Final Report

An Investigation of Low-Cost Protective Cropping

Project leader:

Gordon Rogers

Delivery partner:

Applied Horticultural Research

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VG13075

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An Investigation of Low-Cost Protective Cropping – VG13075

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Level 8
1 Chifley Square
Sydney NSW 2000

Telephone: (02) 8295 2300

www.horticulture.com.au

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Summary

Increased climate variability is a key challenge facing the Australian vegetable industry. Heat waves, heavy rain, unseasonal frosts, hail and other extreme weather events can reduce quality at least, and result in total crop write-off in severe situations. Such events threaten the viability of vegetable farms and impact supply to customers and consumers, creating issues throughout the supply chain.

Technological solutions such as high-tech greenhouses can provide a level of control and certainty. However, the expense of such structures is not justified by returns for many vegetable crops, which can be relatively low value, space consuming, or simply not suited to full protective cultivation. Low cost protected cropping offers a compromise between the cost of high technology and the need to provide some protection to crops from adverse conditions.

An initial review identified shade structures, wind-breaks and floating row covers as the most potentially effective options for vegetable growers. These were subsequently trialed in a large number of growing sites around Australia.

Permanent shade houses and nets can provide full protection from events such as a hailstorm, but were unable to withstand cyclonic conditions in WA. They did not greatly reduce crop temperatures when used as a top-only system. Although yield was unaffected by shading in these trials, it was noted that red shading resulted in darker leaf colour. Capsicum plants grown in the retractable roof Cravo® house were significantly larger and healthier than similar plants grown outside, and would be expected to have greatly increased yield over an extended cropping period.

Using floating row covers for summer production of leafy greens demonstrated a number of potential issues with such systems. These included the difficulty of weed control as well as the potential for small insects such as aphids to multiply inside the protective cover if the sides were not kept well sealed. Floating covers can improve seed germination if conditions are sub-optimal. However, if the crop is well managed then there may be no benefit.

Under cold conditions, however, ‘fleece’ floating row covers can provide major benefits. These materials can significantly improve germination and growth and protect crops from light frosts. Harvest of lettuce was brought forward 1-2 weeks using fleece materials. The lightest fabrics, which are also the cheapest, were sufficiently durable and gave results as good or better than more heavyweight fleeces.

Capsicum plants grown under floating row covers had improved yield and better fruit quality. Floating row covers enhanced plant growth, prevented sunburn and reduced temperatures around the plants during hot weather. They also proved effective at excluding Queensland fruit fly, a major pest of capsicums. The results were best when the row covers were installed early during development.

The same effects, however, were not observed for chilli plants. No increases in either yield or quality were observed for cayenne or birds-eye chillies grown with floating covers. The large size of the plants and more frequent harvests also made use of floating covers problematic for chilli production. However, the materials did provide a significant benefit by excluding fruit fly, which may be important for growers practicing IPM.

The next steps should focus around floating row covers and retractable roof structures, both of which show considerable promise, but for which questions remain. The trials of capsicums under retractable

roof structures should be repeated as the impressive plant growth improvement under these structures was not transplanted into higher yield, suggesting something like water or nutrient availability was limiting yield.

The floating row covers were very promising in alleviating the effects of extreme heat and cold in babyleaf spinach crops. There are more questioned to be answered in relation to this crop group, and floating row covers should be evaluated more thoroughly on baby leaf crops and other leafy vegetables such as head lettuce and Asian greens. The conflicting results with floating row covers on capsicums v's chillies also warrants further investigation. The impact on Queensland fruit fly control could be a major step forward in the management of that serious pest in capsicums and again requires more research.

Keywords

Floating row cover, cover, netting, shade, retractable roof, greenhouse, insect net, fleece, frost, fruit fly, protective structure, plasticulture, capsicum, chilli, baby-leaf, lettuce, spinach

Introduction

Increased climate variability is one of the key threats to the Australian vegetable industry. Heat waves, heavy rain, unseasonal frosts, hail and other extreme weather events can reduce quality at least, and result in total crop write-off in severe situations. Such events threaten the viability of vegetable farms in all of the growing regions. They can also impact supply to customers and consumers, creating issues throughout the supply chain.

