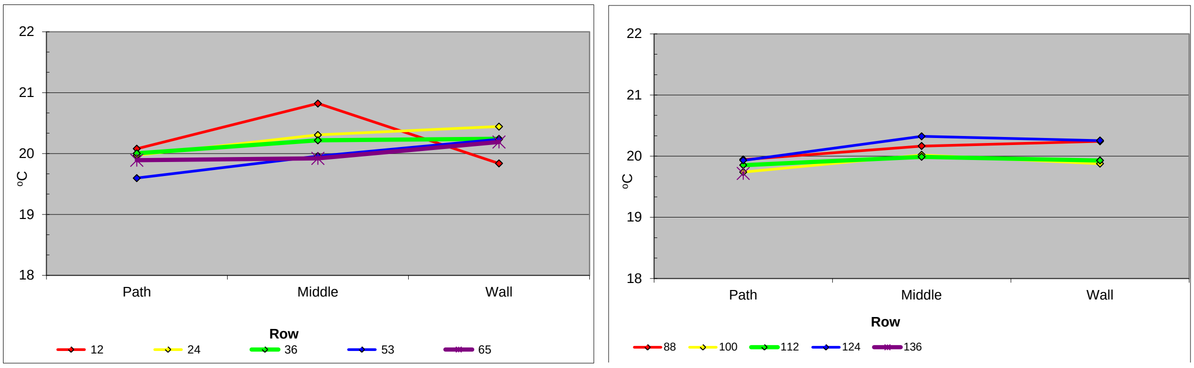


Figure 25 – Temperature uniformity (simple system – modified)

The result was a more acceptable lateral temperature profile.

Greenhouse climate

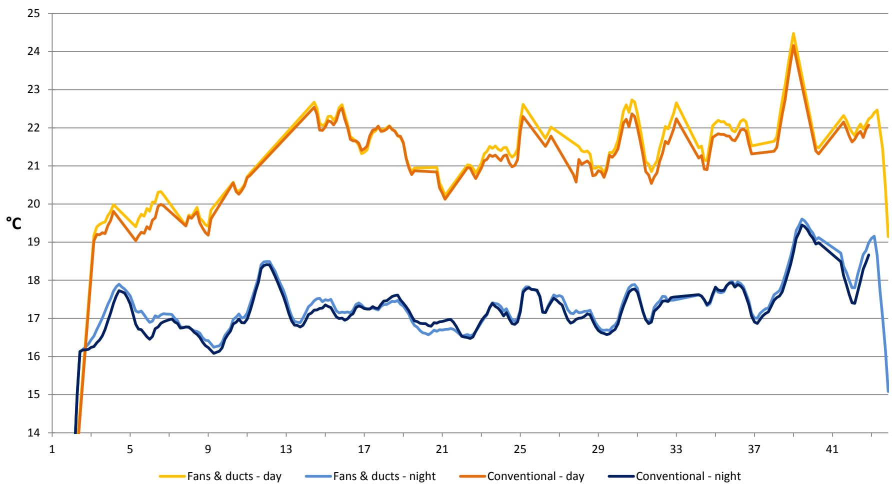


Figure 26 – Greenhouse temperature (simple system)

There was essentially little or no difference in temperatures between the fan and control compartments.

HD

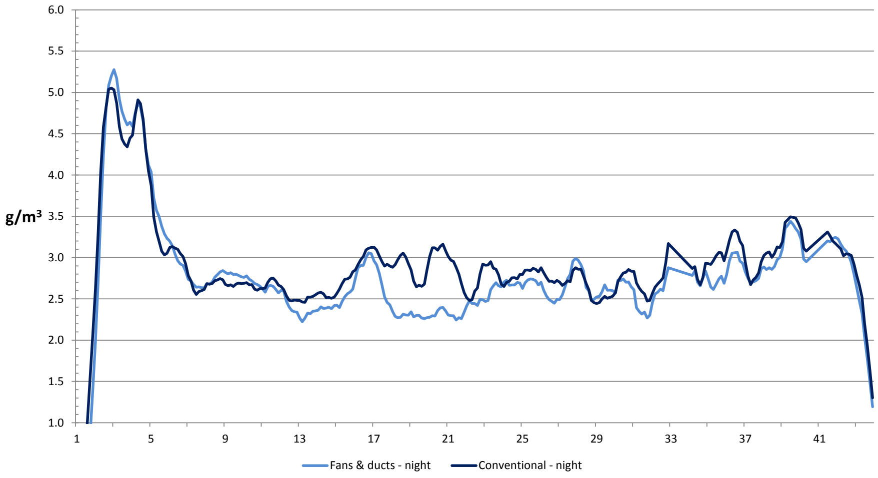


Figure 27 – Greenhouse humidity (simple system)

The main differences in HD between the fan and control compartments were evident at night and after Week 17, when energy savings were being pursued by tighter humidify control.

After Week 22, some crop damage caused by careless crop work led to disease vulnerability in the crop. Therefore, beyond this point, HDs were returned to more traditional levels to circumvent any development of disease. This sustained for most of the remaining production period.

