Original article

The effect of environmental control and plant density on cucumber crop performance in Australian conditions

S. Parks[1,a], L. Spohr[1], T. Olesen and J. Jarvis[1]

[1] NSW Department of Primary Industries, North Loop Road, Ourimbah, NSW 2258, Australia

Summary

Introduction – **Scarce information on the productivity of mini-cucumbers limits assessment of the value of investment in the types of protected systems used in Australia.** *Materials and methods* – **Three experiments on the protected cropping of cucumber examined production at four levels of environmental control technology, and three planting densities, and these data were used in economic analyses. The dependency of fruit development on temperature, and the dependency of yield on temperature and irradiation were also modelled. The temperature-dependency model of time from sowing to peak harvest was used to predict harvest times.** *Results and discussion* – **Increasing the control of the greenhouse climate generally increased production with fruit number increasing by up to 37% (p=0.039). The moderate environmental control was economically feasible but the costs of full control were prohibitive. Increasing the density from 2.24 to 4.48 plants m^{-2} increased crop yield by 69% to 22.2 kg m^{-2} and fruit number by 75% to 114.5 m^{-2}. The time from sowing to peak harvest decreased with increasing temperature, while the plants produced more but smaller fruit at higher temperatures. Maximum yields occurred around 24 °C and generally increased with higher irradiation. The irradiation in the greenhouses was, however, only 55% of full daylight.** *Conclusion* – **Moderate environmental control was found to be a cost-effective technology for improving greenhouse conditions for cucumber production, as was increasing planting density. Harvest times for both protected and field cropping can be predicted using the temperature-dependency model of time from sowing to peak harvest.**

Keywords
Cucumis sativus, hydroponics, mini-cucumber, polyhouse

Significance of this study

What is already known on this subject?
- Production of cucumbers depends on irradiation and temperature with temperature optima identified for some continental and pickling varieties.

What are the new findings?
- Mini-cucumber yield can be predicted using a temperature dependency model. Increasing plant density enhances the gross margin of covered crops.

What is the expected impact on horticulture?
- Better prediction of time to harvest for mini cucumbers. Enhanced production with application of higher planting densities.

Introduction

Cucumber (*Cucumis sativus* L.) is an important and widely cultivated annual vegetable. In Australia, cucumbers are grown year-round due to contrasting climatic zones, with 87,776 tonnes produced for the year ending June 2017 and the majority having being grown under cover (Horticulture Australia, 2018).

Cucumber is day neutral with respect to floral initiation (Warrington and Norton, 1991), so the production of fruit on plants given sufficient water, adequate nutrition and protection from pests and diseases is largely a function of temperature and irradiation. Cucumber successfully germinates from approximately 15 to 36 °C, with less successful germination a few degrees above and below this range (Kurtar, 2010). Germination is most rapid between 27 to 30 °C (Kurtar, 2010). Maximum plant growth occurs around 27 °C (Grimstad and Frimanslund, 1993). The optimum temperature for fruit production is more problematic, confounded by cultural practices (*e.g.*, pruning and fruit thinning, as reported by Marcelis, 1993a), environmental factors (*e.g.*, a decrease in the number of flower buds per node with increasing temperature, as reported by Grimstad and Frimanslund, 1993; and Van der Vlugt, 1983) and differences between varieties (Papadopoulos and Hao, 2000). Varieties also respond differently to variations in temperature, with the development of the 'Corona' variety largely a function of mean temperature, but the 'Aramon' variety is sensitive to day-night temperature differences (Papadopoulos and Hao, 2000). At moderate temperatures and moderate irradiation, plant growth and yields increase with increasing irradiation (Warrington and Norton, 1991; Marcelis, 1993b; Hao and Papadopoulos, 1999; Kläring *et al.*, 2012).

Greenhouses are used for cucumber production to protect the crop inside from wind, hail and rain, and to allow for the controlled delivery of water and nutrients to the crop, the re-use of runoff water and nutrients, and the efficient control of pest and diseases. Control of the internal climate (temperature, humidity, CO_2 and irradiation) is also possible, but the possibility is limited in Australia by the current preference for inexpensive greenhouses that are not designed for sophisticated climate control and cannot be easily retro-fitted with control systems. The greenhouses used are commonly of a tunnel design, with a height of less than 3 m. They are covered with a plastic (polyethylene) film, and typically

[a] Corresponding author: sophie.parks@dpi.nsw.gov.au.

ventilated by rolling up the plastic at both ends. Such tunnels are characterised by large diurnal temperature variations and high vapour pressure deficits in the middle of the day (Parks *et al.*, 2011).