Greenhouses can provide everything from a simple shelter to full environmental control. Such new technologies can offer not only improved productivity, but also a degree of certainty in production outcomes. However, this comes at a significant cost. Many vegetable crops are relatively low value, or require large amounts of space. The expense of establishing a full, climate-controlled greenhouse for such crops cannot be justified by returns. Moreover, such technological solutions do not suit every situation, every crop, or every grower.

Low cost protective structures, as used in other horticultural sectors, can potentially fill the gap between open field production and a full controlled environment. Net houses, wind-breaks and even simple floating row covers, can provide plants with some protection from the elements. They may also have benefits in terms of improved quality, better pest management, reduced contamination of the harvested product and extension of the normal growing season. Even though the system may be primarily designed to prevent total loss in the event of a major climate event, such additional benefits may help justify their expense.

This report details the results of trials around Australia examining the use of low cost protected cropping options for vegetable production. Trials were conducted in many of the major centres for vegetable production, and focused on crops and seasons where adverse weather conditions were most likely to affect production. A total of 10 different locations were used (Figure 1), growing a range of crops including baby-leaf, lettuce, capsicums and chillies and eggplant (NT).

Figure 1. Locations of trial sites around Australia. Results are presented for protected cropping options from all sites except Darwin, where trials are ongoing.

Not all of the options proved successful. In some cases, the lack of a major weather event meant that there was no benefit from a structure. In others, the climate event was so severe the low cost option proved inadequate.

However, some results were positive results. Floating row covers, whether netting or spun-bonded polypropylene (frost cloth), proved to have benefits in a range of situations. Such materials are increasingly used in the UK and Europe. This means material costs are decreasing and mechanised systems are available to apply over large areas. As one of the least expensive options available, they would seem to have real potential for increased application in the Australian environment.

Methodology

Desktop review

The potential for low cost protected cropping of Australian vegetables was initially investigated through a desk-top review. Issues examined included the use of different materials for managing temperature extremes, excluding pests and protecting plants from damaging wind and rain. The review identified the protected cropping options that appeared to have the best potential for cost effective use by vegetable growers.

These recommendations were used to formulate the trials conducted in the following stages of the project. Regions selected included those at risk of climate extremes or which were limited by seasonal temperature growing restrictions. In most trials, air temperature and humidity were recorded underneath and outside the protective structure/cover. Crops were assessed for yield and quality, and in some cases, insect numbers were measured underneath row covers. Trials were grouped according to the protective material used and/or the purpose for protecting the crop.

Permanent shade houses and nets

Options assessed included hail netting, insect-proof netting and retractable roof Cravo® greenhouse. The effectiveness of these options at protecting crops from extreme weather events, insects and heat over summer were assessed. Temperature and humidity loggers were installed under and outside of existing structures and crop yield and quality was assessed at commercial harvest.

Yield was assessed for baby-leaf lettuce and spinach crops inside and outside shade structures. Harvested quadrants were weighed and their storage life assessed. Insect populations within the crop were estimated by vacuuming a measured area for a fixed time with a blower-vacuum.

In the case of capsicum crops, yield was assessed by strip picking plants at commercial maturity. Fruit were weighed and assessed for colour and marketability.

Table 1. Summary of trials examining permanent structures

Netting/structure	Location	Season	Crop
Hail net	Tolga, QLD	Summer 2014-15	Hydro-lettuce
Hail net and Insect Net	Stanthorpe, QLD	Summer 2014-15	Spinach
White / red shade netting	Bairnsdale, VIC	Summer 2014-15	Baby-leaf spinach
Shade netting	Carnarvon, WA	Summer 2014-15	Capsicum
Shade netting	Meadows, Adelaide Hills	Summer 2014-15	Non-crop
Cravo® house	Bundaberg, QLD	Spring 2015	Capsicum

Floating row covers for summer production

Floating row covers may be used during summer to protect crops from high temperatures, sunburn and insect pests as well as to reduce evaporation from both plants and soil. A range of different materials were evaluated for warm weather production of leafy greens in NSW and Victoria. These included netting materials such as InsulNet, VegeNet and fine weave Insect Net. A number of different non-woven spun-bonded polypropylene materials – often described as 'fleece' – were also tested. Even though fleece is primarily intended for cold weather protection, it provides a full barrier against insects while still being permeable to air and moisture.

