Improving greenhouse systems and production practices (greenhouse technology systems component) (Parent - VG07096)

Dr Sophie Parks
NSW Department of Industry and Investment

Project Number: VG07145

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Project VG 07145

FINAL REPORT

Improving greenhouse systems and production practices (greenhouse technology systems component)

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Horticulture Australia Ltd. Project VG 07145

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(greenhouse technology systems component)

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Media summary

Low technology greenhouses offer only limited control of the growing environment but are widely used in the greenhouse industry. However, for growers wanting to upgrade their systems, to date, little information has been available about the impact of investing in new technologies on yields and economics of crop production.

Experiments showed that yield of cucumbers, in terms of total fruit weight and total number, is significantly increased by improving conditions beyond those typical of low technology greenhouses. There was a trend of increased yield as conditions were improved incrementally to fully controlled conditions, typical of high technology greenhouses. Increasing plant density also increased yields, regardless of the level of greenhouse control. Because the crop itself has a cooling effect, increasing plant density could potentially be used as a strategy to reduce heat loads in low technology greenhouses, whilst boosting yield.

Economic analysis showed that investing in new technology to shift from a no control greenhouse, to one with improved ventilation, or to shift from the latter to a medium technology greenhouse was beneficial over the life of the technology (10 years). These results provide clear evidence of the economic benefit of improving greenhouse systems which should encourage the industry to move towards a medium technology-based industry.

Technical summary

Low technology greenhouses offer only limited control of the growing environment but are widely used in the greenhouse industry. However, for growers wanting to upgrade their systems, to date, little information has been available about the impact of investing in new technologies on yields and economics of crop production. Using cucumber as a model, this project aimed to conduct scientific research and financial analysis of greenhouse production to quantify the effect of modifying these systems. Increasing plant density was also evaluated as a potential strategy to boost yields, and provide cooling, in low technology greenhouses.

Data on the conditions in commercial greenhouses, ranging from low to high technology were used to develop greenhouse control treatments for experiments conducted at Gosford Primary Industries Institute, NSW. Four greenhouses were configured to provide a range of environmental conditions being no control, minimum control, moderate control and full control of conditions. Cucumber crops were grown in different seasons to capture the range of conditions in which greenhouse cucumbers are normally produced. Plants were grown at three densities (2, 2.5 and 3 plants/m^2) to examine the effect of density, and the interaction of density and greenhouse control, on marketable and unmarketable yield.

This project showed that marketable yields are significantly increased in terms of total weight of fruits per $m^2$and total fruit numbers per m^2, by improving conditions beyond those typical for low technology greenhouses. Increasing plant density to 3 plants/m^2 significantly increased yields. There was no interaction of the level of climate control and plant density. Benefit cost analysis showed that investing in new technology to shift from a no control greenhouse, to one with improved ventilation returned $65.7 per square metre for every dollar invested over the life of the technology (10 years). To shift from a greenhouse with improved ventilation to a medium technology greenhouse returned $1.70 per square metre for every dollar invested.

These results provide clear evidence of the economic benefit of improving greenhouse systems which should encourage the industry to move towards a medium technology-based industry. The simple strategy of increasing plant density to boost yield and alleviate greenhouse heat loads needs validating in future work. It is also recommended that greenhouse systems be developed for different Australian climates and that technology transfer be used, including a grower manual, to facilitate the improvement of that part of the industry using low technology greenhouse systems.

1. *Introduction*

Background

This project, and the related project *Improving greenhouse systems and production practices (greenhouse production practices component)* (VG07144), was initiated after consultation with growers from the main protected cropping regions of South Australia (Northern Adelaide Plans) and New South Wales (Sydney Basin), who identified a need to improve their low technology greenhouse systems. These systems are widely used by the industry but they offer only limited control of the growing environment. Poor control of greenhouse conditions can lead to limited plant productivity, an increased risk of disease and a less effective integrated pest management program. Use of more sophisticated technology can improve growing conditions. However, in the absence of information about the benefits of investing in new technologies on yields and economics, growers are reluctant to make even small changes. This project aimed to use scientific research and financial analysis of greenhouse vegetable production, using cucumber as a model, to quantify the effect of modifying these systems.

Growing conditions for optimum vegetable production and quality

Poor greenhouse conditions can limit crop productivity and produce quality by affecting physiological processes in plants. Table 1 summarises some of the effects of unfavourable temperatures on the greenhouse vegetables tomato, cucumber and capsicum. Unfavourable temperatures can be limiting even for short periods. For example, a temperature of 40 ^{o}C for three hours on two successive days was demonstrated to reduce fruit set of tomatoes (Picken *et al.*, 1985). Also, limiting temperatures can change the sensitivity of plants to other crop factors. For example, in low temperature conditions (4 ^{o}C), moderate light intensities (300 *u*mol m^{-2} s^{-1} instead of 2000 *u*mol m^{-2} s^{-1} for full sunlight) are excessive, damaging photosynthetic processes in both cucumber and tomato leaves (Govindachary *et al.*, 2004).

Table 1. Influence of temperature on crop production of some greenhouse vegetables (Based on Wein, 1997)

Crop	**Mean optimum temperature range for crop factors ^{o}C***	**Crop factor**	**Temperatures negatively affecting crop factors ^{o}C**	**Crop factor affected**
Tomato	18-24	Germination	>30	Lycopene synthesis
	25-30	Net assimilation rate (vegetative growth)	<10 & >32	Fruit set
	18-25	Pollen viability	<10, <5 & >37.5	Pollen production, pollen germination
Cucumber	25-30	Germination	<11.5	Germination
	18-24	Maximum yield accumulation	<10 & >30	Flower opening
Capsicum	25	Germination	>21 night & >27 day	Fruit set
	21-23	Yield maximum and quality	<12-15 night	Fruit shape

*Assumes that other crop factors are not limiting

High vapour pressure deficit (VPD) is often associated with high temperatures in greenhouses and has a negative impact on the greenhouse crop. When VPD is high, transpiration, and thus leaf-cooling, is restricted and the leaf temperature rises associated with drought stress (Fletcher et al., 2007; Baker et al., 2007). Another negative impact of increasing VPD (>1 kPa) at temperatures greater than 34^oC, is the decline in assimilated CO_2 by greenhouse cucumber plants (Janoudi et al., 1993).

Climatic factors have long been shown to have an important effect on both the quality and nutritional value of vegetables (Weston and Barth, 1997). Greenhouse cucumbers deteriorate rapidly under ambient conditions and are difficult to store for more than a few days. Storage and shelf life can be affected by variety (Cabrera et al., 1992), light intensity and wavelength during development (Lin and Jolliffe, 1996), plant water stress (Thomas and Staub, 1992) and the leaf:fruit ratio on the plant (Joliffe and Lin, 1997). Cucumbers are chilling sensitive, so storage temperatures below 10^oC result in surface pitting, decay and increased water loss (Kang et al., 2002). However, at higher temperatures the fruit soften, yellow and rots develop, often initiated from the stylar end of the fruit.

Chilling injury in cucumbers can be reduced by controlled atmospheres (Mercer and Smittle, 1992) or intermittent warming during storage (Cabrera and Saltveit, 1990). However, such methods are difficult to apply commercially.

Maximum and minimum temperatures during growth and development may affect chilling sensitivity after harvest. For example, preharvest chilling increased tolerance of cut basil (Lange and Cameron, 1997) and harvested kiwifruit (Sfakiotakis et al., 2005) to storage at potentially damaging low temperatures. Kang et al. (2002) found that cucumbers grown with high average day temperatures were resistant to chilling damage compared to those grown under milder conditions. It was suggested that this could be due to increased production of antioxidant enzymes such as superoxide dismutase, which can eliminate radicals produced by stressed tissue.

The high temperatures which can occur in non-ventilated greenhouses may affect chilling sensitivity and/or other postharvest quality attributes of greenhouse cucumbers. Planting density is another factor as high density planting potentially increases fruit shading, which has been demonstrated to reduce storage life (Lin and Jolliffe, 1996).

A summary of greenhouse systems in Australia

Greenhouses are used to protect the crop inside from wind, hail and rain and they can allow for the control of the internal climate, control of the delivery of water and nutrients to the crop, control of pest and disease and the reuse of runoff water and nutrients. In Australia, greenhouse systems are often described according to the sophistication of technology used to manage crop production. This encompasses the design of the greenhouse, the technologies used for heating and cooling, the irrigation system and the controllers that coordinate these. Through these measures, greenhouse technology also affects the capacity of growers to utilise biological control measures for pest and disease management. The categories are low technology, medium technology and high technology.

Low technology greenhouses are most commonly a tunnel (igloo) design with a height of less than 3 metres (Figure 1). These greenhouses are covered with plastic (polyethylene) film with ventilation usually achieved manually by rolling up the plastic at both ends of the greenhouse. Sometimes growers used portable gas heaters to increase overnight temperatures in winter. Many greenhouse systems use hydroponics to deliver water and nutrients through drippers to plants growing in bags of soilless media and the nutrient solution is scheduled automatically with an irrigation controller. However, some low technology systems still produce crops in soil.

Medium technology greenhouses have straight walls of a height approximately between 2 – 4 metres. Several roof styles are used and structures can be single free standing or multispan to provide a large internal space (Figure 1). Medium technology greenhouses are covered in plastic film and ventilation is managed with some, or a combination of, side-wall vents, roof vents and fans, which may or may not be automated. Some shading and evaporative cooling systems (fogging, fan-pad), and heating systems may also be used. A range of vegetable crops are grown with low-medium technology greenhouses including cucumbers, capsicums, tomatoes and chillies.

High technology greenhouses have a wall height greater than 4 meters and are clad in plastic film or glass. A defining feature is the ability to maintain ideal growing conditions using fully automated cooling and heating systems and irrigation controllers. High technology greenhouses are predominantly used to produce tomatoes and growers are involved in crop registration schemes that evaluate crop performance over time.

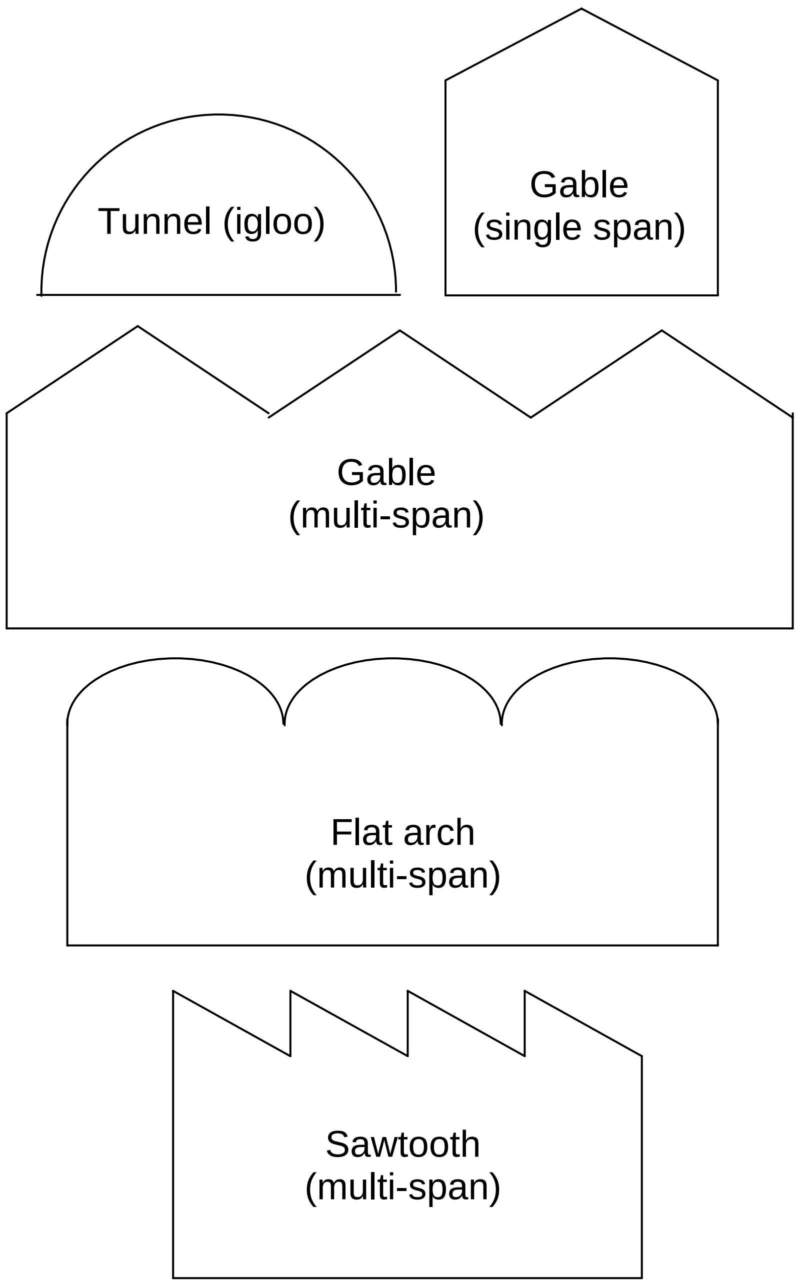

Figure 1. Types of greenhouse structures (based on Badgery-Parker, 1999)

Growers using low to medium greenhouse technology have the greatest difficulty in managing their systems and require more information than is available to assist them make improvements to their systems.

Climate in areas of greenhouse production in Australia

Climate zones of Australia, based on temperature and humidity are shown in Figure 2. Coastal Australia is generally characterised by mild/warm summers and cool winters to the south. Moving north summers become increasingly hot and humid, and winters become milder. Inland Australia is generally dry with hotter temperatures moving north.

High technology greenhouses occur in areas experiencing mild/warm summers and cool to cold winters rather than warmer climatic zones. One reason for this is that greenhouse heating technology is well-established and less complex to manage than cooling technology (Garzoli, 1989). In contrast, low to medium technology greenhouses occur in warm to warm and humid summers and cool to mild winters. Thus, the major climatic factors providing the greatest challenge for low to medium greenhouse production are high temperatures and low temperatures and high humidity. This necessitates the use of cooling techniques and heating at night during winter.