Our primary purpose here is to compare cucumber production in greenhouses with no mechanical heating or cooling, simulating the popular poly-tunnels, with production in greenhouses with more environmental control technology, at three levels of technological sophistication. The technological improvements to cucumber production are then used in conjunction with the costs of the technology to assess the economic benefits of better environmental control systems.

Seedless mini-cucumbers, also called Beit Alpha cucumbers, are used as the experimental material for the study. This type of cucumber was developed in the Netherlands in the 1970's, using crosses of continental and parthenocarpic pickling lines, and has been popular in Australia since the 1980's (Badgery-Parker *et al.*, 2010). There is little information on these types of cucumber in the scientific literature (Parks *et al.*, 2011) so a secondary aim of the paper is to describe some of the basic environmental dependencies of the crop. Some of these dependencies have been considered before for 'continental' and pickling cucumber varieties. Overall, however, the scientific literature on cucumber is thin, and sometimes difficult to interpret. Knowing the temperature optimum for production, for example, is fundamental to protected cropping, yet the published optimum for 'Farbiola' was 25 °C (Grimstad and Frimanslund, 1993), while that for 'Corona' was 19 °C (Papadopoulos and Hao, 2000). To what extent is this difference varietal or related to the conduct of the experiments? The temperature optimum for mini-cucumber production is one of the environmental dependencies addressed here.

Materials and methods

Greenhouse cucumber crops

Three cucumber experiments were carried out at the Gosford Primary Industries Institute, Narara, New South Wales, Australia, (33°22'S; 151°20'E). These experiments 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 mid-winter (21st of July 2008). The second experiment was planted in late summer (27th of January 2009) and the third experiment was planted in early summer (1st of December 2009). The two summer experiments used seedlings of the 'Khassib RZ F_1 hybrid'. For each experiment, four double skinned 9 × 6.3 m polyhouses with a gutter height of 3.6 m were used. The seedlings were planted into coco peat in 7.5-L bags, two seedlings per bag, which is the industry standard, and grown hydroponically using a complete nutrient solution in a run-to-waste system. The plants were trained and harvested according to industry practices.

Table 1. Climate summaries, calculated from planting to harvest, for each of the three experiments. The means were calculated from daily measurements.

	Mean maximum temperature (°C)	Mean minimum temperature (°C)	Mean radiation 400–1100 nm (MJ day^{-1})	Mean maximum relative humidity (%)	Mean minimum relative humidity (%)
External conditions					
Midwinter planting	22.1	9.7	17.6		
Late summer planting	24.5	13.8	17		
Early summer planting	27.6	17.7	20		
Full control					
Midwinter planting	25.8	13		92	55
Late summer planting	26.8	16		99	71
Early summer planting	29.1	18.8		95	51
Moderate control					
Midwinter planting	29.7	12.8		94	63
Late summer planting	27.1	18.3		99	77
Early summer planting	31.3	19.5		96	67
Minimal control					
Midwinter planting	30.2	10.5		96	53
Late summer planting	29.7	15.4		96	63
Early summer planting	33.9	18.8		93	51
No control					
Midwinter planting	31.1	11		98	55
Late summer planting	29.5	15.5		98	63
Early summer planting	33.8	18.5		96	52

Environmental control treatments

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

1) *No control*. This involved no heating; cooling in winter provided only during harvest times by opening doors; and cooling in summer by passive ventilation, by covering of the open ends of the greenhouse with insect mesh.
2) *Minimal control*. This involved no heating; cooling in winter by passive ventilation, through fan louvres opened manually during the day; and cooling in summer by passive ventilation, by covering of the open ends of the greenhouse with insect mesh, and by white-washing the plastic film.
3) *Moderate control*. This involved hydronic heating when required; cooling in winter by passive ventilation, through fan louvres opened manually during the day; and cooling in summer with a fan and fogging.
4) *Full control*. This involved hydronic heating when required; and cooling when required using fogging, and forced evaporation (pad and fan).

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 the temperature and humidity in the full control greenhouse, and adjustment of the temperature inside the moderate control greenhouse. For the experiments, the control systems on the minimal control and no control greenhouses were disabled. Temperature and relative humidity means obtained for the experiments are summarised in the results section (Table 1).

Photosynthetically active radiation measurements were made with a LI-COR (Lincoln, Nebraska, USA) quantum sensor on several clear days, at regular intervals during the day. Within each greenhouse, measurements were made at the top of the canopy at three points from the middle to the edge of the crop. All greenhouses transmitted approximately 55% of the incident radiation, notwithstanding the whitewash on the minimal control treatment.