Replicate units of each material were installed over freshly sown vegetable crops and the edges secured with shovelfuls of soil. Assessments included temperature, humidity and yield under the floating covers compared to the uncovered field. Harvested quadrants of babyleaf vegetables were weighed and their storage life assessed. Lettuces were counted or individually weighed. Insect populations within the crop were estimated by vacuuming a measured area for a fixed time with a blower-vacuum.

Table 2. Summary of trials on floating row covers for summer production of leafy vegetables

Netting	Location	Season	Crop
Insulnet, VegeNet, Groshield	Robinvale, VIC	Autumn 2015	Direct-seeded lettuce
Insulnet	Camden, NSW	Summer 2014-15	Direct-seeded baby spinach
VegeNet, Insect Net	Camden, NSW	Autumn 2015	Direct-seeded baby spinach
VegeNet, Insect Net, Fleece	Camden, NSW	Autumn 2015	Direct-seeded baby spinach
VegeNet	Werribee, VIC	Summer 2015-16	Cos lettuce
VegeNet, Fleece, Aphid Net	Bairnsdale, VIC	Summer 2015-16	Direct-seeded baby-leaf lettuce

Floating row covers for winter production

Whereas floating covers in summer are primarily applied to maintain soil moisture, prevent sun damage and protect crops from pests, during winter the same materials may be applied to raise temperatures around the crop and protect from harsh winter wind and rain. Fleece covers ranging from 17 to 50g/m^2 were tested in Werribee, Victoria and Camden, NSW. The covers were installed over freshly sown vegetable crops and the edges secured with shovelfuls of soil. Assessments included air temperature, soil temperature, humidity and yield under the floating covers compared to the uncovered field. Harvested quadrants were counted or weighed and their storage life assessed. Lettuces were counted or individually weighed. Insect populations within the crop were estimated by vacuuming a measured area for a fixed time with a blower-vacuum.

Table 3. Summary of trials on floating row covers for winter production of leafy vegetables

Netting	Location	Season	Crop
Fleece; Groshield, Elders	Werribee, VIC	Winter 2015	Cos lettuce transplants
Fleece; Groshield, Agryl, Elders fleece	Camden, NSW	Winter 2015	Direct-seeded oakleaf lettuce

Floating row covers for production of fruiting vegetables

Whereas the objective with leafy vegetables is to increase vegetative growth, treatments to increase fruit development may be quite different. Control of fruit fly presents a further challenge. Floating row covers were evaluated for production of capsicums in Silverdale, NSW and Bundaberg, Queensland. Nets were generally applied soon after transplanting or before fruit set. One trial also examined the effectiveness of VegeNet applied at different times during crop development.

Assessments included temperature, humidity, and presence of insects. Fruit fly ingress into the cropping area or under the nets was evaluated using Biotraps baited with cuelure wafers. In some cases, vegetative growth was recorded by weighing whole plants. Yield was estimated by strip-picking plants at various stages of maturity. Capsicums were then assessed in terms of weight, number, colour, overall marketability and pest damage.

Similar trials were conducted on chilli plants. Although the same species as capsicums, chilli fruit and plants are quite different. Control of fruit flies on chillies is particularly challenging. Trials examined use of netting materials to exclude fruit flies from chilli crops, as well as the effects on quality and yield.