Control strategy

For humidity control, minimum pipe temperature between 45°C and 55°C were applied with the higher figure used during the daytime to stimulate transpiration and in response to disease pressure and persistent poor weather conditions. When judged possible, minimum pipe temperature settings in the fan compartment were 5 degrees lower than the control compartment.

CO_2

No CO_2 enhancement was seen in the fans compartment, as a very safe approach was taken in respect of HD control during the day period.

Energy

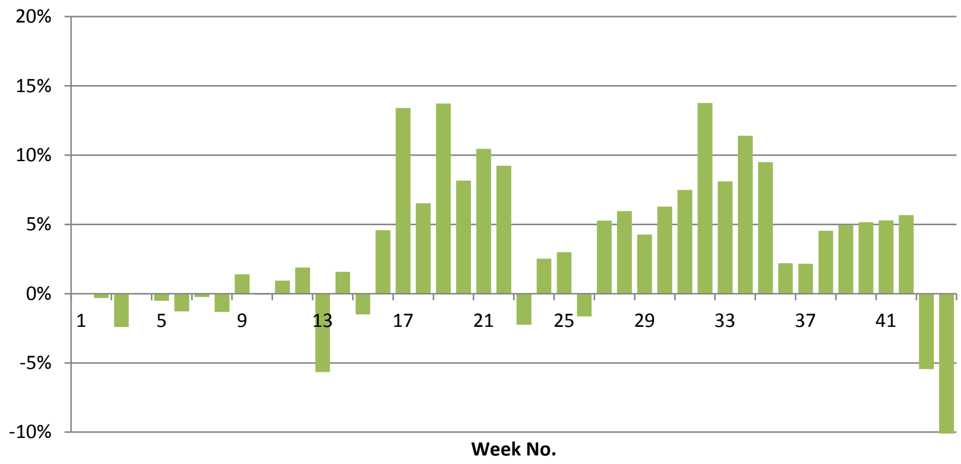


Figure 28 – Weekly heat saving (simple system)

Energy savings shown in Figure 28 are largely associated with nighttime HD control policy. Up to Week 17 little saving in energy was made. For the period of Week 17 to Week 22, lower HD settings produced useful energy savings. Disease issues between Week 23 and Week 26 curtailed the lower HD policy and energy savings were insignificant in this period. Savings were built again from Week 27 onwards, as confidence returned and disease was brought under control.

Heat energy use (gross gas) was 434 kWh/m^2 for the fans compartment and 450 kWh/m^2 for the control, showing a very modest saving of 16 kWh/m^2.

It's difficult to estimate a potential energy saving for this system as the trial encountered a number of unconnected problems which resulted in sub-standard performance. However at times when the system was unaffected by problems, a 7.5% saving was evident. Taking a conservative view of savings, 5% or 22 kWh/m^2 might well be achieved.

Electricity consumption

Annual consumption of the fans and ducts was 3.0 kWh/m^2. From this can be deducted the consumption of roof fans, which would normally be used for this type of crop, but would be unnecessary with the installation of the fans and duct system. With installed capacity of about half the rating of the fans and ducts system, a roof fans system might be expected to consume 1.5 kWh/m^2 over a year, leaving a net consumption of 1.5 kWh/m^2 for the fans and ducts system.

Yield / crop

The yield in the fans compartment was 63.91 kg/m^2, compared with 64.68 kg/m^2 for the control (1.1% reduction). The fans compartment failed to meet its potential yield premium because:

- There was no net CO_2 increase in the fans compartment over the control compartment this year, as the daytime HD, and consequently vent rates, were not reduced.
- Quality of crop work appeared to have a large effect on Botrytis: in the simple fans and ducts house, the percentage missing stem bases in September in areas managed by different workers ranged from 3.1 to 18.8% of plants.

Disease

The crop disease report for the year showed there was no adverse effect from the simple fans and ducts system on levels of Botrytis. However, quality of crop work appeared to have a large effect on Botrytis with some substandard work in the fans and ducts compartment, pushing missing stem base affecting up to 18.8% of plants in September.

Discussion

Heating costs (full system)

In the trial, the heat energy savings achieved in 2011 were lower than in previous years – mainly due to a change of grower on site, and some inexperience with the system. However, the change of grower did demonstrate the relative ease with which the system could be adopted from a standing start.

The average heat saving achieved in the previous seasons (2009 and 2010) is probably a more realistically achievable target for a commercial installation (56 kWh/m^2 gas).

The value of this saving depends on the fuel and system used for heating. At Mill Nurseries Ltd, heating water came from a CHP system. However, the majority of growers still rely on mains gas fuelled boilers. The financial value of the saving based on a gas price of 2.2 p/kWh (65 p/Therm) is £1.23 per m^2.