Experimental design

The cucumber plants were grown at three densities [4.48 (high), 3.36 (medium) and 2.24 (low) plants m^{-2}] within each greenhouse. The experimental design was a split plot, with greenhouse environment system treatment as the main plot and planting density as the sub plot. Within each greenhouse there were two replicates of each planting density. There were four rows in each greenhouse, with measurements made on the fully buffered central four plants in each plot (located in the middle two rows). The experiment was conducted three times (mid-winter: July 2008, late summer: January 2009, early summer: December 2009).

At harvest, fruit were separated into marketable fruit (between 14–16 cm long) and unmarketable fruit (too small, blemished, misshapen or too pale in colour) and fruit numbers and weights per plot were measured, and were expressed per square metre of allocated space.

Statistical analyses

1. Greenhouse experiments. Analyses of variance with a split plot design structure were conducted to assess the effects of the greenhouse environmental control system, planting density, and their interaction, on the marketable and unmarketable fruit weights and numbers, and on the mean fruit weight. GenStat for Windows, 18th Edition (VSN International, 2015), was used for these analyses.

2. Data modelling. Cumulative fruit weights from progressive harvests were calculated for all replicates in all three experiments. A single, simple logistic regression was then fitted to the pairs of replicates for each plant density treatment in each greenhouse, for each experiment:

$$y = a \,/\, (1 + e^{b(c-x)}) \qquad \text{(Eq. 1)}$$

where:
y = fruit weight;
x = days from sowing;
a = total fruit weight, fixed as the mean of the totals for the two replicates;
b = rate parameter;
c = peak harvest, the time of the maximum rate of harvest, which occurs at half the total harvest.

A time to peak harvest for each greenhouse ('c' from Equation 1) was calculated as the mean of the estimates for the three plant densities, given that there were only small and inconsistent differences in time between the density treatments.

The mean temperature during the time from sowing to peak harvest for each greenhouse was calculated as the average of the daily maximum and minimum temperatures recorded over this period. The daily incoming solar radiation for the site was sourced from the Queensland Government's patched point data (http://www.longpaddock.qld.gov.au/silo). This was used to calculate the mean daily incoming solar radiation from sowing to peak harvest inside the greenhouses by assuming, from above, that the lining of the greenhouses transmitted 55% of the radiation.

The relationship between the time from sowing to peak harvest and temperature was calculated by using the following function:

$$y = a\, e^{a(b-x)} + c \qquad \text{(Eq. 2)}$$

where:
y = days from sowing to peak harvest ('c' calculated from Equation 1);
x = mean temperature (°C) during this period;
a, b, c = parameters.

No temperature threshold for growth was used because mean daily temperatures tended to be high. This function (Equation 2) was applied to the weather records for Alstonville (28.9°S; 153.5°E), northern NSW, reported previously (Olesen and Muldoon, 2012), to describe variations in the time from sowing to peak harvest for different times of the year for field-grown cucumbers, and the way in which this variation has changed with late 20th century warming. The times of year were restricted to keep the mean temperatures calculated from the Alstonville records within the temperature range of the fitted function.

Linear regressions were used to describe the relationships between fruit number and temperature, and mean fruit weight and temperature.

The relationship between yield and temperature was calculated by using the first derivative of the logistic curve:

$$y = a\, b\, e^{b(c-x)} \,/\, (1 + e^{b(c-x)})^2 \qquad \text{(Eq. 3)}$$

where:
y = yield (kg m^{-2});
x = mean temperature (°C) during sowing time to peak harvest time;

a, *b*, *c* = parameters, with *c* the temperature at which the peak yield occurs.

The relationship between yield and mean daily incoming solar radiation was calculated by linear regression.

The model of the dependency of yield on temperature and incoming solar radiation was fitted using the following function:

$$y = z\,a\,b\,e^{b(c-x)} / (1 + e^{b(c-x)})^2 \quad \text{(Eq. 4)}$$

where:
y = yield (kg m^{-2})
x = mean temperature (°C) during time from sowing to peak harvest time;
z = mean daily incoming solar radiation (MJ m^{-2} d^{-1});
a, *b*, *c* = parameters, with *c* the temperature at which the peak yield occurs for a fixed *z*.

Results and discussion

Environmental control and cucumber production

There was a strong tendency (p=0.057) for the yield of marketable cucumbers, expressed on a weight basis, to increase with increasing environmental control in the greenhouses (Table 2). Similarly, the marketable yield on a fruit number basis significantly increased with increasing environmental control (Table 2).