Table 4. Summary of trials on floating row covers for production of fruiting vegetables

Netting	Location	Season	Crop
VegeNet	Silverdale, NSW	Summer 2014-15	Capsicum
VegeNet, Insect Net	Bundaberg, QLD	Autumn 2015	Capsicum
VegeNet, Fleece	Bundaberg, QLD	Winter/Spring 2015	Capsicum
VegeNet applied at flowering, fruiting and pre-harvest	Bundaberg, QLD	Summer 2015-16	Capsicum
VegeNet, Vent Net, Aphid Net	Silverdale, NSW	Summer 2015-16	Chilli
VegeNet	Bundaberg, QLD	Summer 2015-16	Chilli

All data was analysed using CoStat to determine significant differences between values.

Outputs

Presentations / workshops

Completed

Lindenow, Vic	9 September 2015	Reducing contaminants in leafy vegetables
Gatton, Qld	26 August 2015	Application of floating row covers to leafy vegetables, controlling contaminants in harvested vegetables
Cranbourne, Vic	11 September 2015	Reducing contaminants in leafy vegetables
Wanneroo, WA	2 October 2015	Application of floating row covers to leafy vegetables, controlling contaminants in harvested vegetables
Bundaberg, Qld	22 October 2014	Using netting to improve yield and quality of capsicum (district agronomists)
	21 November 2014	Using netting to manage fruit fly on capsicum crops (fruit fly forum)
	20 May 2015	Using fleece and netting to improve yield and quality of vegetable crops (district agronomists)
	9 December 2015	Using netting to manage fruit fly on capsicum crops (fruit fly forum)
Brisbane, Qld	25-27 June	National Hort Convention, low cost protected cropping options for vegetable growers
Cowra, NSW	26 April 2016	Netting and fleece for production of babyleaf vegetables

Ongoing

Darwin, NT	20 May 2016	Low cost protected cropping options for vegetables
Brisbane, Qld	23-25 June 2016	National Hort Convention, display and materials on low cost protected cropping options for vegetable growers
WEBINAR	July 6 2016	Low cost protected cropping options for vegetables
Werribee, Vic	11 August 2016	Farm walk Werribee, use of frost protection fleeces for vegetable crops
Sydney	October 2016	Using IPM in protected cropping – Physical barriers
Manjimup, WA	October 2016	Low cost protected cropping options for vegetables
Cairns, Qld	20-25 November 2016	Presentation at the International Symposium on Protected Cultivation in Tropical and Temperature climates (paper

submitted, Acta Hort publication in preparation)

Factsheets and articles

- 4pp page Factsheet – Managing insect contaminants in processed leafy vegetables: A best practice guide.
- 4pp Factsheet – Blankets for vegetables; Using frost cloths to protect plants from weather
- Vegetables Australia, April 2016. A touch of frost – Using 'fleece' for winter frost protection.
- 4pp Factsheet – Floating row covers for vegetables (under production)
- 4pp Factsheet – Physical barriers for fruit fly management in vegetable crops (under production)
- 2pp Factsheet – Shady vegetables; costs and benefits of different shade materials for production of vegetables (under production)

All information and materials generated by the project will be promoted and made available through the ICP project website and the AHR website. This is an ongoing communication activity that will continue over the next 12 months.

Outcomes

Desktop review

Increased climate variability is a threat to the viability of vegetable farms around Australia. Issues include

- More unpredictable weather
- Higher average temperatures and increased frequency of heat-waves
- Increased risk of unseasonal frosts
- Storms and strong winds
- Changes in rainfall patterns.

Shading with nets or screens can reduce crop damage caused by high temperatures. Floating row covers can reduce or increase temperatures, depending on the type of material used. They can help protect crops from mild frosts, prevent sunburn and protect crops from insects.

The low cost protected cropping options with best technical potential and economic feasibility were:

1. Shading screens or shade houses
2. Floating crop covers
3. Wind breaks

Permanent shade houses and nets

In these trials, netting had minimal effect on crop temperatures when used as a top-only over the crop. Adding sides restricts air movement, and can result in either an increase or decrease in temperature and RH, depending on the situation.