Full systems are likely to be much more viable where a low cost low-grade heat source is available as overall energy cost savings are likely to be better. In the extreme, if low-grade heat is free – i.e. from a waste heat source the financial viability of fans and ducts looks very good. Low-grade heat sources can be categorised as follows:

Table 4 – Low-grade heat sources

Source	Cost consequences
Waste heat (from power generation for instance)	Free heat, apart from pumping costs.
Ground source heat pumps	Coefficient of performance (COP) of heat pumps improves as heat flow temperature falls – lower temperature system may be 20% to 30% cheaper to run.
Conventional boilers	Flue gas condensers improve in their ability to recover heat as temperatures go down.

With greater emphasis on saving energy and financial incentives like the Renewable Heat Incentive, the ability to utilise low-grade heat is going to be increasingly important in the future.

Electrical running costs (full system)

The amount of electricity used by the fans and ducts system was identified as being a critical cost and modification over the trial enabled this to be reduced by about half. 2011 trials using lower airflows produced successful results and energy consumption of 5.3 kWh/m^2 (£0.42 per m^2) compared with 11.2 kWh/m^2 at this start of the trial (£0.90 per m^2).

Total net energy benefit (heat minus electricity) for a conventionally heated greenhouse is likely to be in the order of £0.82 per m^2.

Maintenance

Discounting initial teething problems in 2008, the fans and ducts installation has been reliable. To date, maintenance costs have been almost exclusively associated with the fans. Three required replacement bearings which, due to their construction, were relatively easy to fit and cost around £50 per fan. Two fan motors burnt out which required a re-wind, costing £350 each.

The only on-going maintenance items to date have been air filters in the air handling units. Alternative filter media have been identified which cost £1 per fan unit (18 in total). Filters should be replaced at least every six months.

Crop (full system)

Yield increases were recorded in 2009 and 2010 with fans and ducts buy no yield increase was achieved in 2011. A primary cause for the 2011 performance fall was the root disease Pythium which occurred in the fans and ducts crop. Assuming that 2009/2010 represent a more representative performance measure the average yield increase during this period was 3.4 kg/m^2 (6.5%). Assuming a net value of £0.50 per kg, this extra yield is worth £1.70 per m^2.

As the crop was of the loose round variety Encore, additional yield delivered additional income. The same might not be the case with tomatoes on the vine. However, enhanced production could come from producing more vines through an increase in crop density or to make input savings by reducing levels of CO_2 enrichment with an associated reduction in energy use.

The following chart summarises the financial benefits and costs from the main variable items.

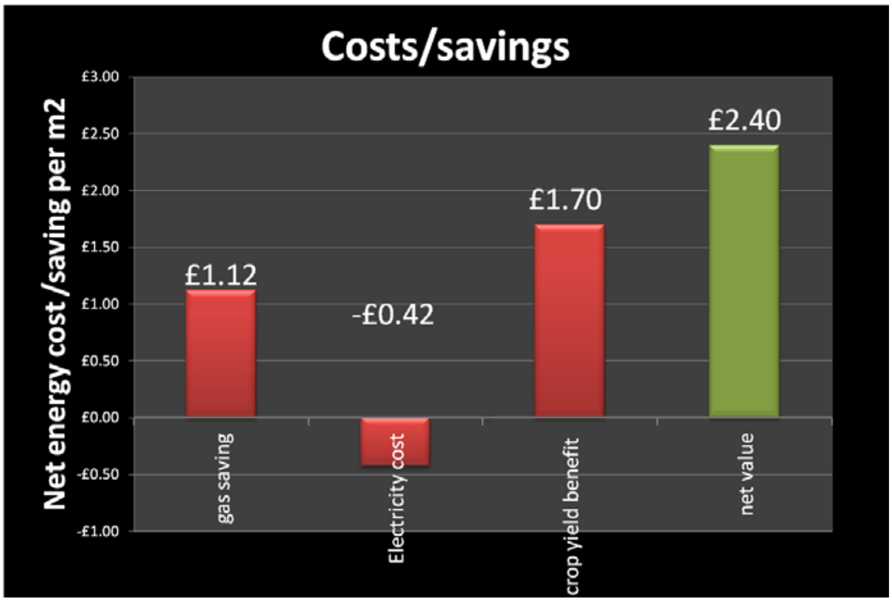


Figure 29 – Fans and ducts (full system) costs / savings

The total likely benefit of installing a full fans and ducts system is £2.40 per m^2.

Simple system

Although heating savings were only 16 kWh/m^2 in the trial, a conservative extrapolation of the saving made when the system was not being hampered by uncontrollable external influences points to a likely saving on a commercial system of 22 kWh/m^2. Electrical fan input was 3 kWh/m^2. After taking account of the fact that these fans would displace the usual roof fans, a net electricity consumption of 1.5 kWh/m^2 is estimated. Excluding any effect on yield, this leaves a net benefit of £0.32 per m^2.

Capital costs of the system are estimated to be about £1.75 per m^2 to include the fans and ducts system at about £1 per m^2 and £0.75 for wiring and installation labour.