The overall marketable yields for the no control, minimum control, moderate control and full control greenhouses were respectively 14.5, 16.0, 18.8, 20.3 kg m^{-2} and 75.7, 80.1, 97.6, 103.3 fruit m^{-2}. The individual weight of marketable fruit was similar across all glasshouses (Table 2).

The yields of unmarketable fruit seemed to decline with increasing environmental control but there were no significant trends (Table 2).

More generally, many of the benefits of improved climate control lie in reductions in temperature extremes and in the prevalence of periods of high vapour pressure deficits, both of which impair carbon assimilation and plant development (Parks *et al.*, 2011).

Effects of plant density on cucumber production

A planting density of 2.24 plants m^{-2} was chosen to approximate current practice. The marketable yields from this planting density (mean 13.1 kg m^{-2}) in all greenhouses (Table 2) compared more than favourably with standard industry yields of 7–10 kg m^{-2}.

Increasing the plant density by 50% to 3.36 plants m^{-2} significantly increased yields by 29% on a weight basis and 34% on a fruit number basis. Increasing the plant density by 100% to 4.48 plants m^{-2} significantly increased yields by 69% on a weight basis and 75% on a fruit number basis. Thus increasing conventional planting densities is a very simple, inexpensive and effective means of increasing production. It may also improve the greenhouse environment by lowering vapour pressure deficit, which when high can inhibit photosynthesis (Shibuya *et al.*, 2009).

There was a commensurate increase in the yield of unmarketable fruit with increasing plant density (Table 2), but this is only a small consideration and possibly even a market opportunity.

Table 2. Production characteristics, combining the winter and two summer experiments, related to the environmental control and plant density treatments. Plant density was replicated twice in each greenhouse. Values are means (*n* = 6), standard errors (SE) and p values.

Treatments		Marketable yield (kg m^{-2})		Unmarketable yield (kg m^{-2})		Marketable fruit (number m^{-2})		Unmarketable fruit (number m^{-2})		Marketable fruit mass (g $fruit^{-1}$)	
		Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Full control											
2.24 plants m^{-2}		15.4	1.6	2.0	0.5	74.6	6.4	11.9	2.3	201.1	6.6
3.36 plants m^{-2}		18.1	2.4	2.1	0.6	96.7	12.9	13.4	3.5	183.6	1.5
4.48 plants m^{-2}		27.3	2.9	3.2	0.9	138.5	16.7	18.1	4.4	196.9	4.9
Moderate control											
2.24 plants m^{-2}		14.0	1.8	2.3	0.3	70.6	8.6	16.2	2.4	189.1	10.0
3.36 plants m^{-2}		18.5	2.1	3.3	0.4	97.6	11.3	25.2	5.1	181.0	9.2
4.48 plants m^{-2}		23.8	1.6	3.6	0.5	124.5	11.6	29.5	6.0	182.6	10.8
Minimum control											
2.24 plants m^{-2}		11.3	1.2	2.8	0.5	56.7	6.8	17.8	2.3	190.9	6.7
3.36 plants m^{-2}		16.5	1.2	4.0	0.8	81.6	7.9	23.7	3.7	195.3	7.7
4.48 plants m^{-2}		20.3	1.5	4.5	0.9	101.9	10.2	26.9	2.9	194.7	9.5
No control											
2.24 plants m^{-2}		11.7	1.6	3.1	0.8	59.8	8.7	18.8	3.2	189.8	5.4
3.36 plants m^{-2}		14.4	2.0	5.1	1.0	74.1	11.7	29.8	4.2	189.7	8.2
4.48 plants m^{-2}		17.3	3.1	5.4	1.4	93.1	18.4	33.4	6.5	181.0	3.9
Effect[z]	df	p value		p value		p value		p value		p value	
Environmental control	3	0.057		0.345		0.039		0.536		0.495	
Plant density	2	<0.001		<0.001		<0.001		<0.001		0.115	
Interaction	6	0.118		0.388		0.233		0.417		0.032	

[z] P values as determined by split plot ANOVA are significant at $p < 0.05$, df = degrees of freedom.

Table 3. Economic comparisons for cucumber production under different scenarios, per square metre, per year. The return is based on the experimental yield multiplied by 2.2 crops per year and by the marketable fruit value (AU$ 2 kg^{-1}). Gross margin is the return minus the variable costs which includes harvesting, plant management, maintenance and system checks, fuel, water and electricity.