Although yield was unaffected by shading in these trials, it was noted that red shading resulted in darker leaf colour in baby spinach, while both white and red shade increased product shelf life. A hailstorm occurred in Stanthorpe during the trial period; although this did not affect the trial site itself, had it done so the netting system would have saved this crop while that in the field would have been unmarketable.

Capsicum plants grown in the retractable roof Cravo® house had at least double the growth, as well as large, dark leaves and a far healthier appearance than similar plants grown outside. In this case, capsicum crops grown in the open field nearby were destroyed by an extreme rainfall event, whereas those in the Cravo house were almost undamaged. Although initial yield assessments did not reflect the differences in plant size and health, had assessments been able to continue for the expected 9 month life of the crop, then large differences would likely have emerged.

Floating row covers for summer production

It had been expected floating covers could provide some shade, reducing sunburn and maintaining more even soil moisture, as well as reducing insect contamination in the crop. However, in these trials a number of issues were observed.

Sealing the nets proved an issue. While insect numbers were certainly reduced under the netting, insects were able to enter the crop through the open ends. The population of Rutherglen bugs was actually increased in one case, possibly due to these insects being protected from natural enemies by the netting. If prevention of insect contamination is a key objective, then nets must be securely fastened and left that way until harvest.

Weeds are often an issue in babyleaf crops, so thorough application of pre-emergent herbicides is essential. Where herbicide application was less than optimal, the warmer, moister environment under row covers increased weed seed germination and growth rates. It also made control more difficult. It is clear that effective weed control in beds prior to planting is essential if row covers are to be used.

One of the key benefits of netting materials on vegetable beds is that soil moisture is retained, reducing irrigation requirements. Although positive effects of floating covers on seed germination were observed in trials conducted during winter, these did not appear in the summer trial when conducted on a high organic matter soil with good irrigation coverage. This demonstrated that floating row covers are most likely to be of benefit if other crop production factors are suboptimal. That is, if crops are being grown in sandy soil and/or irrigation is infrequent or uneven.

None of these trials resulted in significant increases in yield or quality when leafy vegetables were grown under netting. While these materials can provide some protection from insects, wind and strong sunlight, none of these factors was a major issue during the trials, and in fact the negative impacts of nets were more significant. Use of netting materials during summer for leafy vegetable crops is therefore not supported by these results.

Floating row covers for winter production

All of the spunbonded polypropylene 'fleece' materials tested increased germination growth and yield of lettuces grown over winter. The fleeces significantly increased both air temperature and soil temperature, and slightly raised humidity around the crop.

The fleece materials also reduced the number of insects within the crop, which could affect both crop damage and contamination of packed product. It appears that the best strategy may be to use these materials over winter until air temperatures increase to a regular daytime maximum of approximately 20°C. After this time, they may be removed to allow the crop to 'harden up' and possibly develop a richer colour.

There were few differences noted between the materials, with the exception of the 50g/m^2 fleece, which gave less positive results. It is notable that the lightest materials – which are also the cheapest – gave just as good a result (if not better) as heavier fabrics.

Floating row covers for production of fruiting vegetables

Capsicum plants grown under VegeNet floating row cover had improved yield and better fruit quality. Floating row covers reduced the incidence of sunburn and could lower temperatures around the plants during hot weather by providing some shading. The results were best when the row covers were installed when plants were still young, with less significant gains when the covers were installed late in development.

Plant growth was also enhanced under fleece type materials. Although plant maturity was not brought forward by as much as had been hoped, fruit maturity was somewhat advanced under these materials. Durability was an issue, especially under the windy conditions common in Bundaberg.

Although difficult to measure, perhaps one of the most striking effects of both the fleece and the VegeNet was improved plant growth. Plants that were protected from strong light and wind had larger leaves and appeared generally larger and healthier, without the curled leaf edges and sprawling habit of plants that were grown in the open. While this did not always directly result in improved yields, it seems likely that healthy plants will be less susceptible to disease and more resistant to pest attack. By reducing losses of moisture from the soil, plants protected using floating covers are likely to need less irrigation, while all of the covers tested proved effective at deterring one of the most significant pests of capsicums, Queensland fruit fly.