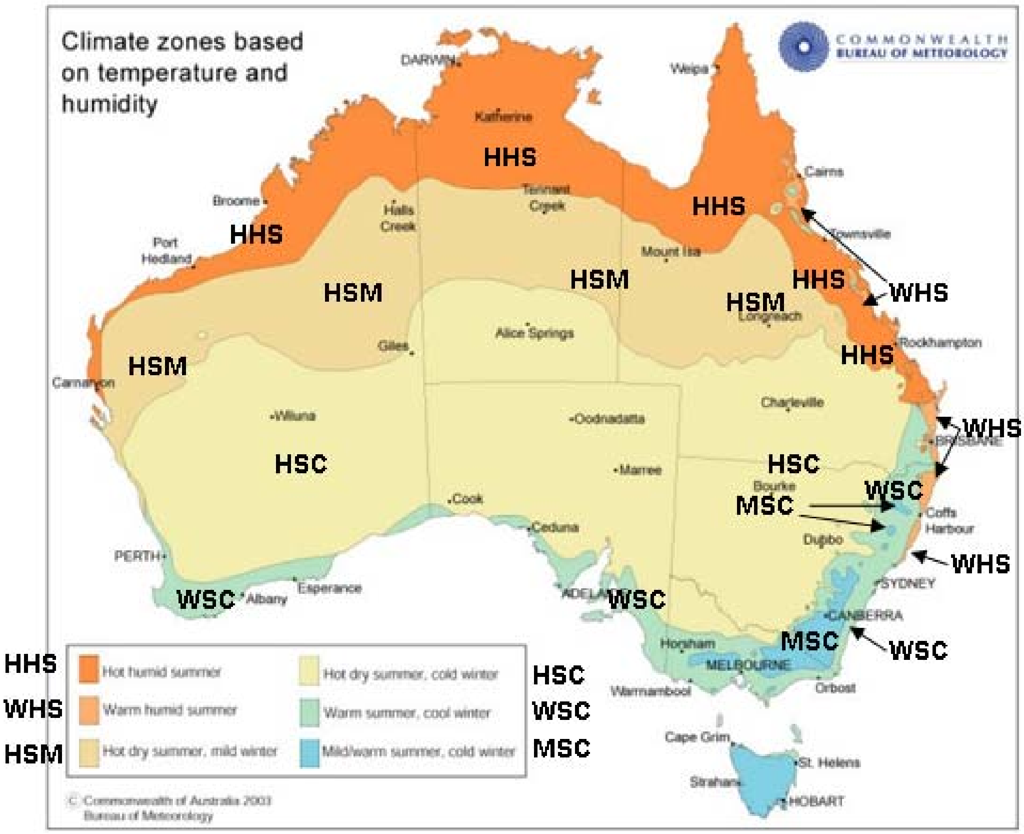

Figure 2. Australian climate zones based on temperature and humidity (Commonwealth Bureau of Meteorology, 2004)

Considerations for managing greenhouse systems in Australia

A greenhouse needs to be designed and managed to allow the removal of its heat load during warm weather. The heat load results from solar radiation being trapped as thermal energy heating up the greenhouse microclimate. Poor greenhouse designs prevent adequate ventilation that would allow the exchange of this heat load with cooler outside air. Poorly ventilated greenhouses are defined as those that cannot maintain an internal temperature within 5^{o}C to 6 ^{o}C of the outside air temperature (Connellan, 2009).

Good ventilation also replenishes CO_2 levels. Additionally, a considerable reduction in maximum temperature can be made by using forced air circulation and evaporative cooling methods (Connellan, 2002). Reflective shade screens can also be effective by reducing incoming solar radiation and the subsequent heat input (Garzoli, 1989). A common practice is to white wash low technology greenhouses to achieve shading but its effectiveness has not been evaluated in Australia.

The improvement of greenhouse design must consider pest management. Minimising the use of pesticide is paramount for occupational health and safety and safe produce. The most efficient way to manage pests in the greenhouse is to exclude them with the installation of fine mesh screens on vents. This does reduce the natural ventilation rate of the greenhouse and increases temperatures and can be accommodated by increasing the area of vent openings (Bartzanas et al., 2009).

Potentially, the crop itself can be managed to improve growing conditions. Transpiration of the crop plays an important role in cooling of the greenhouse. Therefore, increasing leaf area can be the most cost effective way to improve cooling (Katsoulas et al. 2002). This can be achieved by increasing plant density and it may be appropriate in Australia since light received by the crop would not be limited by this practice. This is because the daily light integral required above the greenhouse for tomato, capsicum and cucumber growth of 8 MJ m^{-2} d^{-1} is exceeded in most production areas in Australia in all seasons, even if you assume that light transmission through the greenhouse is as little as 50% (Parks and Worrall, 2005). Growers generally use 2 or 2.5 plants/ m^2, some reducing the density from 2.5 to 2 plants/m^2 in winter, so plants have more room to exploit light in shorter day lengths. A higher density than is currently used by industry may increase yields in high light intensity/warmer conditions but to date this has not been tested in Australia.

In many areas of production in Australia winter nights are cold enough to limit production and so the use of heating is required to improve growth. This is simple to achieve in low technology houses using portable units to heat the greenhouse at night. However, some growers do not use this technology due to expense. Thus, it is pertinent to investigate the economic value of heating in low technology greenhouses.

2. *Aims*

This project aimed to evaluate the productivity of greenhouse systems used in Australia for growing vegetables. An emphasis was placed on the effect of the greenhouse structure and internal climate on the yield and economics of cucumber production.

To achieve the aim, several low-high technology greenhouses were described in terms of their control systems and temperature and humidity profiles under cool and warm conditions. This information was used to formulate the low-medium technology treatments simulated in experiments.

Experiments were designed to:

1. Determine the effect of simulated low-high greenhouses on marketable and unmarketable cucumber yields (and to a limited degree on cucumber quality)
2. Determine the effect of plant density on marketable and unmarketable cucumber yields (and to a limited degree on cucumber quality), with a view to potentially using plant density as an aid in greenhouse cooling
3. Determine the profitability of greenhouse systems and plant density through economic analysis

3. *Methods*

Describing some low to high technology greenhouses

Several commercial greenhouses in Western Sydney were monitored during the project. For each greenhouse, one temperature/humidity combined sensor and data logger was placed inside at the head of the crop and one at approximately the same height outside of the greenhouse. Monitoring was performed every 30 minutes. This provided an indication of the conditions inside the greenhouse compared with the outside and helped to illustrate the challenges faced in production using low technology.

Greenhouse experiments

Three Lebanese cucumber experiments were carried out at the Gosford Primary Industries Institute, Narara, New South Wales, Australia, (33°22'S, 151°20'E). These crops were conducted in different seasons to capture the range of conditions in which greenhouse cucumbers are normally grown. For the first experiment, cucumber seedlings (*Cucumis sativus* L., variety Deena) were planted in winter (21/07/08). The second experiment was planted in late summer, (27/01/09) and the third experiment was planted in early summer (1/12/09). The two summer experiments used seedlings of *Cucumis sativus* L., variety Khassib RZ F1 hybrid. For each experiment, four double skinned 9 x 6.3m polyhouses with a gutter height of 3.6m were used. The plants were grown hydroponically in a run-to-waste system using cocopeat in 7.5L bags as a substrate and supplied with a complete nutrient solution. The cucumber plants were trained and harvested as close as possible to industry practices.

Environmental control treatments

The four greenhouses in each experiment were configured to provide a range of environmental conditions. These were:

1. Full control (high technology). This involved hydronic heating when required and cooling when required using fan, fogging and evaporative pad.
2. Moderate control (medium technology). This involved hydronic heating when required, cooling in winter provided with passive ventilation through fan vents opened manually during the day, cooling in summer with fan and fogging.
3. Minimal control (low technology). This involved no heating, cooling in winter provided with passive ventilation through fan vents opened manually during the day, cooling in summer provided with passive ventilation through open ends of greenhouse covered with insect mesh and white wash painted on plastic film of greenhouse.
4. No control (low technology). This involved no heating, cooling in winter provided only during harvest times by opening doors, and cooling in summer provided with passive ventilation through open ends of the greenhouse covered with insect mesh.

Wet bulb sensors inside each of the greenhouses monitored temperature and relative humidity at the head of the crop. Environmental data on greenhouse conditions inside and outside the greenhouses was continuously received by a Priva Maximiser control system. This system allowed modification of temperature inside greenhouse 2, and temperature and humidity in greenhouse 1. For the experiment, greenhouses 3 and 4 were disabled from the control system. Temperature and relative humidity means obtained for the experiments are summarised in the results section. Light measurements were made with a Licor quantum sensor on several clear days at regular intervals. Within each greenhouse, measurements were made at the top of the canopy at three points from the middle to the edge of the crop. Light conditions in the greenhouses are shown for the late summer experiment in the results section.

Density treatments

The three planting densities were:

1. High – 3 plants.m^2
2. Medium – 2.5 plants.m^2
3. Low – 2 plants.m^2

Each replicate of the 3 densities was randomly allocated to a density experimental unit within the greenhouse. Two plants were grown in a bag (industry standard) of coir and the distance between bags will be changed to achieve the 3 densities. In Figure 3 rows 2 and 3 represent the experimental rows and rows 1 and 4 represent the buffer rows. Data was recorded from the 2 centre plants in each plot with the outer plants acting as buffers.

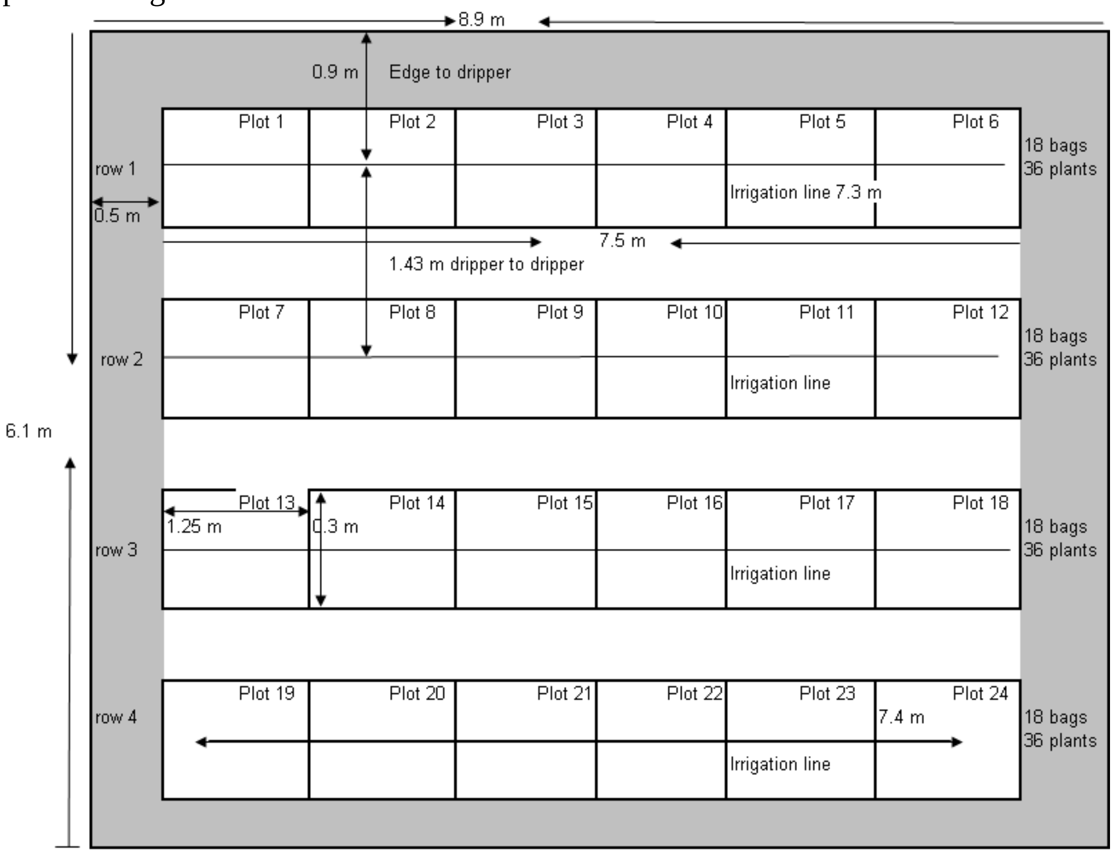

Figure 3. Arrangement of plants in the greenhouse. Plants sampled were in row 2 and row 3. Each plot parallel to plots 1-6 (eg 1, 7, 13 and 19) were of the same density.

Yield measurements

Each week, experimental plants were measured for plant height, leaf number and flower number. Fruits were harvested three times per week and separated into marketable and unmarketable. Marketable fruits were approximately 14-16 cm long. Fruits were deemed unmarketable if they were too small, too big, misshapen, blemished, or too pale in colour. The number and weight of fruits was recorded for each treatment. Harvesting of fruits commenced 57 days after planting for the winter experiment and approximately 40 days after planting for the summer experiments. Harvesting occurred for approximately 8 weeks for all experiments. Following the experiments, experimental plants were dried and weighed.

Quality measurements

Quality as affected by density was measured in fruits from experiment 1 on one occasion. Fruits from the three planting densities were measured from houses 1 and 2 on 29th September with the two replicates combined within each house. The fruit were immediately taken to the postharvest laboratory, weighed, randomised and sorted into treatment units of 5 fruit. Each treatment unit was sealed inside a perforated biaxially oriented polypropylene package, this being a common material used for vegetable retail in Australia.

Treatment units were stored at 2, 5 or 10^{o}C for 11, 14 or 18 days. On removal each batch was placed at 20^{o}C for 3 days. This allowed any disorders to develop before assessment of quality attributes as follows;

1. Weight loss
2. Colour, measured as Hue (Minolta chroma meter, average of 2 points approximately 4cm from the blossom end)
3. Chilling injury grade from 0 (none) to 2 (pitting affecting >10% of surface area)
4. Rots grade from 0 (none) to 2 (rots affecting .1cm^3 of flesh)
5. Firmness measured using a Lloyd Instruments LRX Plus texture analyser (250 Newton load cell with 8mm cylindrical tip), average of two 5mm compressions of the cucumber tissue approximately 10cm from the blossom end.
6. Overall quality grade from 5 (excellent) to 1 (badly degraded)

Quality as affected by greenhouse control was measured in fruits from experiment 1 harvested on 8th October, 3rd December, 8th December and 29th December. Fruit were harvested from each of the four greenhouses in the cool of early morning to minimise temperature differences at harvest. The cucumbers were taken to the laboratory, weighed, randomised and sorted into experimental units of 10 fruit. Each unit was divided between two perforated flow wrap bags and sealed before storage.

October harvested fruit were stored at 2, 5 or 10^{o}C for 7, 12 or 14 days. However, later harvests were stored only at 5^{o}C for 12 days as this time + temperature combination proved marginal for both chilling injury and flesh rots. On removal, cucumbers were stored at 20^{o}C for two days before assessment of quality attributes as previously.

Statistics

Yield measurements

Fruit number and weight of experimental units (four cucumber plants) were expressed on a per metre square basis by dividing data by four, then multiplying by plant density (2, 2.5 or 3). Totals for each experiment were calculated for each treatment and replicate combination. Split plot analysis of variance of fruit weight and number (marketable and unmarketable) was conducted to determine the effects of the greenhouse control system and density, and their interaction, on marketable/unmarketable cucumber weight (kg/m^2) and marketable/unmarketable number (kg/m^2).

Quality measurements

Measurements on cucumber quality were conducted on one replicate of the greenhouse experiments. Thus, only apparent trends can be reported. This work would need repeating to obtain acceptable data for publication in peer reviewed scientific journals.

4. *Results*

Description of six low to high technology greenhouses

Presented here is a brief description of each greenhouse and an example of internal and external temperature, and relative humidity monitored over three days (Figures 4-15). The main observations can be summarised by the following:

1. Mild external temperatures (of about 20^{o}C) were associated with high internal temperatures (>35^{o}C) in the low technology greenhouses (Greenhouse 1 and 4).
2. The one high technology greenhouse was the only greenhouse with an internal temperature lower than the external temperature (Greenhouse 6).
3. The greenhouses were located in an area of Sydney that can experience extreme ambient temperatures, illustrated by external temperatures of >35 ^{o}C recorded at Greenhouse 2, 3, and 6.
4. Since this study, Greenhouse 6 has been installed with foggers providing an example of a simple modification that will improve greenhouse cooling
5. Similar temperature and relative humidity between internal and external conditions in Greenhouse 2 were due to effective ventilation. However, this was at the expense of crop protection from external pest and disease.
6. Heating in Greenhouse 1, 4 and 5 with portable heater units, was sufficient to keep temperatures >5 ^{o}C when external temperatures were about 0 ^{o}C.

Greenhouse 1

Greenhouse systems	**Details**
Greenhouse structure	Single span tunnel with gutter height of 2.8 m, total height of 4.2 m and width of 9.0 m
Cooling technologies	Roll-down roof vent with insect screen Roll-up ends with insect screen
Heating technologies	Portable hot air unit (Figure X)
Control system	Manual
System type – industry definition	Low
System type – experiment definition	No control – moderate control

Figure 4. Greenhouse 1 showing detail of the low technology tunnel with roll up door, and the heater used with plastic tube in winter.