Treatments	Return (AU$)	Variable costs (AU$)	Gross margin (AU$)
Full control			
2.24 plants m^{-2}	67.76	20.87	46.89
3.36 plants m^{-2}	79.64	31.31	48.33
4.48 plants m^{-2}	120.12	41.36	78.76
Moderate control			
2.24 plants m^{-2}	61.60	17.87	43.73
3.36 plants m^{-2}	81.40	26.81	54.59
4.48 plants m^{-2}	104.72	35.66	69.06
Minimal control			
2.24 plants m^{-2}	49.72	17.83	31.89
3.36 plants m^{-2}	72.60	26.75	45.85
4.48 plants m^{-2}	89.32	35.58	53.74
No control			
2.24 plants m^{-2}	51.48	17.23	34.25
3.36 plants m^{-2}	63.36	25.85	37.51
4.48 plants m^{-2}	76.12	34.38	41.74

Table 4. Initial fixed costs of structure and environmental controls (AU$ m^{-2}).

		Full control	Moderate control	Minimal control	No control
Typical structure description	Height	4.5 m to gutter 6.0 m to top	4.0 m to gutter 5.5 m to top	2.8 m to gutter 4.0 m to top	2.0 m to gutter 3.2 m to top
	Span width	9.2 m	9.0–9.2 m	8–9 m	8–9 m
	Skin	Double	Double or single	Single	Single
Construction cost ($ m^{-2})		47.15	27.15	17.85	17.85
Environmental controls ($ m^{-2})					
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
Fan		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 (200 L $tank^{-1}$)		0.39	0.20	0.20	0.20
60 L nutrient container		0.29	0.20	0.20	0.20
Concrete - flooring		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
Cost of environmental controls	$ m^{-2}	122.39	66.79	10.99	10.29
Total initial cost	$ m^{-2}	149.54	93.94	28.84	28.14

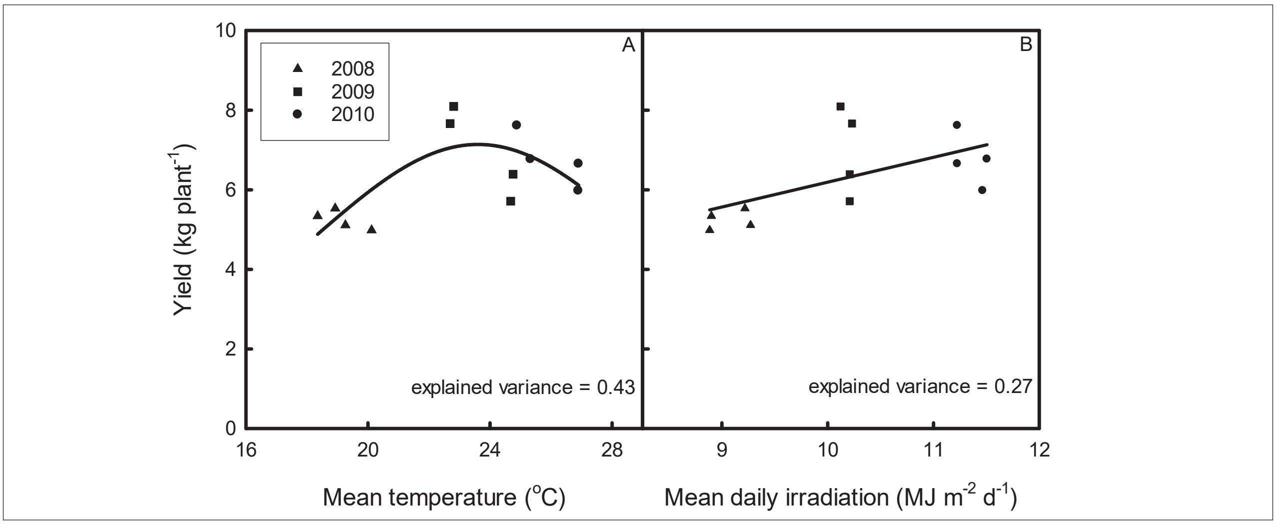

FIGURE 1. Response of cucumber yields to increasing temperature (A) and irradiation (B), combining the mid-winter (2008), late summer (2009) and early summer (2010) experiments.

Economic analysis

Economic analyses of production in the different greenhouse control treatments were conducted using 2011 prices (Parks *et al.*, 2011). Some indicative outputs from the analyses are given in Tables 3 and 4. The highest gross margins were for the moderate and full control greenhouses (Table 3). The gross margins also increased with increased plant density (Table 3).