The same effects, however, were not observed for chilli plants protected by fleece or netting. No increases in either yield or quality were observed for cayenne or birds eye chillies grown with floating covers. The large size of the plants and more frequent harvests also made use of floating covers more problematic for chilli production. The major benefit of using floating covers for chilli plants was protection from fruit fly. This is not insignificant, as control of fruit fly is particularly problematic on chillies, which are an excellent host.

Although the same species as capsicum, there are clear differences in the response to floating covers by these two crops. This demonstrates that the effectiveness of these materials cannot be generalized; each crop, situation and climate needs to be considered independently.

Evaluation and Discussion

While this project has involved a large number of trials of different materials, crops and environments, much remains unknown. For example, even the effects of a single product such as VegeNet varied between crops and environment. In some cases VegeNet reduced temperatures; in other situations temperatures increased; while under mild conditions there was often no change relative to the ambient air. Such variability may be due to factors such as sun strength, wind speed, soil temperature, relative humidity and the crop itself.

Moreover, although in some trials floating row covers increased yields, in other trials there was no effect or even negative impacts. If weeds were not controlled, or insects gained entry under the net, then the effects of floating covers could be distinctly negative.

The difference between capsicums and chillies is an example; both of these crops are *Capsicum annuum*, they vary only in terms of the cultivar and fruit size. Yet, the response of these crops to netting was distinctly different. The observed increases in yield and quality of capsicums did not translate to a similar effect on chillies. If anything, the effects on chillies were negative. The larger size of the chilli plants may be one factor, as these plants were partially constricted by the floating covers. However, other reasons for the different responses are unclear, and could be related to soil type or crop agronomy.

Floating row covers are most likely to be useful in somewhat marginal production environments. These include situations where temperatures are higher or lower than optimal, soil moisture is uneven, or pest pressure is difficult to manage by other means. So, floating row covers can increase germination of direct seeded lettuce in sandy soil with uneven watering, but are likely to provide little benefit in a high organic soil with a well managed irrigation system.

One of the best results gained during these trials involved the application of spun-bonded polypropylene fleece materials as floating covers during colder months. These materials were extremely effective at raising temperatures around the crop and in the soil. They could therefore allow production in areas that are otherwise unsuitable, or help bring a crop to market early in order to achieve premium prices (Figure 2). Perhaps most importantly, they can help protect the crop from extremes of weather, resulting in healthier, more resilient plants and good quality products.

It is interesting to note that the lightest – and cheapest – materials gave just as good a response as heavier weight fleece. This was not at the expense of durability; tearing and disintegration of the fleece was mainly a problem in the 50g/m^2 material, followed by those that weighed 30g/m^2. The lightest material presumably allows more air to flow through it, so by offering less wind resistance was least likely to tear.

Despite this, use of fleece in windy situations is likely to be problematic. Even the lightest fleece proved difficult to secure and tore easily in trial sites in Bundaberg.

Figure 2. Difference in size of lettuces grown during winter in Werribee in the open (L) or under fleece material.

Conversely, the heavy weight of fine weave nets is a significant impediment to their use. Even though these materials have potential to be an effective barrier against many insect pests, the difficulty of creating and maintaining a good seal around the edge can quickly render them ineffective. In addition, by increasing RH around plants, disease may be enhanced.

In general, the results suggest that floating covers that weigh more than 60 to 100g/m^2 can have negative, rather than positive, impacts on growth, depending on the crop in question. Suspending the net on a frame can overcome the issue of weight and restriction of the plants underneath. However, cloche hoops (see Ch.4 in Appendix 2 for details) were found to be too physically difficult, labour intensive and expensive to be a viable option for vegetables. Partial suspension using upended pots was also tested, but simply resulted in patchy growth and overall yield was not increased.

The floating row covers were very promising in alleviating the effects of extreme heat and cold in babyleaf spinach crops. There are more questions to be answered in relation to this crop group, and floating row covers should be evaluated more thoroughly on baby leaf crops and other leafy vegetables such as head lettuce and Asian greens.