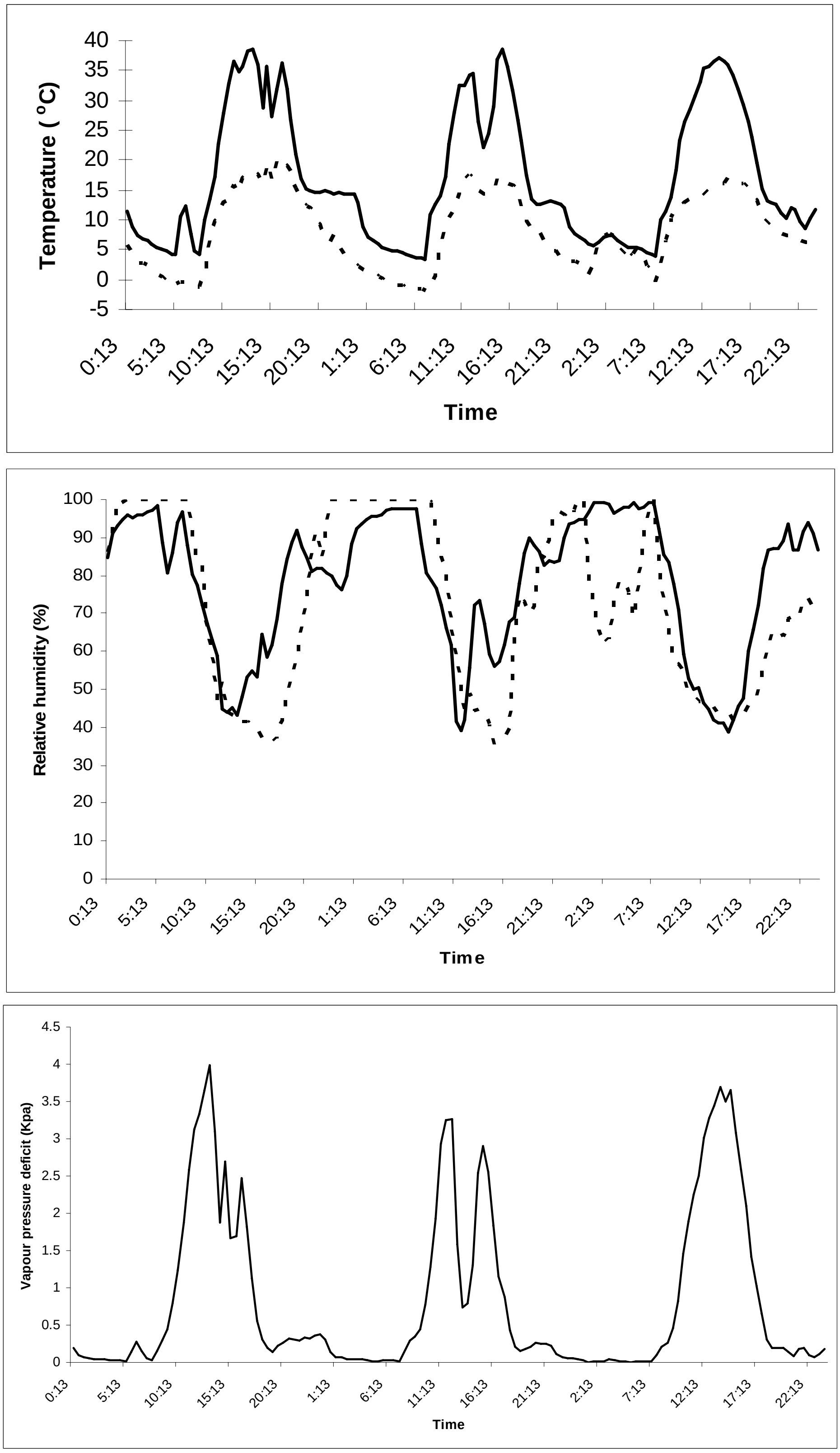

Figure 5. showing temperature, relative humidity and vapour pressure deficit over three days, internally (solid line) and/or externally (broken line) of greenhouse 1.

Greenhouse 2

Greenhouse systems	**Details**
Greenhouse structure	Multi span arch of wood with a gutter height of 2.2 m, total height of 3.4 m and width of 6.0m
Cooling technologies	Side wall ventilation with insect screen, with some insect screens
Heating technologies	None
Control system	Manual
System type – industry definition	Low
System type – experiment definition	No control

Figure 6. Greenhouse 2 showing roll up sides with some insect screens but poor protection of the crop from incoming pests and disease from outside the greenhouse and from bare soil.

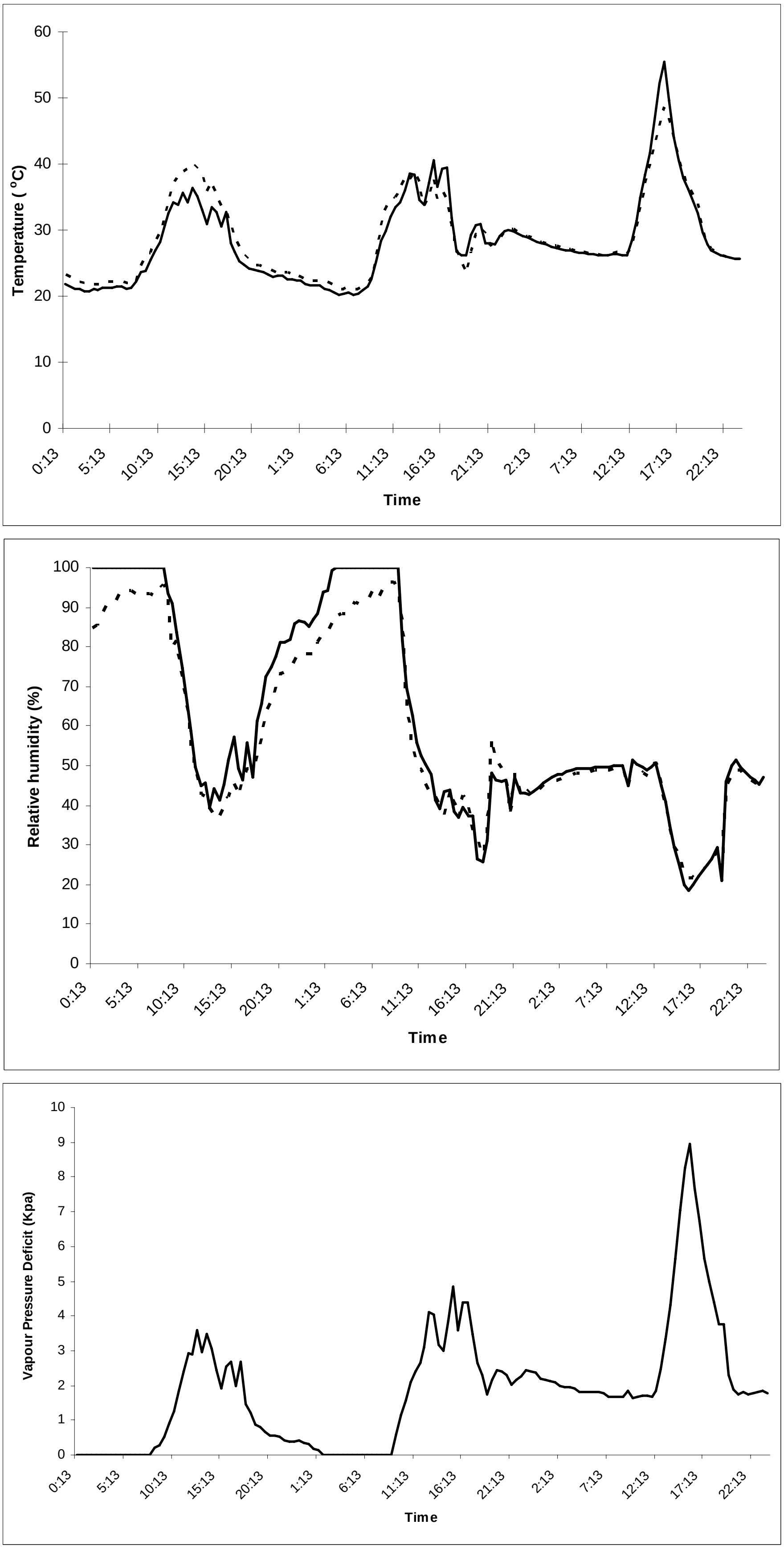

Figure 7. showing temperature, relative humidity and vapour pressure deficit over three days, internally (solid line) and/or externally (broken line) of Greenhouse 2.

Greenhouse 3

Greenhouse systems	Details
Greenhouse structure	Single span tunnel with a gutter height of 3.0 m, total height of 4.2 m and width of 9.0m
Cooling technologies	Rolling vents on ends and rolling roof vents without insect screens
Heating technologies	None
Control system	Manual
System type – industry definition	Low
System type – experiment definition	No control

Figure 8. Greenhouse 3, a low technology tunnel house showing detail of a rolling roof vent.

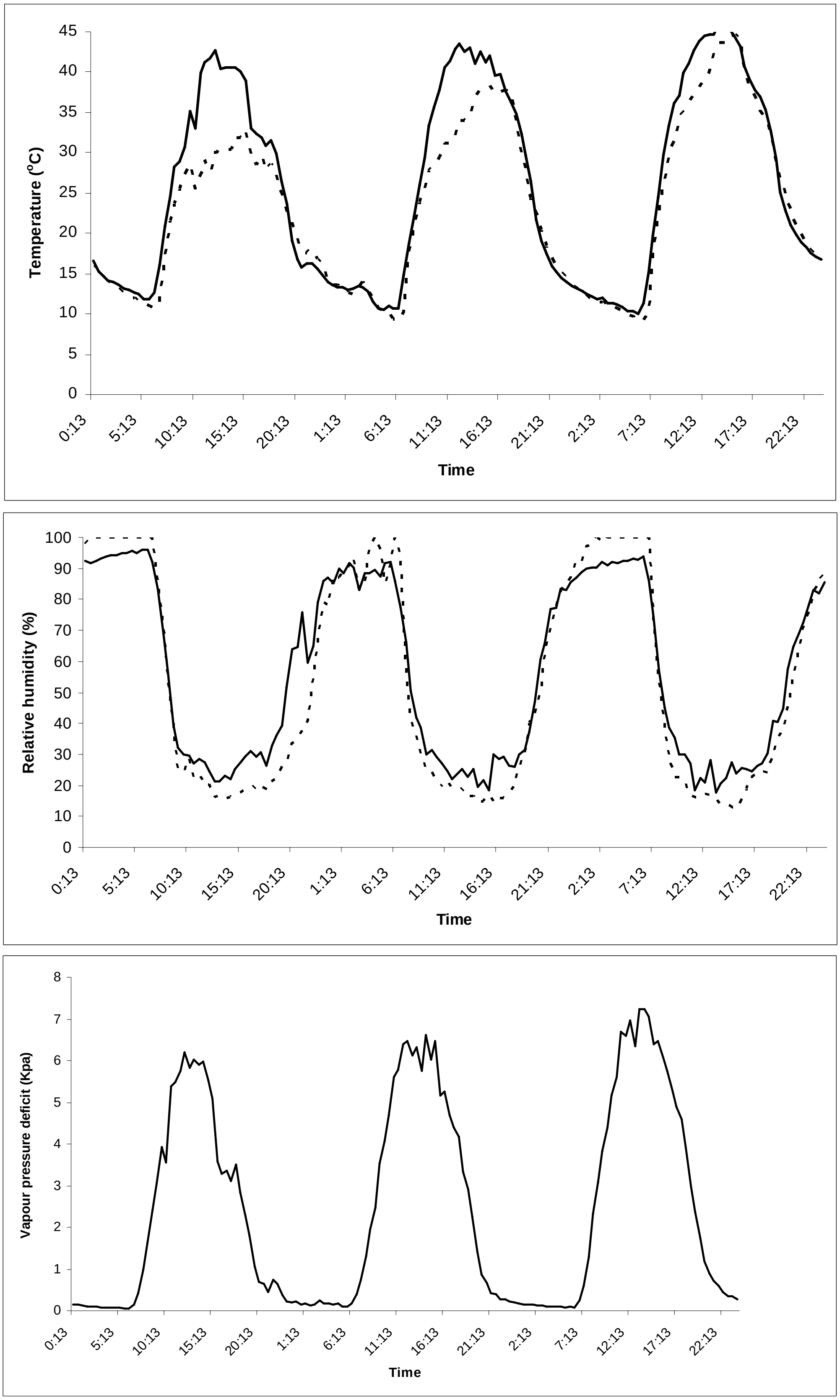

Figure 9. showing temperature, relative humidity and vapour pressure deficit over three days, internally (solid line) and/or externally (broken line) of Greenhouse 3.

Greenhouse 4

Greenhouse systems	Details
Greenhouse structure	Multi-span arch with gutter height of 2.8 m, total height of 4.4 m and width of 9.0 m.
Cooling technologies	Side wall ventilation with insect screen, rolling roof vent with insect screen
Heating technologies	Portable hot air unit
Control system	Manual
System type – industry definition	Medium
System type – experiment definition	Minimal-moderate control

Figure 10. Greenhouse 4, a medium technology greenhouse showing detail of roll up side wall vent with insect screen installed.

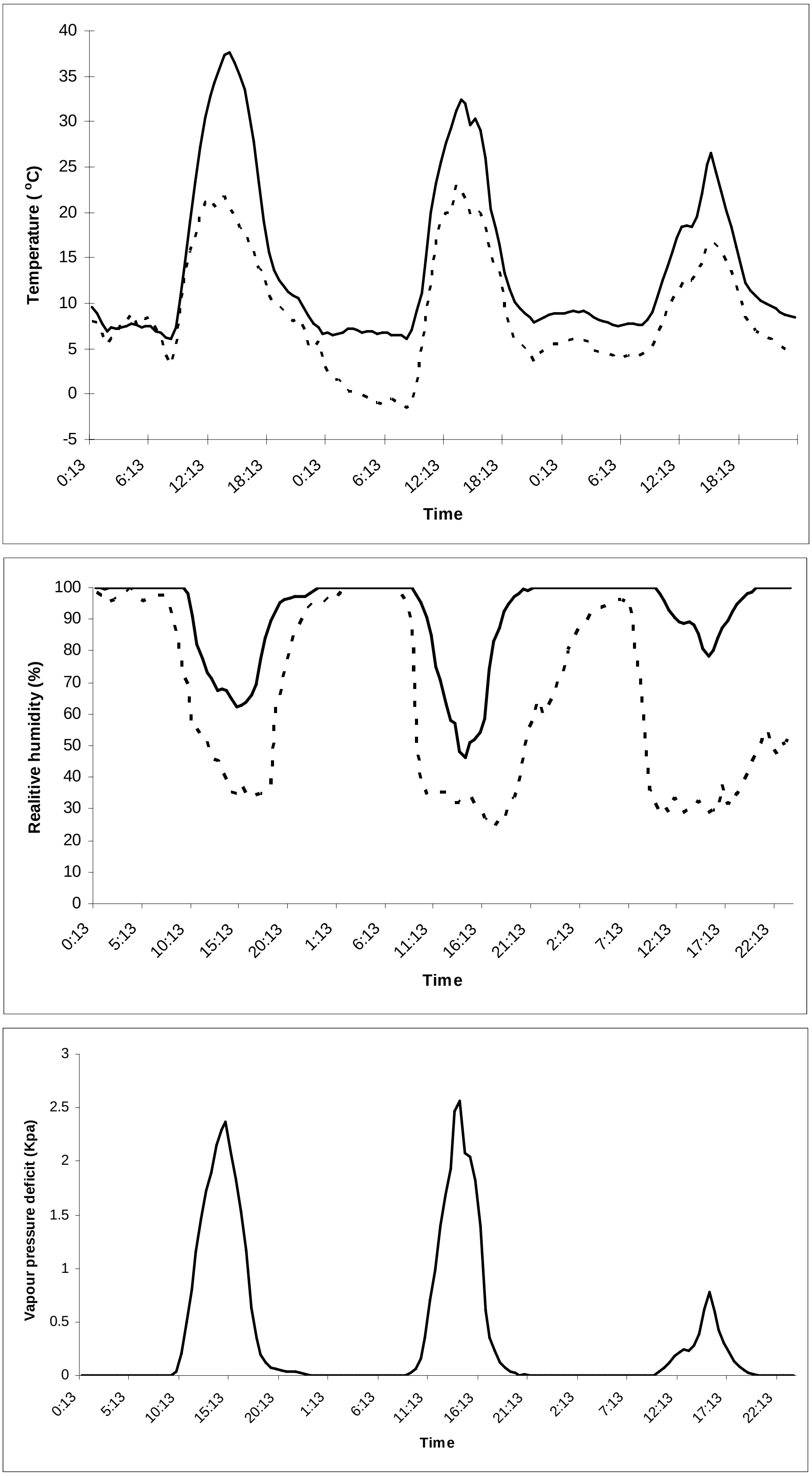

Figure 11. showing temperature, relative humidity and vapour pressure deficit over three days, internally (solid line) and/or externally (broken line) of Greenhouse 4.