However, the cost of building a full-control greenhouse was much greater than that for a moderate greenhouse (Table 4) and when this was included in a benefit-cost analysis it was found that the extra investment in shifting from a moderate to full control greenhouse was not recovered over a ten-year timeframe (Parks *et al.*, 2011). But protected cropping is a dynamic field for technological developments, so there are good prospects for improved designs at lower costs in the near future.

Environmental effects on cucumber development

The overall yields of marketable and unmarketable fruit for each of the four greenhouses, for each of the three experiments, were used to examine the effects of environment on cucumber development. The relationships described are potentially affected by varietal differences because ‘Deena’ was used for the winter experiment and ‘Khassib RZ F_1 hybrid’ for the two summer experiments.

The optimum temperature for fruit production (kg plant^{-1}) was approximately 23.6 °C (Figure 1a), with a 95% confidence interval of 22.2–25.0 °C, but with fairly broad tolerances either side of this temperature. The optimum is similar to that reported for ‘Farbiola’ (Grimstad and Frimanslund, 1993), 25 °C, but higher than that reported for ‘Corona’ (Papadopoulos and Hao, 2000), 19 °C. The crops in this study were grown at different times of the year providing a large range of external mean minimum and mean maximum temperatures: mid-winter (9.6–22.1 °C), early summer (13.8–24.5 °C), late summer (17.7–27.6 °C) and greenhouse control treatments provided variable internal conditions (Table 1).

Production increased linearly with increasing irradiation (Figure 1b) consistent with previous work (Kläring *et al.*, 2012). Combining the temperature and irradiation relationships into a single model (Equation 4) explained 60% of the variance.

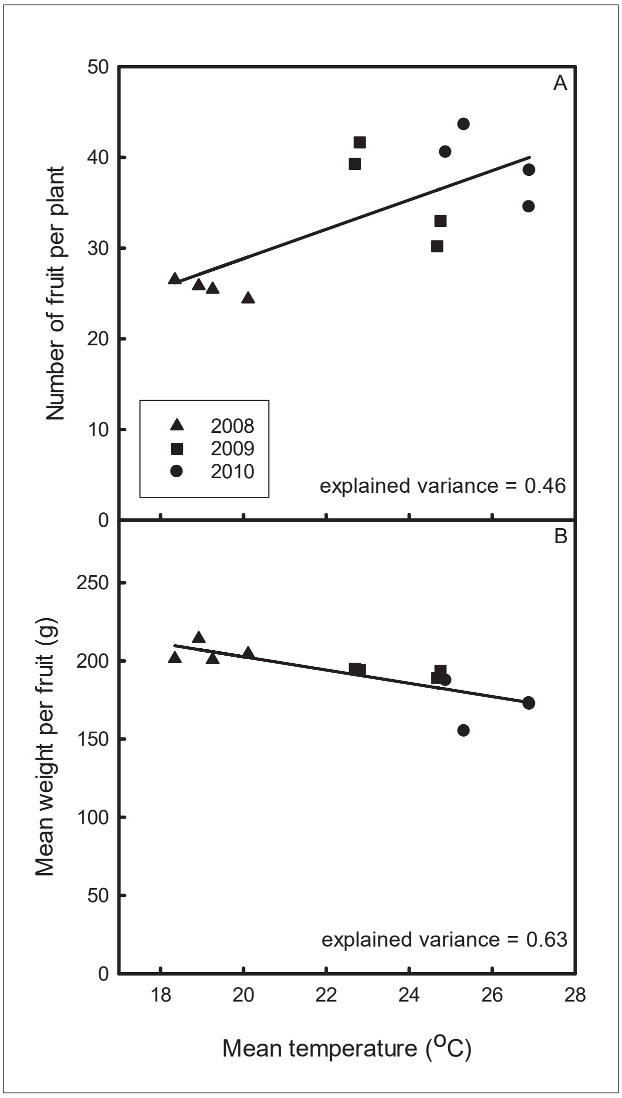

FIGURE 2. Linear regressions between cucumber fruit number per plant and temperature (A) and between mean weight per fruit and temperature (B) combining the mid-winter (2008), late summer (2009), and early summer (2010) experiments.

The number of fruit per plant increased with increasing temperature (Figure 2a). Given that previous work has shown that cucumber flower bud formation tends to be higher at lower temperatures (Grimstad and Frimanslund, 1993), it may be that other temperature-dependent factors, such as carbon availability, are important in determining fruit set. Individual fruit weight decreased with increasing temperature (Figure 2b), which is to say, decreased with increasing fruit number. This is consistent with a crop load effect (Marcelis, 1993a) but there may be other influences, such as temperature effects on fruit maturation, or variety.