The conflicting results with floating row covers on capsicums v's chillies also warrants further investigation. It is possible that regional differences in soils type and/or differences in crop management between the Qld capsicum trials and the NSW chilli trials could account for the different yield responses. We suggest the chilli trials are repeated in Bundaberg.

The impact on Queensland fruit fly control could be a major step forward in the management of that serious pest in capsicums and again requires more research.

Crop shading using more permanent structures has been widely reported to increase growth and yield of vegetable crops. However, the degree of shading must clearly be matched to light levels, particularly PAR (photosynthetically active radiation). If shading is too dark plants will become etiolated and weak and growth will be reduced. If too little shading is used then the cost of the structure will not be justified by improved productivity. Hail nets do clearly have some useful applications. Hail nets placed over crops such as hydroponic leafy Asian vegetables have produced excellent results in terms of yield, quality and shelf life. When the hail nets were brought to the ground these acted as a windbreak, further improving the growing environment and also reducing ingress of disease and insects (J Ekman, pers. com.). During this project hailstorms destroyed crops of spinach at Stanthorpe, damage from which the trial spinach crop under netting was protected.

The results showing the difference in leaf colour of plants grown under red netting could be of commercial significance; darker green colour could be regarded as an improvement in quality, while yield remained the same and shelf life was improved.

The results from the retractable roof Cravo® house were also very promising. The capsicums grown inside this structure were barely recognizable as the same species as the capsicums grown outside, even though the same variety was used (Figure 3). Plant health, size, vigour and commercially productive life were greatly increased using this system.

Figure 3. Capsicum plants in Bundaberg grown in the open field (L) or inside a retractable roof greenhouse. Seedlings were planted at approximately the same date.

While the Cravo® system is a relatively expensive 'low cost protected cropping' option, this relatively new technology is likely to be cost-effective for some higher value vegetable crops at least.

The trials of capsicums under retractable roof structures should be repeated as the plant growth improvement under these structures was not translated into higher yield, suggesting something like water or nutrient availability was limiting yield. This is quite possible, as the grower was new to the retractable roof structures, and may not have optimised the production system by the time of the trial, and these trials should be repeated.

In summary, the next steps should focus around a broader evaluation of floating row covers and retractable roof structures, both of which show considerable promise, but for which questions remain.

Recommendations

There remains much to be understood about the effect of different shading materials and floating row covers on crop growth.

Findings and issues that are worthy of further exploration include:

- Red netting for production of salad greens; effects on quality, yield and shelf life of a range of vegetable crops.
- Criteria for use of fleece materials – optimising application time, responses of different crops, temperature limits for effective use (high and low).
- The degree to which floating covers can reduce irrigation requirements of different crops, and the extent to which savings in power and water can contribute to the cost of establishment.
- Floating covers suitable for Australian conditions; the materials tested during these trials were sourced directly or indirectly from overseas suppliers. If these were designed for use in Europe they may not have sufficient UV-C stabilizer to protect them from Australian conditions.
- Issues with re-use / recycling / disposal of floating row cover materials. None of the materials tested was biodegradable. The fleece materials are certainly single use as they tear easily. While woven netting materials may be re-usable over several seasons, it seems reasonable that they need to be cleaned between uses to avoid spreading weed seeds, plant pathogens or other pests around different areas of the farm.
- The impact of floating row covers and shade materials on pest management practices. As these materials change the environment around plants, they favour some pests while potentially eliminating others. For example, fruit flies are excluded, while aphids and weeds may thrive. Nets can interfere with cover sprays, or may make them unnecessary for some pests. Implementing low cost protected cropping systems therefore means changing pest management practices. For example, the release of beneficial insects under covers may help control pests. Growers wishing to use floating covers or shading therefore need to understand what other procedures they need to change.
- Investigate the economics of floating row covers in leafy vegetables and capsicums, perhaps using a case study approach.
- Focussed studies on the use of floating row covers to control Qld Fruit Fly – this is potentially a major breakthrough in the management of this important pest.
- Broader trials on the usefulness of floating row covers on leafy vegetable crops to include more babyleaf crops, head lettuce and baby Asian greens.
- Repeat the floating row cover chilli trials in Qld.
- Repeat the Cravo® retractable roof trials now that the grower is more experienced in capsicum crop agronomy under the system to provide a more realistic assessment of the yield and quality differences between retractable rooves and the open field.