In the trial year crop yield was in fact 1.1% lower than the control area. However, the reason for this was largely due to a difference in crop care between the experimental and control areas and some non-associated disease. A reasonable payback for such equipment would be around three years. To achieve this, a yield benefit of £0.58 per m^2 (1.7%) is required. Albeit not proven, this seems possible.

Engineering (full system)

Primary design

Primary design must consider:

- Heating capacity required.
- Total airflow.
- Uniformity of airflow and heat distribution.
- Electricity consumption.

Heating capacity

Where heating is to be integrated into the system, it can either be sized to provide all necessary heating for complete temperature support, or sized to provide good local air humidity conditions.

In the latter case, it is commonly accepted that delivering air at or about greenhouse temperature is sufficient. As a sizing example, for a 5 m tall greenhouse requiring one air change per hour an airflow of 50,000 m^3/hr per Ha would be required. For humidity control with outside air at 8°C and a greenhouse temperature of 20°C, 210 kW/Ha of heat would be required. As a guide, heating water temperatures of 30–50°C are likely to satisfy this heat requirement. A conventional humidity control system using heat from pipe rails would probably be rated at 400 kW per Ha, with a maximum pipe temperature of 50°C.

Where total heating delivery is required, for instance where a site is using low-grade recovered heat, then between 1.25 MW/Ha – 2.0 MW/Ha is required to maintain a greenhouse temperature of 20°C when the outside temperature is -5°C, depending on whether the greenhouse uses a thermal screen.

It is worth noting that heated pipe rails also provide the means by which picking trolleys are moved through the crop. As such, retention of the rails with some facility to add heat through the system might be seen as desirable, and would reduce the necessary delivery rating of the fans and ducts heating system.

Airflow

Ventilation systems are typically sized according to the number of times per hour that the air held within the greenhouse is either circulated or replaced with outside air. This is known as the air change rate. With electricity consumption being a significant cost, the lower the air change rate the better.

The original installation at Mill Nurseries Ltd has an air change rate of two times per hour. This was reduced to one air change per hour in 2011 and this has proven to be sufficient where improved climate control is the sole objective.

Air delivery rate may have to be higher when using low-grade heat sources and may in the extreme be as high as four changes per hour. This could incur electricity costs of £3.20 per m^2 – a significant figure when compared with boiler-only heating costs of around £10–£12 per m^2.

Uniformity of airflow and heat distribution

Achieving satisfactory temperature uniformity proved to be a major challenge in this project. In part, this was because only one duct was used for every eight rows (12.8 m) with high speed air delivery from the duct D holes (8–10 m/s).

Ducts were modified to provide air delivery perpendicular to the duct surface (i.e. at 90° to the direction of the air travelling down the duct. Installations which use more ducts and lower air speeds are intrinsically better a delivering even airflow.

In specifying air delivery characteristics, it is probably more important to specify the level of temperature uniformity required and allow the designer to choose an appropriate air delivery rate configuration to suit the system in question. The greatest variation in temperature occurs during the main heating season (winter) when the vents are closed. As a guide, the differential between the warmest and coldest points should be less than 1.5°C and preferably nearer 1.0°C.

An alternative approach is to survey the greenhouse before fans are installed and specify that the temperature uniformity should be no worse than with the existing heating and ventilation system.

Electricity consumption

It is useful for specifiers to define a target electricity consumption with one air change per hour (50,000 m^3/hr) the installation at Mill Nursery used 10 kW/Ha. This should be a reference point rather than a specific requirement. As long as growers are aware of the importance of this, competing suppliers quotes can be easily compared.

Air handling unit

The heart of the fans and ducts system is the Air Handling Unit (AHU) – see Figure 30. As the primary air delivery mechanism containing the fan, mixing box and heat exchanger, it is the most expensive component of the fans and ducts system. As such, savings which can be made in its construction and configuration will impact significantly on the economics of any complete system.

Figure 30 – One AHU supplying two ducts

In the trial system, one AHU was used to deliver air to each duct. Recently, suppliers are offering AHUs that serve two or more ducts. They require additional interconnecting ducting but overall offer a lower installed cost per m^2 of greenhouse.

Another idea to reduce costs, and which is applicable to new greenhouse construction is to construct a primary air delivery duct along one wall of the structure to act as the feed for all lateral ducts in the greenhouse. This gets rid of the unitary AHUs cutting the cost of fans and heat exchangers.

The adjacent photograph shows such as system (fitted with evaporative cooling pads).

Conclusions

The implementation of the fans and ducts technique has shown consistent benefit over the three years of implementation of the project. Such benefits will improve in the future as techniques are refined and growing practices adapted to best work with the fans and ducts system.

Basic engineering of a fans and duct system has been established and tested and the running costs and operational benefits evaluated.