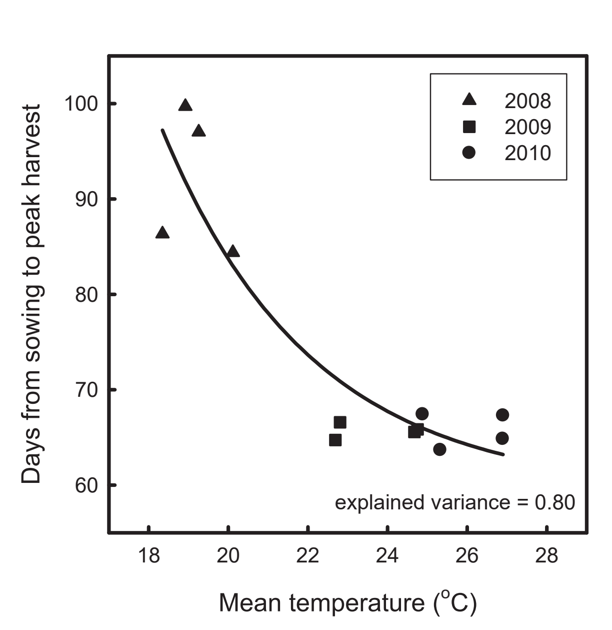

Figure 3. Exponential relationship (Equation 2) between duration of cucumber fruit development (days from sowing to peak harvest estimated from Equation 1) and temperature, combining the mid-winter (2008), late summer (2009), and early summer (2010) experiments.

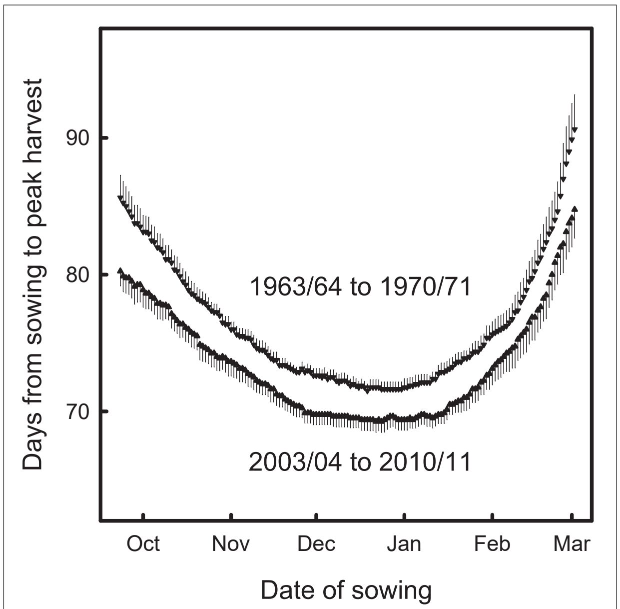

Figure 4. Effects of climate warming in northern NSW on harvest time. Relationship between time from sowing to peak harvest and date of sowing for two periods: 1963–1971 and 2003–2011 for field-grown cucumbers in northern NSW. The differences between the two curves represent a reduction in days from sowing to peak harvest between the two time periods. The estimates on the y-axis were made based on the line fitted to Figure 3 and are within the temperature limits of that line. The results are given as means and standard errors.

The time from sowing to peak harvest decreased in an exponential fashion with increasing temperature with a minimum development time of approximately two months (59 days; Figure 3). Similar decreases in cucumber development times with increasing temperature over much the same temperature range have been shown previously (Grimstad and Frimanslund, 1993; Marcelis, 1994; Slack and Hand, 1983). In our experiment, temperature and irradiation were highly correlated and it was not possible to identify separate influences. Others have shown that the time from anthesis to harvest decreased with increasing irradiation (Marcelis, 1993b), and that both temperature and sunshine hours influence the development rates of field-grown pickling cucumbers in Poland (Kalbarczyk and Kalbarczyk, 2012).

The relationship in Figure 3 is useful for predicting harvest times for both protected and field cropping. To illustrate this we applied the relationship to the field cropping of cucumber in the northern rivers of NSW in the 1960's/70's and then again for the 2000's/10's (Figure 4). Climate warming from the first to the second period advanced the harvest date by several to many days depending on the time of year. The result was very similar to that for the effects of climate change on the development of field grown pickling cucumbers in Poland over the same period (Kalbarczyk and Kalbarczyk, 2012).