Greenhouse 5

Greenhouse systems	Details
Greenhouse structure	Flat arch/sawtooth multi-span with gutter height of 3.0 m and total height of 4.5 m
Cooling technologies	Sidewall rolling vent with insect screen, rolling roof vents without insect screen
Heating technologies	Portable hot air unit
Control system	Manual
System type – industry definition	Medium
System type – experiment definition	Minimal-moderate control

Figure 12. Multi-span greenhouse with sidewall rolling vent and rolling roof vent (unscreened).

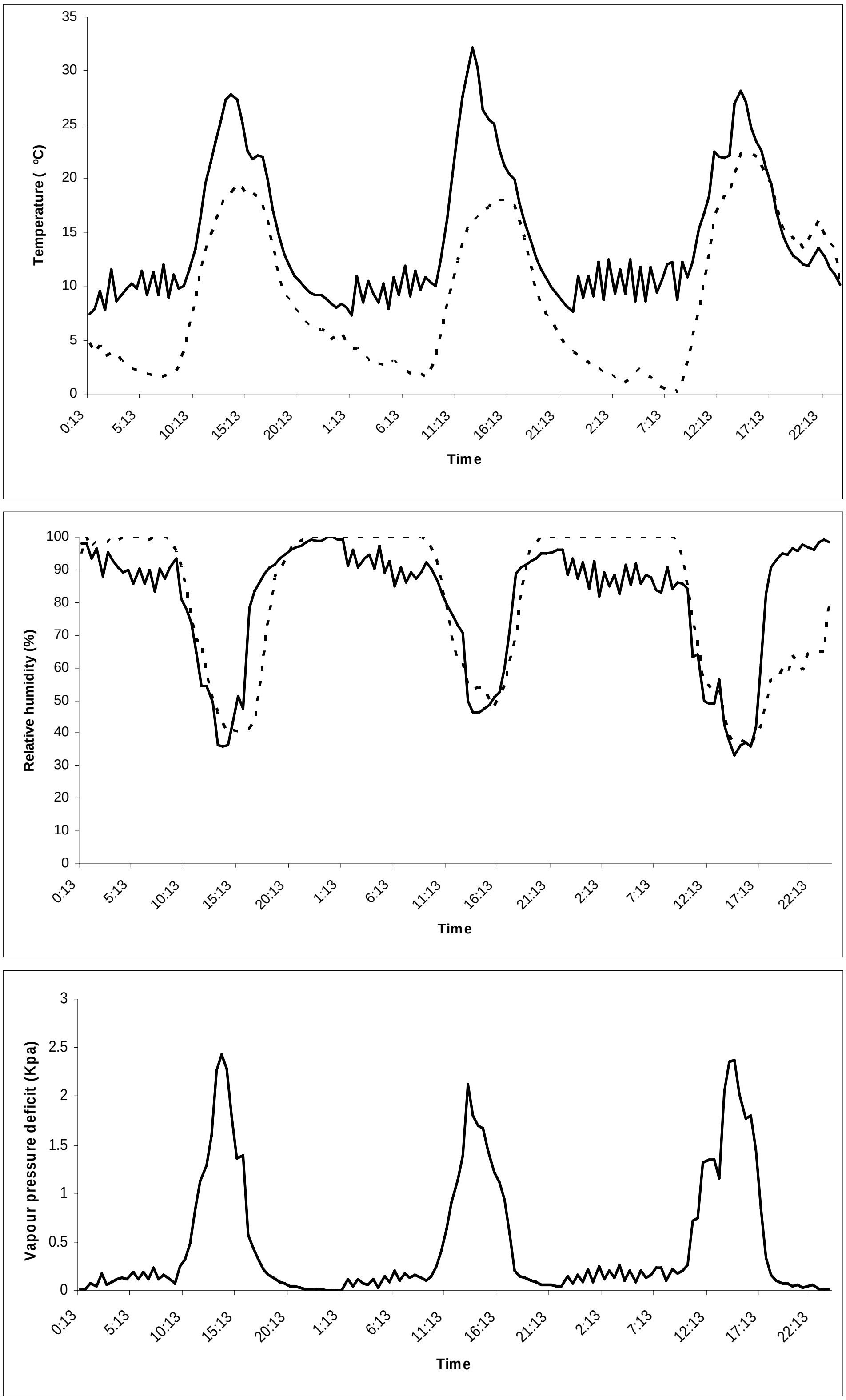

Figure 13. showing temperature, relative humidity and vapour pressure deficit over three days internally (solid line) and/or externally (broken line) of Greenhouse 5.

Greenhouse 6

Greenhouse systems	**Details**
Greenhouse structure	Multi-span gable with a gutter height of 4.5 m, total height of 6.0 m and width of 9.2 m, single skin
Cooling technologies	Rolling roof vents (unscreened), circulation fans, (fogging installed since study)
Heating technologies	Hot air ducted to greenhouse from boiler and thermal screen
Control system	Fully automated
System type – industry definition	High technology
System type – experiment definition	Moderate to full control

Figure 14. Greenhouse 6, a high technology greenhouse seen here by the generous greenhouse height.

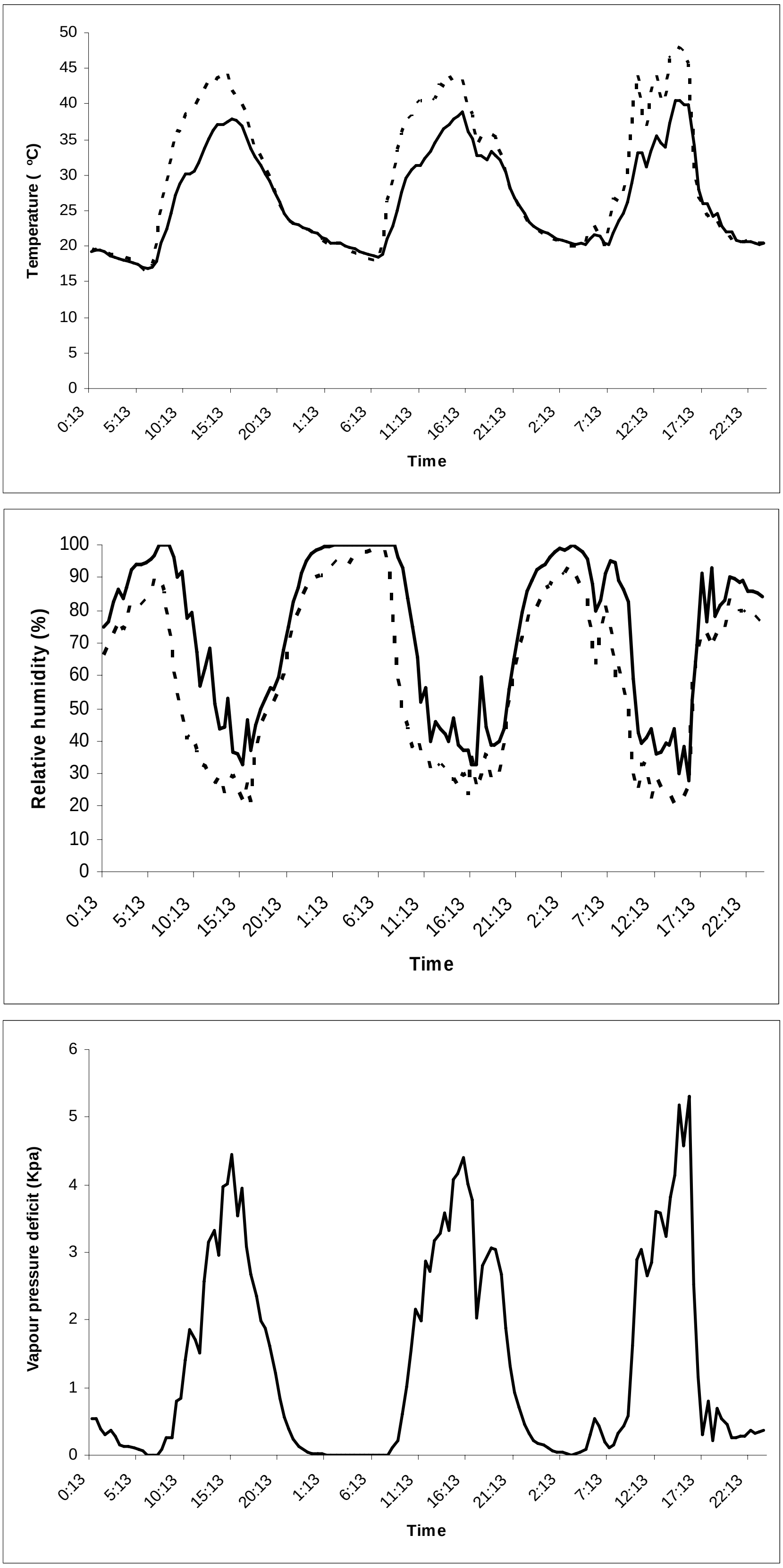

Figure 15. showing temperature, relative humidity and vapour pressure deficit over three days, internally (solid line) and/or externally (broken line) of Greenhouse 6.

Greenhouse experiments

Growing conditions

Temperature conditions for the experiments depended on the season of planting (Table 2). The greenhouse treatments modified the range of temperatures for growing conditions, the range being narrowest for the well-controlled greenhouse and widest for the uncontrolled greenhouse (Table 3).

Table 2. Actual external temperature summaries for the location of the experiments (Gosford Primary Industries Institute, Narara, NSW)

Experiment (season of planting)	Average minimum-maximum external temperature (^oC)	# days <14 ^oC	# days >35 ^oC
Mid-winter	9.7 – 22.1	107	1
Late summer	13.8 – 24.5	34	2
Early summer	17.7 – 27.6	9	6

Table 3. Actual internal temperature and humidity summaries for each greenhouse control treatment during each experiment

Green-house control	Experiment (season of planting)	Average minimum to maximum internal temperature (^oC)	Average minimum to maximum internal relative humidity (%)
House 1: Full control	Mid-winter	13.0 – 25.8	55 – 92
	Late summer	16.0 – 26.8	71 – 99
	Early summer	18.8 – 29.1	51 – 95
House 2: Moderate control	Mid-winter	12.8 – 29.7	63 – 94
	Late summer	18.3 – 27.1	77 – 99
	Early summer	19.5 – 31.3	67 – 96
House 3: Minimal control	Mid-winter	10.5 – 30.2	53 – 96
	Late summer	15.4 – 29.7	63 – 96
	Early summer	18.8 – 33.9	51 – 93
House 4: No control	Mid-winter	11.0 – 31.1	55 – 98
	Late summer	15.5 – 29.5	63 – 98
	Early summer	18.5 – 33.8	52 - 96

The profile of temperatures within the greenhouse was obtained by hanging temperature sensors within the crop at different heights. The location of the sensors within the crop and greenhouse control treatments influenced the temperature profiles. Figure 16 illustrates the temperature profiles for the 13th December, 2008 which ranged from 17.2 – 32.8 ^oC.

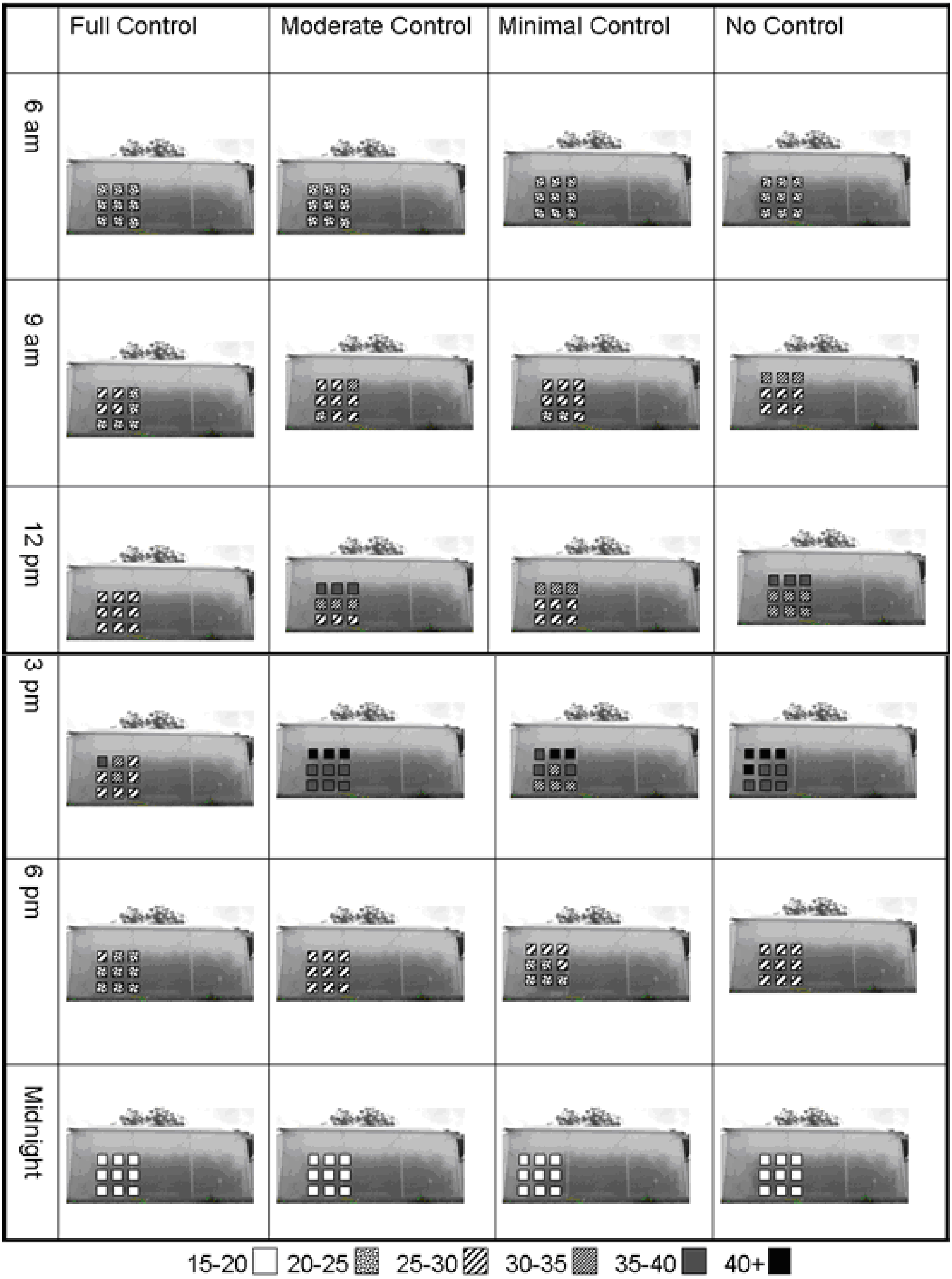

Figure 16. The profile of temperatures within the greenhouses for a warm day (13/12/08). The nine boxes on each greenhouse represent the temperature range (^{o}C) for individual sensors placed between the two centre rows, from the middle of the house to the edge of the crop, at three heights from the ground (30, 100, 260 cm).