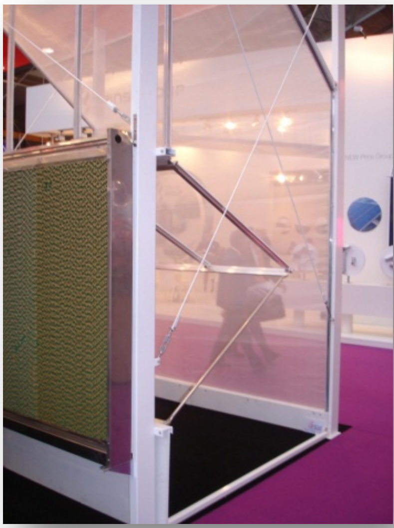


Figure 31 – Glasshouse integrated AHU

A full fans and ducts system will be particularly beneficial to growers who are using a low temperature heating source (heat pump, boiler condenser) or waste heat, as this heat will be cheaper than that derived from a conventional boiler.

Where a low-grade / cheap heat source is not available, the yield benefit is a key element of the economics of a system as the returns from energy savings alone are insufficient to justify the capital expenditure. Yield increase comes largely from the effect of higher CO_2 levels, which can be achieved by lower levels of ventilation and tolerance of lower HDs.

The low-cost 'simple' fans and ducts system which does not incorporate heating coils or outside air mixing features is likely to look more appealing for growers who are not using low temperature heating sources. Although the experiment has not produced robust figures for the value of this technique in the one year that it has been studied, enough information is available to indicate potential benefit with substantially reduced capital costs. Payback in two years should be achievable if this promise can be realised.

Commercial development of fans and ducts techniques in the Netherlands is testament to its potential here, and sufficient evidence is available to allow growers to take measured investment decisions with this equipment.

For the future, more work is needed to evaluate the interaction between full fans and ducts and emerging low temperature source heating systems to determine performance. An extended comparative monitoring programme on 'simple' fans and ducts vs. traditional air mixing is required to obtain more statistical and physical evidence showing the costs benefits of the technique.

Knowledge and technology transfer

The following technology transfer activities have been carried out over the life of the project:

HDC News – February 2009.

Commercial Greenhouse Grower – June 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.

Hampshire Isle of Wight tomato study group site visit – May 2010.

TGA technical committee update – June 2010.

Commercial Greenhouse Grower – July 2010.

Project review meeting – September 2010.

Project open day – September 2010.

HDC Energy News – December 2010.

Project review meeting – October 2011.

HDC / PTG pepper event – March 2012.

HDC News – tbc.

TGA conference – September 2012 (booked).

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 local use or 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 three–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.

Co-efficient of performance (COP)

The ratio of heat produced to energy (typically electricity) input.

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Appendix 1 – Disease report by Dr T. O'Neill (2011 cropping year)

Effect of assisted air movement and climate control using fans and ducts on grey mould (Botrytis cinerea) in protected tomato – 2011 (PC 278a)

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 in 2011, the fourth year of monitoring in this glasshouse. In a second experiment in a different glasshouse on the same site, the effect of a simple fans and ducts system was examined in a crop of Encore grafted onto Beaufort rootstock. It was not possible to randomise replicates in either experiment as the systems used to modify the aerial environment were each installed in one glasshouse only, with an equivalent area in adjacent houses. Any differences recorded may therefore be due to effects on Botrytis caused by: a) a difference in the aerial environment resulting from the air movement systems; b) inherent differences in the aerial environment of the two houses; c) differences in quality of crop work or other factor; d) a combination of these factors.

Levels of leaf and stem Botrytis in the air optimiser experiment were close to zero at assessment in April and June 2011. At a final assessment on 30 September, the mean proportion of missing stem bases was 2.8% and 2.4% in the air optimiser and the control houses respectively.

Levels of leaf and stem Botrytis were greater in the simple fans and ducts experiment throughout the season. At the final assessment on 30 September, the mean proportions of missing stem bases were 4.4% and 5.1% in the fans and ducts and the control houses respectively; the mean number of stem lesions at this time was 5.3 per row in the fans and ducts house and 7.1 per row in the control house.

These results indicate there was no adverse effect from either the air optimiser or the simple fans and ducts system on levels of Botrytis. Quality of crop work appeared to have a large effect on Botrytis; in the simple fans and ducts house, the % missing stem bases in September in areas managed by different workers ranged from 3.1 to 18.8% of plants.

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. In 2009, at the end of cropping the mean numbers of girdling stem Botrytis lesions and missing stem bases were less in the house with fans and ducts than the control house. After the 2009 crop, the distribution of air holes along the ducts was altered in order to produce more uniform air movement along rows. In 2010, levels of Botrytis were much lower than in the previous two years. In October 2010, there was no difference between the air optimiser and control house in the number of surviving heads.

The objectives in 2011 were:

- To determine the overall incidence and pattern of Botrytis stem lesions in two glasshouses of cv. Encore where environment control was by (i) Priva air optimiser system and (ii) conventional hot water pipes.
- To determine the overall incidence and pattern of Botrytis stem lesions in two glasshouses of cv. Encore grafted onto Beaufort rootstock, where environmental control was by (i) a simple fans and ducts system used in conjunction with conventional hot water pipes, (ii) conventional hot water pipes.

Methods

Site

Mill Nursery, Keyingham, Hull, East Yorkshire. Experiment 1 was in compartments 12 and 14; Experiment 2 was in compartments 16 and 18.