Acknowledgments

This study was supported by the Horticulture Innovation Australia Limited (project VG07145: Improving greenhouse systems and production practices). We would like to thank Basem Al-Khawaldeh for collecting the greenhouse costs presented in this study.

References

Badgery-Parker, J., James, L., Jarvis, J., and Parks, S.E. (2010). Commercial greenhouse cucumber production (Australia: New South Wales Department of Primary Industries), 20 pp.

Grimstad, S.O., and Frimanslund, E. (1993). Effect of different day and night temperature regimes on greenhouse cucumber young plant production, flower bud formation and early yield. Sci. Hortic. *53*, 191–204. https://doi.org/10.1016/0304-4238(93)90067-Z.

Hao, X., and Papadopoulos, A.P. (1999). Effects of supplemental lighting and cover materials on growth, photosynthesis, biomass partitioning, early yield and quality of greenhouse cucumber. Sci. Hortic. *80*, 1–18. https://doi.org/10.1016/S0304-4238(98)00217-9.

Horticulture Innovation Australia Limited (2018). 2016/2017 Australian Horticulture Statistics Handbook. https://horticulture.com.au/resource/australian-horticulture-statistics-handbook/.

Kalbarczyk, R., and Kalbarczyk, E. (2012). The role of sunshine duration and air temperature in shaping variability in developmental stages of the cucumber (*Cucumis sativus* L.) in Poland 1966–2005. Acta Sci. Pol. Hortoru. *11*, 155–178.

Kläring, H.-P., Klopotek, Y., Schmidt, U., and Tantau, H.-J. (2012). Screening a cucumber crop during leaf area development reduces yield. Ann. App. Biol. *161*, 161–168. https://doi.org/10.1111/j.1744-7348.2012.00560.x.

Kurtar, E.S. (2010). Modelling the effects of temperature on seed germination in some cucurbits. Afr. J. Biotech. *9*, 1343–1353. https://doi.org/10.5897/AJB2010.000-3016.

Marcelis, L.F.M. (1993a). Fruit growth and biomass allocation to the fruits in cucumber. 1. Effect of fruit load and temperature. Sci. Hortic. *54*, 107–121. https://doi.org/10.1016/0304-4238(93)90059-Y.

Marcelis, L.F.M. (1993b). Fruit growth and biomass allocation to the fruits in cucumber. 2. Effect of irradiance. Sci. Hortic. *54*, 123–130. https://doi.org/10.1016/0304-4238(93)90060-4.

Marcelis, L.F.M. (1994). Fruit shape in cucumber as influenced by position within the plant, fruit load and temperature. Sci. Hortic. *56*, 299–308. https://doi.org/10.1016/0304-4238(94)90048-5.

Olesen, T., and Muldoon, S.J. (2012). Effects of defoliation on flower development in atemoya custard apple (*Annona cherimola* Mill. × *A. squamosa* L.) and implications for flower development modelling. Aust. J. Bot. *60*, 160–164. https://doi.org/10.1071/BT11299.

Papadopoulos, A.P., and Hao, X. (2000). Effects of day and night air temperature on growth, productivity and energy use of long English cucumber. Can. J. Plant Sci. *80*, 143–150. https://doi.org/10.4141/P99-021.

Parks, S., Spohr, L., Al-Khawaldeh, B., Orr, L., and Ekman, J. (2011). Improving greenhouse systems and production practices. Final report VG07096 (Sydney: Horticulture Australia Ltd.), p. 39–49.

Shibuya, T., Sugimoto, A., Kitaya, Y., and Kiyota, M. (2009). High plant density of cucumber (*Cucumis sativus* L.) seedlings mitigates inhibition of photosynthesis resulting from high vapor-pressure deficit. Hortsci. *44*, 1796–1799.

Slack, G., and Hand, D.W. (1983). The effect of day and night temperature on the growth, development and yield of glasshouse cucumbers. J. Hort. Sci. *58*, 567–573. https://doi.org/10.1080/00221589.1983.11515158.

Van der Vlugt, J.L.F. (1983). The effect of temperature on formation and abortion of flower buds in gynoecious cucumber plants. Sci. Hortic. *20*, 323–328. https://doi.org/10.1016/0304-4238(83)90146-2.

Warrington, I.J., and Norton, R.A. (1991). An evaluation of plant growth and development under various daily quantum integrals. J. Am. Soc. Hort. Sci. *116*, 544–551. https://doi.org/10.21273/JASHS.116.3.544.

Received: Jan. 00, 2018
Accepted: Jan. 00, 2018