Figure 16 highlights that the head of the crop is exposed to the most heat stress, particularly in the less controlled greenhouses. Even in the fully controlled greenhouse, the edge of the crop is susceptible to high temperatures.

Light conditions in the greenhouses are shown for the late summer experiment in Figure 17 based on photosynthetically active radiation (PAR). Approximately 50-60% of light was transmitted through the greenhouses for each experiment. Figure 17 shows that light conditions were similar for each greenhouse during this experiment, despite whitewash having been applied to greenhouse three. A more limited data set was produced for the early summer experiment due to a lack of clear weather, needed for a comparison of light in the greenhouses.

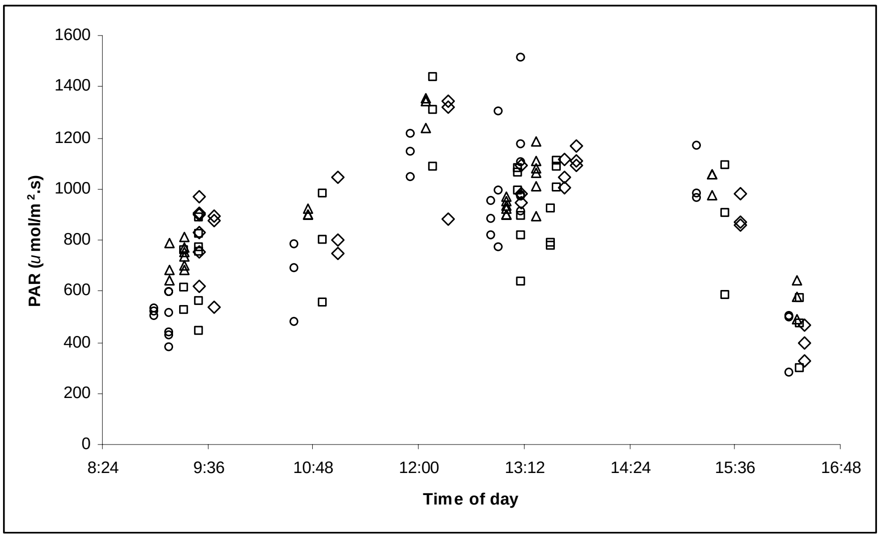

Figure 17. Light conditions at the top of the canopy for all greenhouses during the late summer experiment. Measurements were made on five occasions. Each greenhouse was measured at three points from the middle of the house to the edge (diamond-greenhouse1, square-greenhouse 2, triangle-greenhouse 3, circle-greenhouse 4).

Marketable and unmarketable yields

The experiments showed that increasing control of the greenhouse environment significantly increased cucumber yield in terms of marketable fruit number and weight totals per crop (Figure 18 and 19). The total weight and numbers of unmarketable fruits were not significantly different across greenhouse treatments. This was also the case when they were converted to a proportion of total marketable and unmarketable yield.

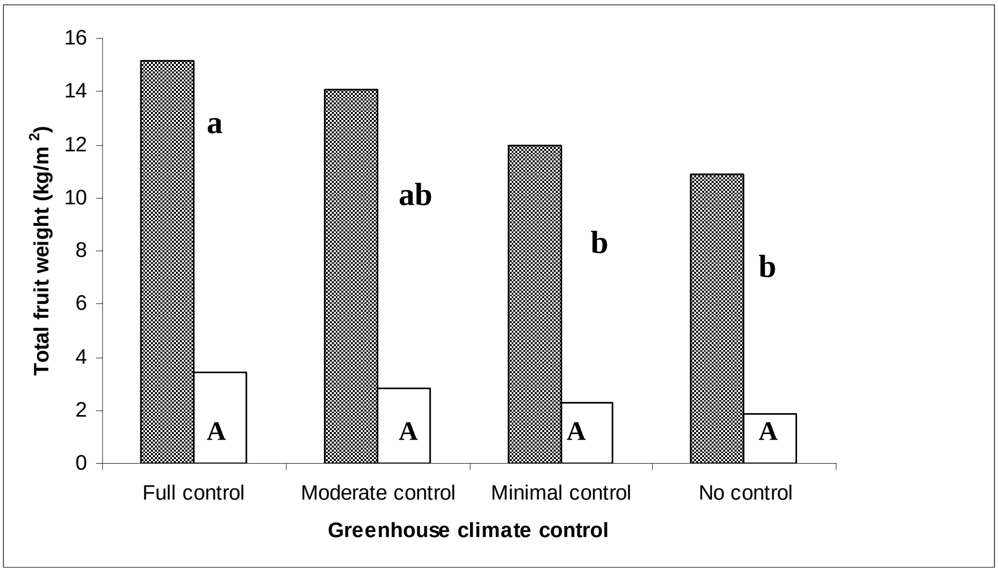

Figure 18. Effect of greenhouse environmental control on marketable (shaded column) and unmarketable (unshaded column) total weight of fruits per crop. LSD = 3.18 for marketable fruits and LSD = 2.03 for unmarketable fruits. Columns are means (n = 3) and those with the same letter are not significantly different.

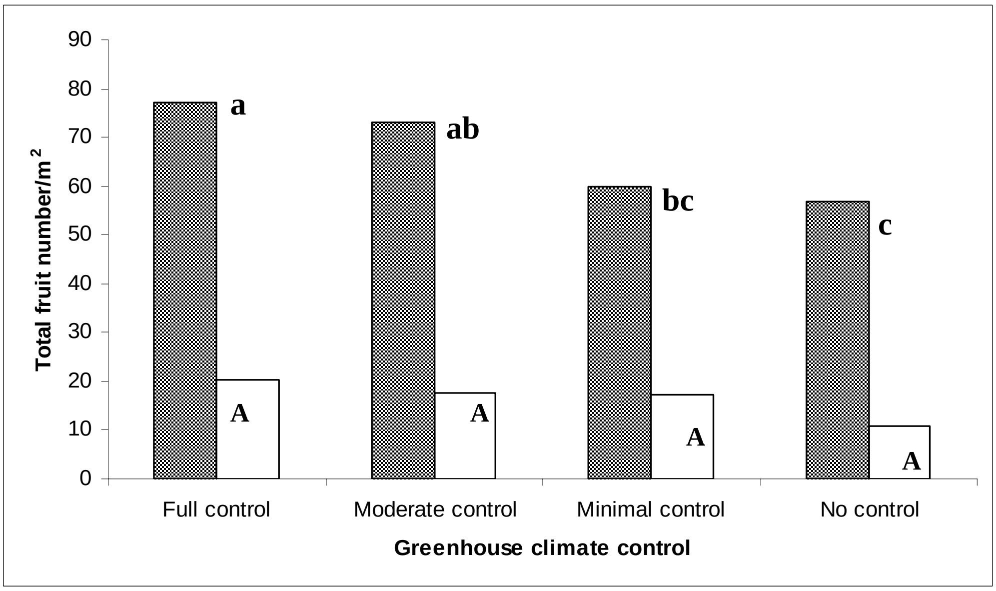

Figure 19. Effect of greenhouse environmental control on marketable (shaded column) and unmarketable (unshaded column) total number of fruits per crop. LSD = 14.85 for marketable fruits and LSD = 15.41 for unmarketable fruits. Columns are means (n = 3) and those with the same letter are not significantly different.

Increasing plant density to three plants per m^2 significantly increased yields (Figure 20 and 21). This was regardless of the level of greenhouse climate control. There were significant effects of greenhouse control and plant density, but no interaction of these occurred (with total cucumber yield expressed on a square meter basis).

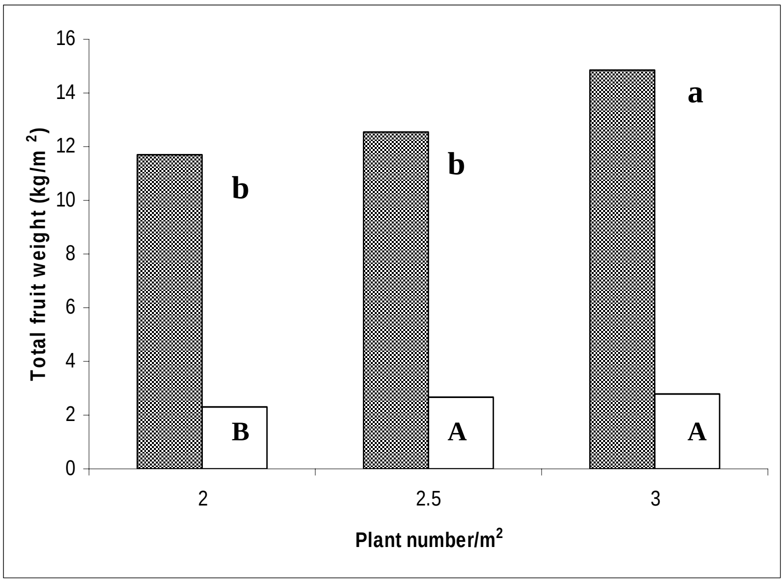

Figure 20. Effect of plant density on total marketable and unmarketable fruit weight. LSD = 1.30 for marketable fruits and LSD = 0.36 for unmarketable fruits. Columns are means (n = 3) and those with the same letter are not significantly different.

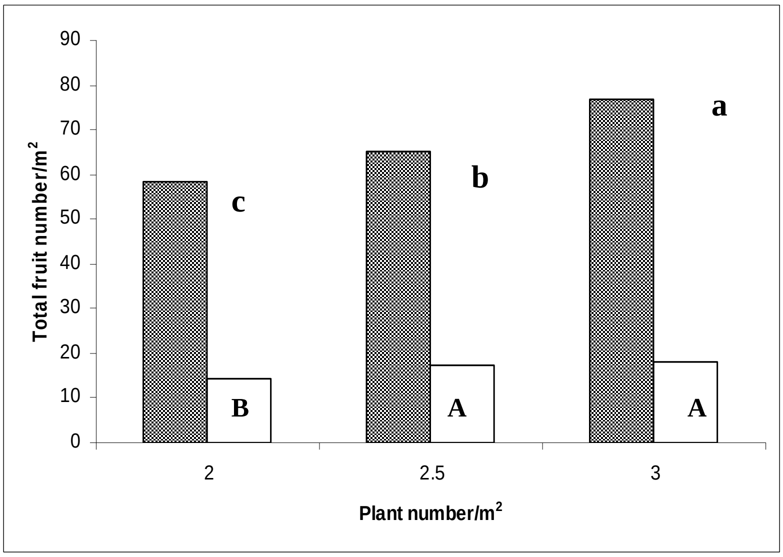

Figure 21. Effect of plant density on total marketable and unmarketable fruit number. LSD = 5.99 for marketable fruits and LSD = 2.41 for unmarketable fruits. Columns are means (n = 3) and those with the same letter are not significantly different.

Crop quality

Some crop responses to the greenhouse environmental control treatments were noticeable. A good example of heat stress was demonstrated in the early summer experiment. Extreme heat caused visible plant damage in the minimally controlled greenhouse on 11/01/2010 where the external temperature reached 28.4^{o}C but the internal temperature was 40.6^{o}C (Figure 22).

Figure 22. Heat damage in leaves due to contact with hot surfaces in the minimally controlled greenhouse. The plant on the right has suffered damage to the growing tip which will slow growth.

Comparison of internal temperatures on this day among the four greenhouses (Figure 23), which are identical in structure, highlights the effectiveness of cooling techniques in the moderate control greenhouse (fogging) and full control greenhouse (fan and pad evaporative cooling) to manage heat loads.

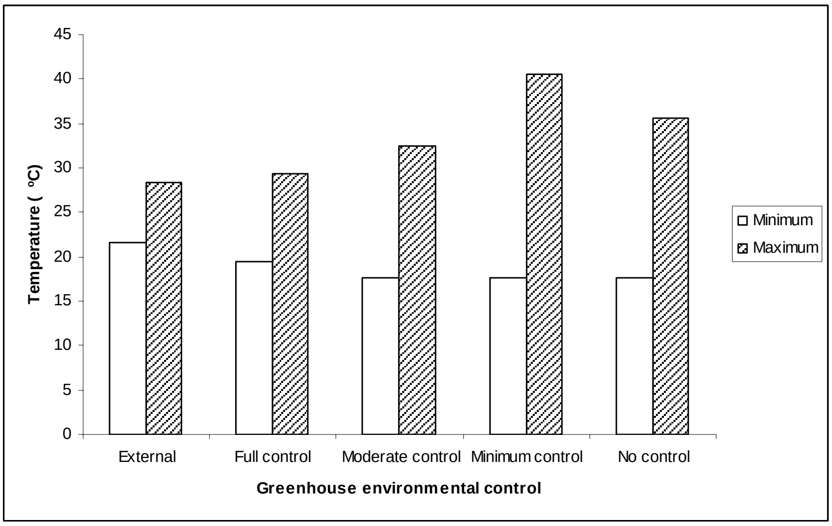

Figure 23. Minimum and maximum temperatures for 11/01/2010 when plant damage occurred in the minimally controlled greenhouse.

The appearance of the crop was not vastly different from one greenhouse to the other, with the exception that the greenhouse with no control often wilted in the heat (Figure 24).

No control Minimal control Moderate control Full control

Figure 24. The early summer experimental crop in each greenhouse on 13/01/2010 (above) and 21/01/2010 (below). Notice the wilting of the plants in the no control greenhouse.

The lack of heating during the winter experiment produced a slower crop in no control and minimal control greenhouses (Figure 25). Reduced ventilation of the no control greenhouse resulted in condensation inside the greenhouse, and in areas of the house where condensation was concentrated, this was associated with leaf symptoms of chlorosis and necrosis. Many fruits in this house often appeared paler (Figure 26).

No control Minimal control Moderate control Full control

Figure 25. Cucumber plants growing under different levels of greenhouse control on 2/10/2008 (above) and 21/11/2008 (below).

Figure 26. Effect of the conditions in the uncontrolled greenhouse environment on the cucumber crop during the winter experiment: lower fruit paler in comparison to fruit above from a healthier crop (left), leaf damage on leaves associated with condensation (right) .

Fruit quality of the winter crop

Plant density appeared to have little effect on the quality attributes measured on fruit from two greenhouses. Cucumbers grown at 3 plants.m^2 appeared slightly softer than those at lower planting densities, reducing the overall quality. However, these apparent differences were not readily visually apparent and certainly unlikely to be commercially significant.

Storage time and temperature did affect all quality attributes. Cucumbers stored at 2^oC became pitted due to chilling injury at all storage times tested. However, increasing the storage temperature to 10^oC did not greatly improve storage life. After 11, 14 or 18 days storage at 10^oC (+ 3 days at 20^oC), flesh rots developed in 29, 54 and 62% of cucumbers respectively. Both chilling injury and flesh rots were evident after 14 days storage at 5^oC + shelf life, although symptoms were not as severe as observed at the other storage temperatures.