Crop production

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. The air optimiser comparison was done in a crop of cv. Encore on its own roots; the simple fans and ducts system comparison was done in a crop of cv. Encore grafted onto cv. Beaufort rootstocks. Usually each plant had two heads. Two applications of Switch (cyprodinil + fludioxonil) were made to all crops before first pick (by the grower). Thereafter, no fungicides with activity against *B. cinerea* were applied to the monitored areas. Leaf trimmings were left on the floor beneath the hanging gutters according to standard practice for the nursery...

For Experiment 1, 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.

With the simple fans and ducts system in Experiment 2, ducts were located every sixth row on both sides of the central pathway in one half of the house (compartments 15 and 16). There were no fans and ducts in an equivalent area in the control house (compartments 17 and 18).

Disease assessments

Crops were assessed for Botrytis on 26 April, 24 June and 30 September 2011. 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).

Botrytis levels were low and there was rarely more than one leaf or stem lesion per stem. A \`total\` 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 September assessment, the number of surviving heads was counted. Shoots which originated below head height and were 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.

At the assessments on 24 June and 30 September, the number of missing stem bases was counted in each of seven rows (every tenth row) spread throughout the house. The aim was to determine the variation between rows which might arise due to different crop workers. Crop workers are each assigned a certain number of rows and manage that area of crop for the full season. Losses per row across the house were mapped to crop worker.

In compartment 12 (Experiment 1), assessments were done on five rows of crop in the area with ATUs, comprising alternate rows from one ducted row to the next ducted row. This resulted in assessment of two ducted rows, one row midway 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 14), without ATUs, 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.

With the simple fans and ducts system (Experiment 2), assessments were done on six adjacent rows from one duct to the next in compartment 16. This resulted in assessment of two ducted rows, two adjacent to duct rows and two central rows. An equivalent area was assessed in the adjacent glasshouse without fans and ducts (compartment 18).

Experiment design and analysis

Randomised designs were not possible because there was no replication of houses containing ATUs or simple fans and ducts. Assuming that the crops and glasshouse environment in different halves of the same house were identical except for the ATUs, or simple fans and ducts, different rows and parts of rows in the same house were treated as pseudo-replicates. For Experiment 1, a total of 144 plants per row were examined, comprising 72 on either face and 36 per quarter length of row (18 per quarter face). For Experiment 2, a total of 176 plants per row were examined, comprising 88 on either face and 44 per quarter (22 per quarter face). 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

Experiment 1 – Air optimiser system

Levels of Botrytis were very low in April and June and still comparatively low at the final assessment on 30 September (Table 1). The proportion of missing stem bases on 30 September was 2.8% and 2.4% in the air optimiser and the control houses respectively.

Table 1: Effect of air optimisers on Botrytis in tomato cv. Encore – 2011 (720 plants assessed over 5 rows)

Treatment	No. stem bases missing	No. stem tops missing	No. Botrytis lesions	
			Stem	Leaf
26 April				
Air optimiser (House 12)	1	0	0	0
Control (House 14)	1	0	0	0
24 June				
Air optimiser (House 12)	4	1	1	0
Control (House 14)	4	4	2	0
30 Sep				
Air optimiser (House 12)	20	-	7	0
Control (House 14)	17	-	22	1

The number of surviving plant heads per quarter row on 30 September was slightly but significantly ($p < 0.001$) greater in the air-optimiser house (30.4) than the control house (28.0) (Table 2). Distance from the fan row and distance along the row from the central pathway had no effect (Table 2). There were no significant interactions (Table 3).

Table 2: Effect of air optimisers on number of surviving heads in tomato, cv. Encore – 30 September 2011

Treatment and position	Quarter row from central path				
	1	2	3	4	Mean
Air optimiser (hse 12)					
Fan row	32	31	29	29	30
Quarter way	32	31	30	30	31
Mid way	32	29	32	31	31
Means	32	30	30	29	**30.4**
Control house (hse 14)					
Fan row	29	29	28	30	29
Quarter row	27	28	28	27	27
Mid way	29	28	30	28	29
Means	28	28	28	28	**28.0**

Table 3: Effect of four factors on Botrytis in tomato cv. Encore – 30 September 2011 – Air optimiser heating system trial

Factor	df	F probability			
		No. stem bases missing	No. live heads	No. botrytis stem lesions (any type)	Total botrytis
Fan (F)	1	0.638	**<0.001**	**0.019**	0.259
Distance (D)	2	0.223	0.531	0.112	0.061
Face (Fa)	1	0.638	0.338	0.571	0.378
Quarter (Q)	3	0.736	0.493	0.212	0.202
F x D	2	0.820	0.220	0.686	0.911
F x Fa	1	0.164	1.000	0.571	0.378
D x Fa	2	0.820	0.395	0.982	0.896
F x Q	3	0.736	0.358	0.403	0.551
D x Q	6	0.760	0.775	0.636	0.628

Significant effects are shown in bold. The direction of significant effects is shown in proceeding tables.