Greenhouse control appeared to impact on quality in storage. Although the cucumbers from the four houses looked similar at harvest, differences developed during storage. Cucumbers from the uncontrolled greenhouse appeared to have poorer quality attributes following storage than those from the fully controlled greenhouse, the other houses generally yielding intermediate results. After 12 days at 5^oC + 2 days at 20^oC, cucumbers from the uncontrolled greenhouse had more flesh rots, developed greater pitting due to chilling injury, yellowed faster and were softer than those from the fully controlled greenhouse.

Differences among the houses were most apparent in later harvests, there being fewer differences among the cucumbers harvested in October than those in December. For example, mean chilling injury grades after storage were similar for all houses for the October harvest, ranging from 1.2 – 1.5. In contrast, average chilling injury grades of cucumbers harvested on 8th December ranged from 0.3 to 1.4.

There was a trend of incidence and severity of flesh rots increasing between 8th October and 3rd December, then again between 8th December and 29th December. Flesh rots varied among the four houses as well as according to harvest date, appearing to be the most severe in the uncontrolled greenhouse and the least severe in the fully controlled greenhouse.

Impact of greenhouse technology and density on profitability of cucumber production

Methodology

An enterprise budget for greenhouse cucumber in NSW in 2008/09 was specifically developed for this analysis which represents industry standard practice.

Using the enterprise budget and the experimental trial results, two analyses are conducted;

1. Partial or marginal analysis
2. Benefit cost analysis

The first of these analyses, the partial or marginal analysis, examines the elements of the enterprise budget which change as a result of the change in the activity with all other elements remaining the same. Partial budgeting is used to assess the net benefits from investment in the level of greenhouse control technology allowing for comparison of alternative technologies.

Analysis of the greenhouse control technology trial results is undertaken over the three crop period of the trial. The increase in the incremental net benefit for each greenhouse control scenario is compared to the baseline 'no control' scenario which is reflective a low technology greenhouse control production system and is expressed in percentage terms.

Benefit-cost analysis (BCA), an economic analysis tool for decision making was chosen as the most appropriate economic method to assess each alternative over several years. BCA has been used to compare the value of net benefits arising from the greenhouse control scenarios over a ten year project life. BCA is a widely used tool for comparing alternative courses of action by calculating the net benefits produced in each scenario and comparing these with a base case. In this case we compare the net benefits from each incremental shift in greenhouse environmental control, from 'no control' to 'minimal control' to 'moderate control' to 'full control'.

Discounting techniques are used to allow net benefits in each crop in each year to be aggregated. The ratio of the present value of benefits to the present value of costs, the benefit-cost ratio (BCR) should be greater than one and indicates that a positive economic return was achieved and that the project is economically feasible. A BCR less than one indicates a negative economic return. Net Present Value (NPV) for each scenario was also calculated – the NPV of a project is the difference between the discounted benefits and discounted costs and should be positive.

Assumptions and data sources

Data for the analysis was sourced as follows:

- Yield and agronomic data were taken from greenhouse experiment results.
- Enterprise budgets developed were based on NSW I&I greenhouse vegetable crop budgets with input from research horticulturalist and industry specialists and are based on the four levels of control.

- Costs of greenhouse structures and control technologies were estimated by industry specialists and technical specialists.

The following assumptions were made in the analysis;

- Benefits and costs accrue over the life of the greenhouse.
- Four greenhouse environmental control scenarios were compared
- In the BCA, benefits and costs extend for 10 years at mean experimental trial levels
- A discount rate of 4% is used to calculate BCR and NPV.

Cost of greenhouse controls

The capital cost of the greenhouse systems can be broken into two areas;

1. The cost of the structure itself
2. The cost of the environmental controls

Cost of greenhouse structure

The capital costs of the greenhouse structure include galvanised steel tubing and the cost of the greenhouse cover film. The costs of the greenhouse structure for the four different levels of greenhouse environmental controls used in the experiments are outlined in Table 4.

Table 4. Cost of greenhouse structure ($\$/m^2$)

	Full control	**Moderate control**	**Minimum control**	**No control**
Structure description				
Height	4.5m to gutter 6.0m to top	4.0m to gutter 5.5m to top	2.8m to gutter 4.0m to top	2.0m to gutter 3.2m to top
Span width	9.2m	9.2m	8-9m width	8-9 width
Skin	Double	Double	Single	Single
Cost /m^2	$47.15*	$27.15	$17.15	$17.15

* assume for the purposes of this analysis that cost of structure for ‘full control’ and ‘moderate control’ are the same

Researchers and industry experts agree that it is not feasible to shift from a ‘minimum control’ or ‘no control’ greenhouse to a ‘moderate control’ or ‘full control’ as the structure in itself it not suitable for the installation of the required environmental control equipment. For this reason when comparing between the investment required for ‘moderate control’ and ‘full control’ we assume the same capital costs for the structure. Likewise, between ‘minimum control’ and ‘no control’ we also assume the same capital costs for the structure. To shift from either ‘minimum control’ or ‘no control’ to ‘moderate control’ or ‘full control’ the investment required for the greenhouse structure would however be significant.

Cost of environmental control

To achieve the level of environmental control in each of the greenhouses, costs are included for the following technologies where applicable;

- the controller,
- fertigation,
- irrigation,

- fogging,
- drainage system,
- benches (hydroponic gutters),
- fans,
- evaporative cooling pads, frame and pump
- tanks
- nutrient containers
- water treatment
- heating
- electricity infrastructure and supply
- gas infrastructure and supply

The cost per square metre for each of these environmental controls is estimated in Table 5 below.

Table 5. Cost of environmental controls ($\$/m^2$)

	Full control	**Moderate control**	**Minimum control**	**No control**
Controller	$30.00	$16.00	$1.05	$1.05
Fertigation	$12.00	$3.20	$0.67	$0.67
Irrigation	$8.00	$6.00	$2.00	$2.00
Fog	$4.50	$1.80	$0.00	$0.00
Drainage system	$5.00	$2.00	$0.20	$0.20
Benches (hydroponic Gutters)	$3.46	$2.08	$0.00	$0.00
HV125M 1250mm HV fan 240 volt (with auto shutters)	$5.66	$5.66	$0.00	$0.00
Evaporative cooling pads	$0.94	$0.94	$0.00	$0.00
Evaporative cooling frame and pump	$0.98	$0.98	$0.00	$0.00
Tanks 200L /tank	$0.39	$0.20	$0.20	$0.20
60 L nutrient container	$0.29	$0.20	$0.20	$0.20
Concrete-Material and Labour (weed mate)	$12.60	$4.20	$1.42	$1.42
Water treatment	$5.00	$0.00	$0.00	$0.00
Heating system	$10.28	$6.85	$0.00	$0.00
Electricity connection cost	$5.57	$3.98	$2.78	$2.78
Gas line to the new greenhouses	$2.17	$2.17	$0.00	$0.00
Supply water & Gas service	$3.54	$3.54	$1.77	$1.77
Shade (paint curtain)	$12.00	$7.00	$0.70	$0.00
Total	**$122.39**	**$66.79**	**$10.99**	**$10.29**

Yield impacts

Each crop was harvested 2 or 3 times per week over an eight week period. Yield and fruit numbers were measured on an ‘experimental unit’ basis where an experimental unit comprised 4 cucumber plants. Yield and fruit number are calculated on a per square metre basis by dividing the experimental unit by 4 then multiplying by plant density (2, 2.5 or 3). Split plot analysis of variance of fruit yield and number (marketable and unmarketable) was conducted to determine the effects of the greenhouse control system and density, and their interaction, on marketable and unmarketable yield and number of fruit.

The greenhouse control experiments show that increasing the control of the greenhouse environment is important to significantly increasing crop yield and fruit number. The plant density trials showed that plant density can be used to significantly increase yields at any level of greenhouse control. There was no interaction of greenhouse control and density.

Table 6. Greenhouse control yield impacts. The total marketable weight shown is the mean of the three replicate crops. Statistical analysis showed that the 95% confidence limit was 3.179. In other words, the marketable weight was +/- 3.179 around the mean.

	Marketable weight (kg/m^2)
Full control	15.17
Moderate control	14.05
Minimum control	11.98
No control	10.90

Production costs

Table 7. Production costs – environmental control ($/m2).

Variable cost	**Full control $\$/m^2$**	**Moderate control $\$/m^2$**	**Minimal control $\$/m^2$**	**No control $\$/m^2$**
Vents labour	$0.00	$0.00	$3.19	$2.13
Shade application	$0.00	$0.00	$0.10	$0.00
Harvest	$13.79	$11.55	$9.97	$9.30
Training	$5.48	$4.18	$2.50	$3.19
Leaf removal	$0.56	$0.23	$0.92	$0.99
Release predators	$0.05	$0.03	$0.03	$0.03
System irrigation check	$2.75	$2.42	$7.27	$7.27
Final cleaning	$0.61	$0.61	$0.46	$0.46
Maintenance	$0.92	$0.84	$0.71	$0.87
Spray cost	$0.71	$0.84	$0.51	$0.54
Plant removal	$0.31	$0.23	$0.10	$0.08
Electricity	$1.59	$1.43	$0.72	$0.72
Fuel	$4.18	$4.18	$0.00	$0.00
water	$0.36	$0.28	$0.29	$0.29
Total	**$31.31**	**$26.81**	**$26.75**	**$25.85**

Marginal analysis

The marginal analysis was conducted in an ex-post framework – where no account of future costs and benefits beyond the timeframe of the trial period was attempted. For this reason, the benefits from investment in greenhouse control technology are undervalued in this analysis.

Greenhouse experiment

Flow of costs and returns

The flow of costs and returns included in the analysis of the greenhouse control trial are shown in Table 8. The figures are expressed in real 2010 dollars.

Table 8. Flow of costs and returns – greenhouse control trial

Scenario		**Crop 1 $/m^2**	**Crop 2 $/m^2**	**Crop 3 $/m^2**
Full control				
Initial costs	$149.54			
Variable costs		$14.23	$14.23	$14.23
Returns		$30.34	$30.34	$30.34
Moderate control				
Initial costs	$93.94			
Variable costs		$12.19	$12.19	$12.19
Returns		$28.10	$28.10	$28.10
Minimal control				
Initial costs	$28.84			
Variable costs		$12.16	$12.16	$12.16
Returns		$23.96	$23.96	$23.96
No control				
Initial costs	$28.14			
Variable costs		$11.75	$11.75	$11.75
Returns		$21.80	$21.80	$21.80

Net benefit increase

Table 9 shows the marginal analysis of benefits and costs for each level of environmental control – incrementally moving from the 'no control' scenario through to the 'full control' scenario.

When comparing scenarios, extra benefits from production may arise from extra income as a result of higher yields, or from savings in avoided production costs. For example production costs are saved if pest and disease control costs are lower in the comparison scenario, or if harvesting and marketing costs are lower in the comparison scenario as a result of lower yields. Extra costs from production may arise from income lost as a result of lower yields, or from higher production costs. Production costs may be higher in this analysis if yield is higher in the comparison scenario as harvesting and marketing costs associated with this higher yield will be greater.

The increase in the incremental net benefit (sum of the net value of incremental production less the incremental initial cost of the greenhouse structure and environmental control technologies) for each step of the environmental control ladder is shown in Table X, and is expressed in dollar and percentage terms.

Table 9. Analysis of net benefit increase – greenhouse control trial

SCENARIO	Extra Benefits from Production	Extra Costs of Production	Net Value Incremental Production	Initial cost	Incremental net benefit increase	
	$/m^2	$/m^2	$/m^2	$/m^2	$/m^2	%
Full control v's Moderate control						
Crop 1	$2.24	$2.04	$0.20	$55.60		
Crop 2	$2.24	$2.04	$0.20			
Crop 3	$2.24	$2.04	$0.20		-$55.01	119%
Moderate control v's Minimum control						
Crop 1	$4.14	$0.03	$4.11	$65.10		
Crop 2	$4.14	$0.03	$4.11			
Crop 3	$4.14	$0.03	$4.11		-$52.77	-804%
Minimum control v's No control						
Crop 1	$2.16	$0.41	$1.75	$0.70		
Crop 2	$2.16	$0.41	$1.75			
Crop 3	$2.16	$0.41	$1.75		$4.54	225%

From this analysis it can be seen that moving from ‘no control’ to ‘minimal control’ provided a net benefit increase. This indicates that investment in this level of environmental control technology would result in an increase in net benefits to the producer within the timeframe of the marginal analysis. An incremental net loss is seen in the ‘minimal control’ to ‘moderate control’ and ‘moderate control’ to ‘full control’ technology shifts within the timeframe of the trial analysis.

Benefit cost analysis

The BCA was conducted in an ex-ante framework – where costs and benefits from the trial period are included as well as future costs and benefits. Investment in any of the structures and technologies described in this analysis to shift from one level of greenhouse environmental control to another is a long term investment. For this reason the period of analysis should be over the technical life of the greenhouse structure and greenhouse environmental control technologies. It has been estimated by industry experts that a likely life of a greenhouse structure and greenhouse environmental control equipment is 10 years.

BCA is used to compare the value of net benefits arising from the shift from ‘no control’ to ‘minimal control’, from ‘minimal control’ to ‘moderate control’ and from ‘moderate control’ to ‘full control’ with the additional investment in the greenhouse structure and environmental control equipment over a ten year project life. BCA is a widely used tool for comparing alternative courses of action by calculating the net benefits produced in each scenario and comparing these with a base case. In this case we compare the net benefits from a shift to each level of increased environmental control.

The present value of the net worth of these incremental net production benefits and costs is then compared with the present worth of the initial investment in the greenhouse structure and environmental control equipment to calculate the benefit cost ratio (BCR). It is assumed that the extra benefits and extra costs of production seen over the three cucumber trial crops with an average of 2.2 crops grown each year continue for ten years.

The discount rate used was an annual rate of 4%.

BCA investment in greenhouse controls after 10 years

Table 10 shows the results of the benefit cost analysis over a ten year project life of a shift from 'moderate control' to 'full control'.

Table 10. Benefit cost analysis – Full control v's Moderate control over 10 years

Year	Extra Benefits	Extra Costs	Net Benefit Flow	Discounted Benefits	Discounted Initial Costs	Discounted Net Benefits
	($\$/m^2$)	($\$/m^2$)	($\$/m^2$)	($\$/m^2$)	($\$/m^2$)	($\$/m^2$)
Initial cost	0.0	55.6	-55.6		55.6	
1	4.9	4.5	0.4	0.4		-57.4
2	4.9	4.5	0.4	0.4		0.4
3	4.9	4.5	0.4	0.5		0.5
4	4.9	4.5	0.4	0.5		0.5
5	4.9	4.5	0.4	0.5		0.5
6	4.9	4.5	0.4	0.5		0.5
7	4.9	4.5	0.4	0.5		0.5
8	4.9	4.5	0.4	0.6		0.6
9	4.9	4.5	0.4	0.6		0.6
10	4.9	4.5	0.4	0.6		0.6
	Present value benefits			5.2		
	Present value costs				55.6	
	Net Present Value (NPV)					-50.4
	Benefit Cost Ratio (BCR)					0.09

The results of the BCA show that an additional investment in environmental control technology to shift from a 'moderate control' to a 'full control' greenhouse results in a negative BCR. In this situation the present worth of the net benefits from production associated with 'full control' over 'moderate control' did not exceeded the present worth of the investment in (cost of) the environmental control technology. In this case the investment in environmental control technology is not recovered within the project life.

Table 11 shows the results of the benefit cost analysis over a ten year project life of a shift from ‘minimal control’ to ‘moderate control’.