Examination in June of the occurrence of missing stem bases across whole houses showed a slight variation between rows in both houses (0–0.6% in air optimiser house; 0–1.3% in the control house) (Table 4). The incidence of missing stem bases was greater, and the variation between rows was greater, in September (0–2.8% and 0–5.0% in the air optimiser and control houses respectively. The mean incidence of missing stem bases at the final assessment was slightly greater in the control house (1.9%) than the air optimiser house (1.1%).

Table 4: Effect of air heating system, location in glasshouse and crop worker on occurrence of missing plants in tomato, cv. Encore – 2011

Path	Worker	% missing stem bases		Path	Worker	% missing stem bases	
		24 Jun	30 Sep			24 June	30 Sep
House 12 – ATU fans and ducts [a]				House 14 – control [a]			
10	J	0.3	0.3	80	K	0	0
20	J	0.3	2.2	90	K	0.6	1.3
30	M	0	0.6	100	A	1.3	5.0
40	G	0.6	0.3	110	R	1.3	1.3
50	G	0	0	120	E	0	2.2
60	S	0.6	2.8	130	EE	0.3	1.3
69	S	0.3	1.6	140	T	0.3	2.2
Mean		**0.3**	**1.1**	Mean		**0.5**	**1.9**

[a] 320 plants/path;

Experiment 2 – Simple fans and ducts system

Levels of Botrytis on these grafted plants were greater throughout the season than on ungrafted plants (Experiment 1). At the first assessment on 26 April a total of 13 Botrytis lesions were found in the fans and ducts house, significantly more ($p = 0.044$) than in the control house (two lesions). This was largely in one area associated with poor crop work in paths 33–39. For subsequent assessments, paths 48–54 an equivalent set of six rows between two ducts, was monitored to avoid the area of poor crop work.

At the final assessment on 30 September the proportion of missing stem bases was 4.3% in the simple fans and ducts house and 5.1% in the control house (Table 5). The total number of stem Botrytis lesions at this time was 63 and 85 in the fans and ducts house and control house respectively.

Table 5: Effect of a simple fans and ducts system on Botrytis in tomato cv. Encore grafted on Beaufort rootstock – 2011 (1056 plants assessed over six rows)

Treatment	No. stem bases missing	No. stem tops missing	No. Botrytis lesions	
			Stem	Leaf
26 April				
Fans and ducts (House 16)	4	5	11	2
Control (House 18)	4	2	1	1
24 June				
Fans and ducts (House 16)*	12	6	44	0
Control (House 18)	3	7	30	3
30 Sep				
Fans and ducts (House 16)	46	-	63	0
Control (House 18)	54	-	85	1

*Paths 33–39 assessed in April, paths 48–54 subsequently, due to crop worker effect in former area.

The effect of row position with respect to fans and ducts row and distance from the central pathway along the row is shown in Table 6. The higher level in the fans and ducts house in April was due to poor crop work as noted earlier. At subsequent assessments there was little difference between the two houses and no consistent pattern with regard to row position or distance along the row.

Table 6: Effect of a simple fans and ducts system on total number of stem Botrytis lesions per quarter row (44 stem bases) – 2011

Treatment and position	Quarter row from central path				
	1	2	3	4	Mean
26 April					
Fans and ducts (house 16)*					
Fan row	0.50	0.25	0.75	0	0.38
Adjacent row	0	0.25	0.25	0	0.13
Central row	0	0.25	0	0.25	0.13
Mean	0.17	0.25	0.33	0.08	**0.21**
Control (house 18)					
Dummy fan row	0	0	0	0	0
Dummy adjacent row	0	0	0	0	0
Dummy central row	0	0	0	0.25	0.06
Mean	0	0	0	0.08	**0.02**
24 June					
Fans and ducts (house 16)					
Fan row	1.0	1.25	1.0	0.25	0.87
Adjacent row	0.75	2.0	0.5	0.75	1.0
Central row	0.75	0.75	1.5	0.5	0.87
Mean	0.83	1.33	1.0	0.5	**0.92**
Control (house 18)					
Dummy fan row	0.5	0.75	0.25	0.5	0.5
Dummy adjacent row	3.0	0.75	0.25	0.25	1.0
Dummy central row	0	0	0	0	0.87
Mean	1.17	0.5	0.17	0.25	**0.52**
30 Sep					
Fans and ducts (house 16)					
Fan row	1.5	2.75	2.0	0.5	1.69
Adjacent row	1.75	1.5	1.25	0.75	1.31
Central row	0.75	0.5	1.75	1.0	1.0
Mean	1.33	1.58	1.67	0.75	**1.33**
Control (house 18)					
Dummy fan row	3.1	1.75	1.25	2.25	1.56
Dummy adjacent row	2.5	1.0	1.75	1.0	1.56
Dummy central row	1.75	2.25	2.75	2.0	2.19
Mean	1.75	1.67	1.92	1.75	**1.77**

*Paths 33–39 for assessment 1 only; paths 48–54 were used for subsequent assessments due to a high level of worker crop damage in the former area.