Table 11. Benefit cost analysis – Moderate control v’s Minimal control

Year	Extra Benefits	Extra Costs	Net Benefit Flow	Discounted Benefits	Discounted Initial Costs	Discounted Net Benefits
	($\$/m^2$)	($\$/m^2$)	($\$/m^2$)	($\$/m^2$)	($\$/m^2$)	($\$/m^2$)
Initial cost	0.0	65.1	-65.1		65.1	
1	9.1	0.1	9.0	9.0		-56.1
2	9.1	0.1	9.0	9.4		9.4
3	9.1	0.1	9.0	9.8		9.8
4	9.1	0.1	9.0	10.2		10.2
5	9.1	0.1	9.0	10.6		10.6
6	9.1	0.1	9.0	11.0		11.0
7	9.1	0.1	9.0	11.4		11.4
8	9.1	0.1	9.0	11.9		11.9
9	9.1	0.1	9.0	12.4		12.4
10	9.1	0.1	9.0	12.9		12.9
	Present value benefits			108.6		
	Present value costs				65.1	
	Net Present Value (NPV)					43.5
	Benefit Cost Ratio (BCR)					1.7

Table 12 shows the results of the benefit cost analysis over a ten year project life of a shift from ‘no control’ to ‘minimal control’

Table 12. Benefit cost analysis – Minimal control v’s No control

Year	Extra Benefits	Extra Costs	Net Benefit Flow	Discounted Benefits	Discounted Initial Costs	Discounted Net Benefits
	($/m^2)	($/m^2)	($/m^2)	($/m^2)	($/m^2)	($/m^2)
Initial cost	0.0	0.7	-0.7		0.7	
1	4.8	0.9	3.8	3.8		3.1
2	4.8	0.9	3.8	4.0		4.0
3	4.8	0.9	3.8	4.2		4.2
4	4.8	0.9	3.8	4.3		4.3
5	4.8	0.9	3.8	4.5		4.5
6	4.8	0.9	3.8	4.7		4.7
7	4.8	0.9	3.8	4.9		4.9
8	4.8	0.9	3.8	5.1		5.1
9	4.8	0.9	3.8	5.3		5.3
10	4.8	0.9	3.8	5.5		5.5
	Present value benefits			46.2		
	Present value costs				0.70	
	Net Present Value (NPV)					45.5
	Benefit Cost Ratio (BCR)					65.7

The results of the BCA show that an investment in environmental control technology to shift from a ‘minimal control’ to a ‘moderate control’ greenhouse and from a ‘no control’ to a ‘minimal control’ greenhouse results in a positive BCR. In this situation the present worth of the net benefits from production associated with ‘moderate control’ over ‘minimal control’ and ‘minimal control’ over ‘no control’ exceeded the present worth of the investment in (cost of) the environmental control technology. In this case the investment in environmental control technology is recovered within the project life and a return on the investment greater than the discount rate is achieved. Our results indicate that for every dollar invested in shifting from a ‘no control’ to ‘minimal control’ greenhouse $65.7 per square metre is returned. For every dollar invested in shifting from a ‘minimal control’ to ‘moderate control’ greenhouse $1.7 per square metre is returned for every dollar invested.

5. *Discussion*

This study shows that marketable cucumber yield significantly increases as greenhouse environmental control is improved above the limited control provided by low technology greenhouses. The trend of increased yield, as conditions are improved incrementally, clearly demonstrates that even some improvement of conditions will be beneficial for crop production.

Under improved greenhouse conditions, cucumber quality is also likely to improve.
In the late winter experiment, where effects on quality were investigated, cucumbers grown under the most controlled environmental conditions were the most tolerant of chilling temperatures. These fruit maintained colour and firmness following storage and were least likely to develop rots. Cucumbers grown in uncontrolled conditions (higher day temperatures and lower night temperatures than the most-controlled treatment) were either more susceptible, or had similar chilling injury, compared to cucumbers grown under the most controlled conditions. They may well have been more bitter, since cold temperatures can exacerbate this, but this was not measured (Kano and Goto, 2003). Cucumbers grown with high day temperatures are more resistant to chilling injury than those grown at lower day temperatures (Kang et al., 2002) but this was not reflected in the current work.

This study showed, for the first time, the positive effect of investing in greenhouse technology on the profitability of cucumber production in Australia. In this case study, the most profitable concern was not high technology but medium technology which is perhaps reflected in the Australian greenhouse industry, where high technology is used predominantly for tomato production. Analysis of the greenhouse industry in Turkey showed that tomato production was more profitable than cucumber production in greenhouses (Canakci and Akinci, 2006). Other studies have shown the economic advantage of upgrading greenhouse technology. For example, using high tunnels compared with low tunnels for vegetable production in temperate Canada (Waterer, 2003), and moving from a soil to soilless system for greenhouse cucumber production in Turkey (Engindeniz and Gul, 2009), improved the profitability of crop production.

The results demonstrate that investing in climate control for greenhouses can not only increase yield but also produce a crop with improved storage potential. However, work needs to be repeated to validate the results and further work would determine the critical factors affecting fruit quality.

Low technology greenhouses represent a large sector of the Australian greenhouse industry but they do not provide ideal growing conditions, suitable conditions for biological control of pests and diseases, or comfortable conditions for workers.

The greenhouse case studies have highlighted in particular, that high greenhouse temperatures and high vapour pressure deficit (VPD) present a key challenge in Australia, even when ambient temperatures are mild. For example, an ambient temperature of approximately 20^{o}C was associated with an internal temperature of 37^{o}C in two of the greenhouses that were monitored (greenhouses 1 and 4). For much of Australia, the median maximum ambient temperature in summer exceeds 24^{o}C (the temperature for optimum crop production of cucumber), which is likely to correspond to high internal temperatures in poorly ventilated greenhouses. When ambient temperatures are high, crops in low technology greenhouses have no reprieve. The internal temperature of 46 ^{o}C observed in greenhouse 3 is sufficient to cause critical injury in cucumber leaves (Oda et al, 1994). Generally, extreme temperatures can directly damage greenhouse plants and fruits or cause temperature induced water stress (associated with low humidity and high VPD) leading to poor production and quality losses (Gruda, 2005).

High temperatures reduce the efficacy of biological control measures. For example, they are associated with inhibition of silicon-induced suppression of powdery mildew (Schuerger and Hammer, 2003), and the reduced efficacy of *Trichoderma harzianum* and *Aureobasidium pullulans* against *Botryis cinerea* infection in cucumber and tomato (Dik and Elad, 1999). Disease, for example *Pythium aphanidermatum*, can also be exacerbated at high temperatures when inoculated at a high density to cucumber roots causing sudden plant death (Kyuchukova et al., 2006).

Cool temperatures, in the simulated low technology control treatments, were associated with compromised cucumber yield. Although the effect of season was not replicated in the current work, the suboptimal night temperatures associated with the low and minimal control treatments were associated with proportionally more unmarketable fruits. In these cooler conditions, biological control methods may also be compromised, for example, for control of *B. cinerea* (Elad and Yunis, 1993).

Discomfort of workers is exacerbated in low technology greenhouses at relatively mild external temperatures. The risk of heat-related injuries is increased and growers must be vigilant to ensure these do not occur. The factors affecting heat stress including temperature, humidity, ventilation, intensity of activity and type of clothing, should be considered when working in the greenhouse environment (Epstein and Moran, 2006). Given the difficulty of climate control in low technology greenhouses, a simple strategy is to allow breaks of 10-30 minutes per hour from exposure to temperatures between 30 to 36 ^{o}C and cessation of work in conditions above 36 ^{o}C based on recommendations for working in the heat (Public Service Association of NSW, 2003). In contrast, as the high technology house has the ability to reduce temperatures inside the greenhouse relative to outdoors, worker comfort and safety is easier to manage.

Improving the climate control of Australian greenhouses

A range of measures are available to improve the greenhouse climate, in Australian greenhouses to address high heat loads, replenishment of CO_2 and low temperatures.

Ventilation

To improve natural ventilation side wall and roof vents are desirable (Buffington et al., 2010). Ventilation can also be improved with the installation of fans which requires knowing the volume of air to be moved from the greenhouse in order to make the best selection (Buffington et al., 2010). In any case, ventilation in Australia must consider the use of insect screens and it is recommended that ventilation be used with other cooling methods since ambient temperatures are often higher than optimal in summer.

Shading

Several techniques can be used to provide shading for greenhouse cooling. These include the use of screens, foam technology and whitewash, and high plant density to increase shading by the crop canopy.

As part of the minimal control treatment in this study, the greenhouse was whitewashed for both summer experiments. This did not noticeably reduce internal temperatures and yield was not significantly different compared to that of the uncontrolled treatment. However, further work would have to be conducted to evaluate the effect of whitewash in hot conditions. This may be of benefit since it has been shown previously that is an effective means of reducing greenhouse temperature and crop water stress (Baille et al., 2001). A new shade technology has also had promising results. Liquid foam is injected between layers of a double skinned roof of a polyethylene covered greenhouse with the advantage of being removed within 30 minutes of the system being shut off. Use of this technology on hot days proved to reduce the internal temperature in the greenhouse by 6 ^{o}C compared with unshaded greenhouses (Aberkani et al., 2010).

When vapour pressure deficit (VPD) is high, transpiration, and thus leaf-cooling, is restricted and the leaf temperature rises associated with drought stress (Fletcher et al., 2007; Baker et al., 2007). However, increasing plant density in young cucumber seedlings has been shown to mitigate the inhibition of photosynthesis at a high VPD (Shibuya et al., 2009). Increasing the leaf area of a mature crop has been shown to play an important role in cooling the crop (Impron et al., 2008). The use of increasing plant density to mitigate the extreme effects of high greenhouse temperatures looks promising for Australian conditions since this work showed that yield and profit are not compromised at a high density. Additionally, increasing planting density from 2 to 3 plants.m^2 did not appear to affect commercial quality attributes of the harvested cucumbers, despite previous research showing that shading decreases the quality of cucumbers (Lin and Jolliffe, 1996).

Evaporative cooling

In Australia, the maximum daily wet bulb temperature for summer can be used to indicate areas at risk of high temperatures that will affect greenhouse vegetable production. Wet bulb temperatures indicate the temperature to which air can be cooled using evaporative cooling technology. The wet bulb temperature is measured with a thermometer wrapped in a material that is kept wet. The thermometer is effectively cooled by the evaporation of water from the material and has lower readings than an unmodified thermometer. As the humidity of the air increases the ambient temperature decreases nearer to the wet bulb temperature. In commercial practice greenhouses can be cooled to within about 2^{o}C of the wet bulb temperature using well designed greenhouses and evaporative cooling or fogging.

A map of the maximum daily wet-bulb temperature for summer (95th percentile) is shown in Figure X. The 95th percentile of maximum daily wet bulb temperatures is suitable to indicate risk of high temperatures, as only the hottest 4-5 days occurring in summer are excluded. As an example, the coast from Sydney to Gympie (Queensland) has a maximum daily wet bulb temperature range of 24-26 ^{o}C in summer. With evaporative cooling greenhouse temperatures can be theoretically cooled to 26-28 ^{o}C. Further north (eg Bundaberg), greenhouse temperatures can only be cooled to 28-30 ^{o}C. One must also consider that these figures exclude the 4-5 days in summer above these temperature ranges which can have serious consequences for crop production. Additionally, the capacity to cool air with evaporative cooling and fogging in coastal areas is reduced because of generally high humidity in summer (Figure X). The inappropriate use of evaporative cooling was demonstrated in the semi-humid tropical climate of Central Thailand. In the study, tomato production in netted greenhouses, mechanically ventilated when the temperature reached 30^{o}C, was compared with polyhouses cooled using a fan and pad system. Although this showed that total fruit yield was similar between the greenhouse types, the proportion of marketable yield was lower in the houses with evaporative cooling, largely due to more fruit cracking (Max et al., 2009).

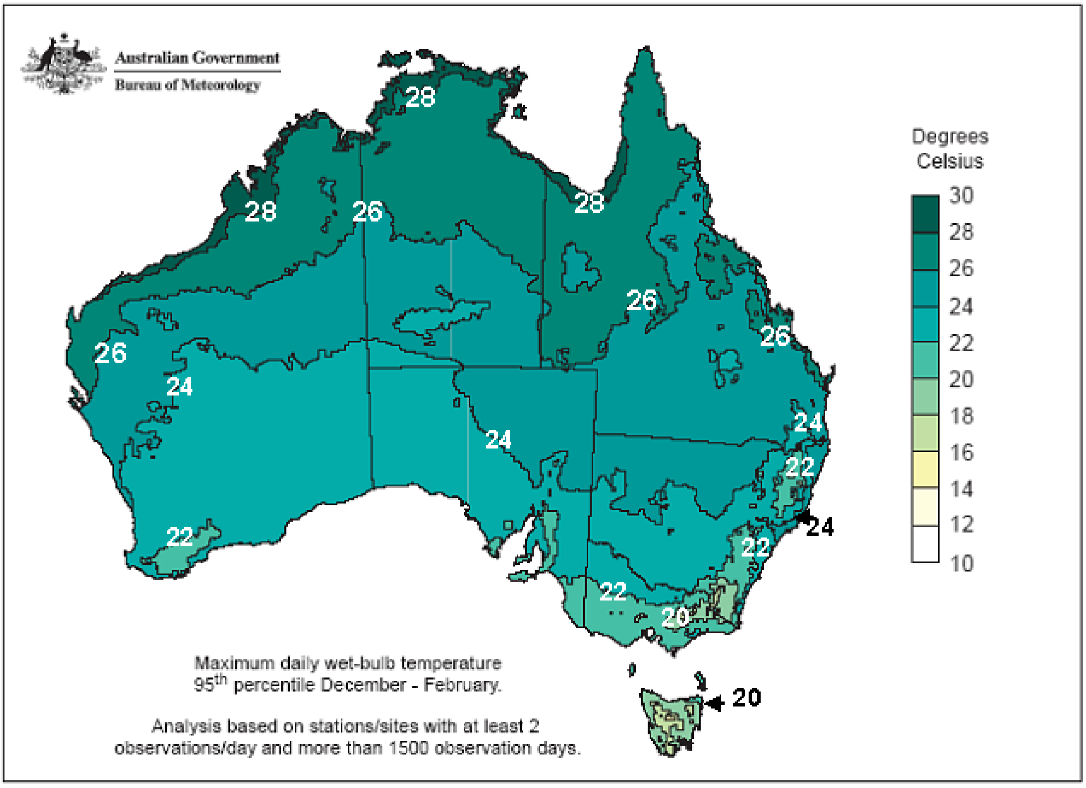

Figure X. Maximum daily wet-bulb temperature 95th percentile December-February (Commonwealth Bureau of Meteorology, 2004)

Increasing thermal efficiency

This study showed that heating the greenhouse in winter as part of moderately controlled greenhouses to improve yields is economically feasible. In addition to providing heating, increasing thermal efficiency is important. This can include the use of thermal screens and improving air-tightness of greenhouses (Baille et al, 2006; Both et al., 2007).

Automation

Computer control of greenhouse conditions allows for efficiency in crop production, is labour saving and enhances workplace safety (Spanomitsios, 2001). Mathematical models can be used to estimate the optimum ventilation rates and other measures needed for optimum crop growth. However, it can only work if the local climate and greenhouse design is considered. Such models have been developed for some regions, for example, in Shanghai for cucumber production in summer and winter in medium technology greenhouses (Luo et al. 2005ab). Modelling can also be used to predict how greenhouse modifications might impact on greenhouse microclimate, such as the installation of insect screens on vents (Bartzanas et al., 2009). Currently, the Australian industry does not have recommendations for greenhouse designs and systems based on climate zones but these would be extremely beneficial.

6. *Technology transfer*

In lieu of a technology transfer component in this project, it was proposed that a preliminary adoption strategy be developed to guide technology transfer beyond this project. In addition to the strategy outline below, several extension activities have already occurred where information from the project has been delivered through workshops and print articles (Appendix).