The number of surviving plant heads on 30 September was significantly greater (p = 0.004) in the fans and ducts house (34.6) than the control house (32.6) (Table 7) At this time there was a significant effect of row face and a row distance x face interaction on the total number of Botrytis stem lesions (Table 8). The mean number of Botrytis stem lesions was greater on face 1 than face 2 in both houses (Table 9), and varied with distance along the crop row. It is probable that these differences are spurious and have arisen by chance, due to the low numbers of stem lesions on any single quarter row face.

Table 7: Effect of a simple fans and ducts system on number of surviving heads in tomato cv. Encore, grafted onto Beaufort – 30 September 2011

Treatment and position	Quarter row from central path				
	1	2	3	4	Mean
Fans and ducts (hse 16)					
Fan row	35	34	34	35	34
Adjacent row	35	35	35	34	35
Central row	36	34	35	35	35
Means	35	34	35	35	**34.6**
Control (hse 18)					
Dummy fan row	33	35	33	35	34
Dummy adjusted row	31	33	32	34	32
Dummy central row	32	30	32	33	32
Means	32	32	32	34	**32.6**

Table 8: Effect of four factors on Botrytis in tomato cv. Encore on Beaufort – 30 September 2011 – Simple fans and ducts trial

Factor	df	F probability			
		No. stem bases missing	No. live heads	No. botrytis stem lesions (any type)	Total botrytis
Fan (F)	1	0.437	**0.004**	0.085	0.073
Distance (D)	2	0.094	0.501	0.806	0.561
Face (Fa)	1	0.437	0.251	**0.005**	0.094
Quarter (Q)	3	0.060	0.644	0.485	0.198
F x D	2	0.702	0.282	0.097	0.099
F x Fa	1	1.000	0.277	0.216	0.333
D x Fa	2	0.883	0.808	**0.019**	0.177
F x Q	3	0.765	0.651	0.592	0.766
D x Q	6	0.615	0.800	0.234	0.241

Significant effects are shown in bold. The direction of effects is shown in proceeding tables.

Table 9: Effect of a simple fans and ducts system on total number of Botrytis stem lesions – 30 September 2011

House and row	Face	Quarter row from central path				Mean
		1	2	3	4	
Fans and ducts house						
Fan row	1	2.5	4	2.5	0.5	2.4
	2	0.5	1.5	1.5	0.5	1.0
Adjacent row	1	2	1.5	1	0	1.1
	2	1.5	1.5	1.5	1.5	1.5
Central row	1	1.5	0.5	1.5	1	1.1
	2	0	0.5	2	1	0.9
Mean	1	2	2	1.7	0.5	1.5
	2	0.7	1.2	1.7	1.0	1.1
Control house						
Dummy fan row	1	1.5	2.5	2	3.5	2.4
	2	0.5	1	0.5	1	0.8
Dummy adjacent row	1	3	0.5	2.5	0	1.5
	2	2	1.5	1	2	1.6
Dummy central row	1	2.5	4	3.5	2	3.0
	2	1	0.5	2	2	1.4
Mean	1	2.3	2.3	2.7	1.8	2.3
	2	1.2	1.0	1.2	1.7	1.3

In summary, these results provide no evidence that the simple fans and ducts system increases stem Botrytis. There is limited evidence that it increased the number of surviving plant heads per quarter row (from 32.6 to 34.6). However, given the lack of true replication when comparing the simple fans and ducts house and the control house, this result should be treated with caution.

Examination in June and September of the occurrence of missing stem bases across whole houses showed both a large variation between rows and a difference between houses. The incidence of missing stem bases was around 2.5 times greater in the simple fans and ducts house than the control house on both dates (Table 10). There were high incidences of missing stem bases in rows 20 and 40 of the simple fans and ducts house reflecting poor crop work in this area; this largely accounts for the difference between the two houses. There was no consistent trend in either house according to the rows we assessed.

Table 10: Effect of air heating system, location in glasshouse and crop worker on occurrence of missing plants in tomato, cv. Encore – 2011

Path	Worker	% missing stem bases		Path	Worker	% missing stem bases	
		24 Jun	30 Sep			24 June	30 Sep
House 16 – Simple fans and ducts [b]				House 18 – control [b]			
10	P	0.5	3.1	90	D	1.5	6.3
20	PP	4.9	18.8	100	DD	0.8	3.4
30	PP	2.3	4.7	110	DD	1.0	4.4
40	A	2.1	10.4	120	F	0.5	1.0
50	E	1.0	2.9	130	G	0.3	1.8
60	V	0.8	5.2	140	B	1.0	1.3
70	A	1.0	3.6	149	B	0	0.8
Mean		**1.8**	**6.9**	Mean		**0.7**	**2.7**

[b] 384 plants/path.

In both Experiment 1 and Experiment 2, most Botrytis stem lesions originated at de-leafing wounds. Spent fruit trusses were pulled off as they turned brown and no lesions developed at these sites. No powdery mildew was observed.