The primary goal of technology transfer from this project is the adoption of strategies and technology that improve greenhouse conditions for vegetable production. This could be achieved through an integrated approach of the following:

1) Creating the awareness of the finding that real economic benefits can be made by improving greenhouse performance
2) Developing information packages on technology options and other strategies for improving crop conditions in greenhouses, which could include additional information as a part 2 of the best practice manual for simple hydroponics
3) Filling the knowledge gap on appropriate greenhouse designs and technology for Australian climates.

Existing avenues of extension can be used in part to deliver information from this project to industry. However, adoption will require further investment. Growers will be made aware of the benefits of improving greenhouse systems through fora such as the Protected Cropping Australia biennial conference in Adelaide in 2011 and other workshop or field day opportunities, and through articles in industry magazines such as Practical Hydroponics and Greenhouses, AgToday and Vegetables Australia. Adoption will be enhanced amongst growers with the skills to evaluate their crop production and business performance. The same skills will allow them to assess the value of investing in new technology. The project lead by Jeremy Badgery-Parker, *National greenhouse industry business and productivity analysis system* (VG08045), is currently addressing this issue.

Improving practices in greenhouse systems has a strong impact on crop conditions and has been the focus of the related project *Improving greenhouse systems and production practices (greenhouse production practices component)* (VG07144) with the development of the best practice manual for simple hydroponics. The development of a training module based around a combination of knowledge from this best practice manual and the best choice on greenhouse technology is paramount to strong adoption by growers using low technology systems and will require funding of a future project.

This project has highlighted that the best choice in greenhouse technology for improving crop conditions depends on the local climate. In light of this, it is evident that information on appropriate technology will need to be tailored for individual greenhouses, based on their location. Potentially, mathematical models developed for the housing industry in Australia could be modified for the Australian greenhouse industry for this purpose. This has been made a recommendation for further scientific research.

7. *Recommendations*

Industry

A clear finding from the current research is that improving greenhouse conditions, achieved through greenhouse modification, or by upgrading to completely new technology, improves yields and is economically rewarding. Therefore, a key recommendation of this work is that the greenhouse industry should improve existing low technology systems and aim towards medium technology greenhouse systems as a goal. It is recommended that knowledge gaps be addressed and that technology transfer be used to facilitate the improvement of that part of the industry using low technology greenhouse systems. As outlined in the technology transfer strategy, the industry recommendations are to:

1) Create awareness amongst growers of the real economic benefit of improving greenhouse performance
2) Develop information packages for growers on technology options and other strategies for improving crop conditions in greenhouses
3) Develop appropriate greenhouse designs and technology for Australian climates

Scientific

Experimental research will be needed to address the industry recommendations from this project. These are to:

1) As a strategy to improve crop conditions, validate the use of high crop density as a method for cooling of low technology greenhouses. The current research showed the economic benefit of increasing plant density but this recommendation additionally addresses the problem of excessive heat loads in low technology greenhouses.

2) Through mathematical modelling of climate data and greenhouse properties, develop and design greenhouse systems appropriate for Australian climates. Following development of designs, validation of these designs in typical commercial settings.

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9. *Appendix*

Technology transfer

Greenhouse grower workshop run by Kaye Ferguson and Barbara Hall: Adelaide, Tuesday 1st September, 2009

Cucumber Production

Are you growing cucumbers in low-medium tech greenhouses?

Do you wonder how the greenhouse climate affects cucumber yield and quality?

Do you wonder if you are over or under irrigating your cucumbers in cocopeat?

Sophie Parks, a researcher from NSW DPI will hold a workshop in Virginia and will present information from her trials on how temperature, humidity and planting density affect the yield and quality of cucumbers.

Sophie has also researched hydroponic growing media and will provide a rough guide to irrigating hydro cucumbers growing in cocopeat.

Date: **Tuesday 1st September**

Time: **4pm**

Where: **The Wheatsheaf Hotel Virginia (dining room)**

Dinner provided for workshop participants

RSVP by Monday 31st August to:

Kaye Ferguson

Ph: 8303 9627 or kaye.ferguson@sa.gov.au

Greenhouse grower workshop run by Sophie Parks, Basem Al-khawaldeh, Joshua Jarvis and Carly Murray, Gosford Primary Industries Institute, NSW, Wednesday 20th January, 2010.

NSW GOVERNMENT | Industry & Investment

Greenhouse growers' workshop Gosford Primary Industries Institute
Wednesday 20th January 2010

Program:

- Tea and coffee on arrival in the Visitors Centre
- Introduction and walk through current greenhouse cucumber experiment on greenhouse environmental control and plant density (see notes attached)
- Visit the Market Access section to look at a hot water shower treatment experiment on cucumbers
- Visit Entomology section to look at current greenhouse work
- Lunch and wrap up

Post your visit, if you would like to discuss anything further please contact us:

Sophie Parks, Jeremy Badgery-Parker, Basem Al-khawaldeh, Jenny Ekman

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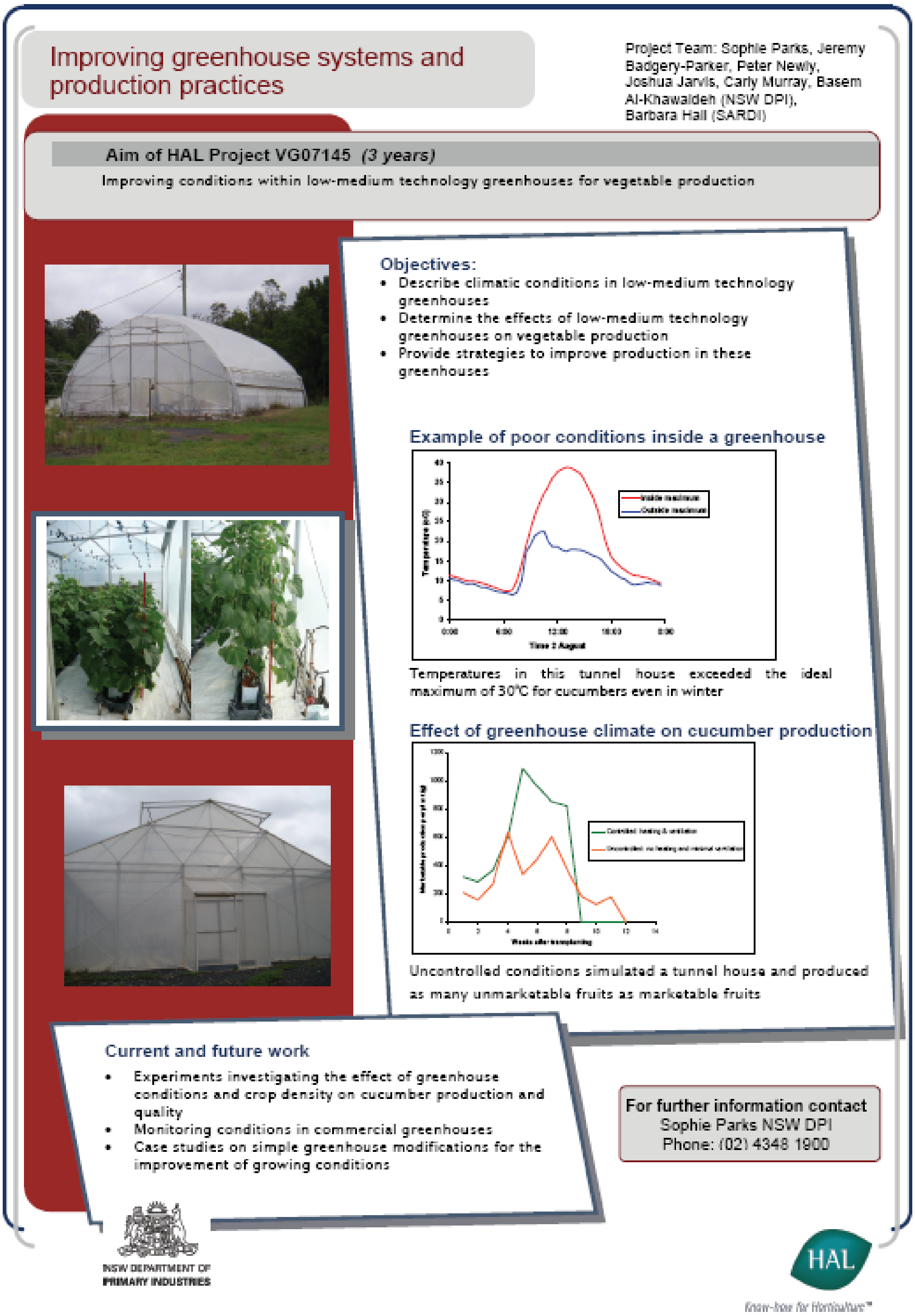
Figure X. Attendees enjoying a cool drink following the workshop

Poster: Australian Hydroponic and Greenhouse Association conference (19-22 July 2009, Sydney)



Cuke quality falls in plastic tunnels

Technical officer, Carly Murray, helping to set up the cucumber trial at Gosford Primary Industries Institute.

INVESTING in climate control for greenhouse-grown cucumbers can increase yields and quality, and improve storage potential.

According to results from a project targeted at growers using older technology, low plastic covered tunnels are colder on cool days, hotter on warm days and more humid than higher technology greenhouses.

"Low-tech conditions reduce yields, increase the number of unmarketable fruits, and reduce the quality of fruits generally," said Dr Sophie Parks (pictured) of the Primary Industries division of Industry and Investment NSW.

"Approximately 80 per cent of growers use low-technology greenhouses.

"However, simple cost-effective measures such as increasing passive ventilation can dramatically improve yields."

Dr Parks led a spring experiment at the Gosford Primary Industries Institute, simulating well-controlled and poorly controlled conditions to demonstrate the importance of the greenhouse environment on yield and quality.

As part of a Horticulture Australia Ltd project to improve vegetable greenhouse systems and production practices, cucumber plants were grown in four greenhouses, each with a different climate control regime ranging from complete control of temperature and humidity, to no control of the ambient conditions within.

Maximum day temperatures were higher in the uncontrolled greenhouse with no cooling, compared with houses that had venting systems, especially when venting was combined with evaporative cooling.

"For example, on warmer days the maximum temperature, mid-canopy, was between 35 and 40 degrees in the uncontrolled greenhouse, and between 25 and 30 degrees in the fully controlled greenhouse," Dr Parks said.

"Heating systems in the more controlled greenhouses increased the average night temperature by approximately four degrees, preventing temperatures dropping below 13 degrees during fruit development."

The poorest greenhouse control resulted in the humidity reaching 100pc more frequently than the others.

Dr Parks said the general trend was increased total production as greenhouse climate control improved.

The fully automated greenhouse produced higher marketable fruit numbers per week.

Peak production occurred two weeks earlier in the two houses with the greatest climate control, yet the timing of decline was similar for all houses.

Unmarketable fruit was highest in the poorest conditions, and represented roughly 50pc of total production of total fruit numbers and weights.

In contrast, unmarketable fruit represented about 16pc of total production in the fully controlled greenhouse.

Increasing plant density did not improve yield under poor conditions, or affect storage quality of marketable fruit in the four greenhouses.

Dr Parks' colleague at Gosford, Dr Jenny Ekman, looked at post-harvest quality and found although cucumbers from the four houses looked similar at harvest, significant differences developed during storage (see separate story).

The experiment will be conducted three times to provide a set of data that captures the range of conditions across seasons.

■ Contact Sophie Parks, Gosford, (02) 4348 1914, sophie.parks@industry.nsw.gov.au

How firm are your cucumbers?

THE way seedless cucumbers are grown has a big effect on how well they store after harvest and, therefore, on customer satisfaction.

Dr Jenny Ekman, a researcher from the Primary Industries division of Industry and Investment NSW, tested cucumbers grown under different greenhouse conditions to see how well they performed after harvest.

Seedless cucumbers are difficult to store for any length of time – below seven degrees injures them, causing skin pitting and sliminess, and at higher temperatures they quickly soften and rot.

"Cucumbers grown with control of temperature and humidity were better in every way than those grown without it," Dr Ekman said.

"They stayed firm, green and crisp after storage.

"The cucumbers grown without those controls were more likely to decay, yellow and soften.

"We were surprised by how big the differences were because they all looked similar at harvest."

Research on other crops has suggested that fruit "adapt" to their environment – fruits grown with cold nights may cope with cold storage better than those grown under milder conditions.

The opposite was true – Dr Ekman said cucumbers grown with cold nights stored worse at low temperatures.

The researchers also found that rots in the fruit increased as the plants aged.

"Infection often occurs during flowering, but the fungus doesn't grow until the fruit is picked," Dr Ekman said.

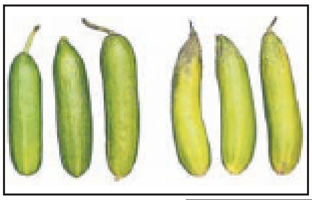
"It is a bit like when a person gets tired or run down, they are more likely to catch flu.

"When a fruit is picked its supply of food and water from the parent plant is taken away so the fruit has to rely on stored reserves.

"If it's not healthy in the first place, it will quickly deteriorate and rot."

The Gosford project has been facilitated by Horticulture Australia Ltd in partnership with AusVeg and funded by the vegetable levy and Industry and Investment NSW.

■ Contact Jenny Ekman, Gosford, (02) 4348 1942, jenny.ekman@industry.nsw.gov.au



Difference between cucumbers from the best performing greenhouse and the worst after 12 days storage at five degrees then two days at 20 degrees. Cucumbers grown under the poorest conditions had more flesh rots, developed more pitting due to chilling injury, yellowed faster and were softer than those grown under the best conditions.

Improving control of tomato bacterial canker

RESEARCH into the bacteria that causes canker in tomatoes is assessing its diversity within Australia, and comparing disinfectants to determine the most efficient means of eradication.

Bacterial canker is an important disease in Australian tomato production that can cause total losses.

The disease is caused by systemic vascular infection by the bacteria *Clavibacter michiganensis* (Cmm).

"There may be new strains of the bacteria present in Australia, since it can be seed borne and imported seed has generally been untreated since the relaxation of quarantine requirements in the early 1990s," said Dr Leanne Forsyth, a plant pathologist from the Primary Industries division of Industry and Invest-ment NSW.

"The only effective control methods are the quarantine and eradication of infected plants.

"External symptoms have altered in recent decades."

Whether this is due to the use of newer tomato cultivars which react differently to infection or due to the introduction of new genetic strains of the bacteria is unknown.

Dr Forsyth and her colleagues, Len Tesoriero and Tehgan Crown, at the Elizabeth Macarthur Agricultural Institute, Camden, are comparing strains from Australia with others collected from around the world.

Dr Forsyth says control is dependent on reducing both the spread and the severity of the disease.

Reducing the spread should primarily rely on good hygiene, supplemented by preventative anti-bacterial methods.

Cmm is capable of producing long lasting, chemical and heat resistant endospores, thought to allow its survival in soil and infected plant debris for long periods.

It can survive in tomato debris, in alternative weed hosts, in water and in soil.

At the Gosford Horticultural Institute, Fiona Lidbetter and Pauline Cain are comparing the use of different disinfectants on different surfaces and substrates to determine the most efficient way to eradicate the bacteria.

Dr Forsyth says as industry moves towards water recirculation or reuse of waste water, it will be necessary to develop effective disinfection strategies to ensure the disease does not spread uncontrollably through crops.

Activation of natural plant defence chemicals is now a common mechanism for controlling a number of diseases including Fusarium wilt and Phytophthora root rot.

In the US, considerable work has been done on Bion (Acibenzolar-s-methyl) and its combination with copper sprays to reduce the spread of Cmm within and between plants.

Some reports show different biological control agents have potential to be combined with chemical sprays to reduce the spread and incidence of disease.

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