Intellectual Property/Commercialisation

No commercial IP generated

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- N River Rd Farm, Carnarvon
- Redgold Farms, Robinvale
- Riviera Farms, Bairnsdale
- Tableland Hydroponics, Tolga
- Werombi Farm Produce, Silverdale
- Young Sang & Co, Bundaberg

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	Emma Winley
	Marc Hinderager
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Bundaberg Fruit and Vegetable Growers	Bree Grima

	Patrick Logue
Primary Principles	Jeremy Badgery-Parker
Total Horticultural Consulting	Brad Giggins
Landcare NT	Caroline Biggs

Appendices

Appendix 1 – Review of low cost protected cropping for vegetables

Appendix 2 – Full report on all trials including

- Reviews of different technologies
- Summary of netting materials tested, trials completed and results
- Materials and Methods for each trial
- All data, results and analyses
- Conclusions

Appendix 3 – Selection of extension materials

An investigation of low cost protective cropping

VG13075

Review

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Prepared for

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July 2014

Weather data is taken from www.bom.gov.au and may include observations that have not been fully quality controlled.

Primary Principles Pty Ltd

info@primaryprinciples.com.au

www.primaryprinciples.com.au

1 Executive summary

Increased climate variability is a threat to the viability of Australian vegetable growers and to the industry more broadly[1]. The following weather events are already occurring more frequently, a trend that is predicted to increase:

- More variable weather
- Higher average temperatures
- Heatwaves
- Greater risk of frost (wider frost window)
- More frequent extreme events

Retail markets don't care about weather; they want fresh produce supplied at a consistent quantity and quality all year round. It is left to the growers to manage weather variability, and somehow deliver, irrespective of conditions.

Australian vegetable growers have always had to deal with a variable climate — it is their "stock and trade", and they do it well. Growers have some tools available to deal with variability, and one of those is low cost protected cropping to help growers manage risk.

Growing vegetable crops in a protected environment offers a level of insurance against adverse impacts of extreme events, e.g.

- Shading can reduce crop damage caused by high temperature extremes
- Floating row covers can reduce temperature, protect from frost and also help with the control of insects.

This review is part of a broader project funded by Australian vegetable growers and HAL. It reviews the currently available low costs technology available, describes the function of each, assess the technical and economic feasibility of the different technologies to reduce risk in ten major vegetable growing areas across Australia.

Conclusions

The three type of protected cropping with greatest technical potential and economic feasibility to manage risk and improve financial returns within a five-year period are:

- shading screens or shade houses
- floating crop covers
- windbreaks

In all regions, current and projected near future summer daytime temperatures, especially the one in five year extremes, exceed upper thresholds for most vegetable crops reviewed

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[1] Rogers G. and Montagu K. (2013) Understanding and managing impacts of climate change and variability on vegetable industry productivity and profits VG12041

from autumn through to spring. Expected impacts on yield from high temperatures could be between 20% and 50%[2].

Shade canopies appear to be the best medium term low cost protected cropping (LCPC) option for all the vegetable production in many regions assessed, except Devonport. A 50% shade can be expected to reduce maximum temperatures by up to a 6°C. Shade cloth, insect netting and plastic cladding can all be used to reduce light transmission. Indicative benefit-to-cost ratio for shade canopies is up to 3:1.

Floating covers are likely to be a suitable LCPC option for crop establishment and transition seasons for low growing crops. It is unclear whether row covers will increase day maximum temperatures or not, with contradictory reports in the literature. It will be important to measure the actual temperatures under the covers during summer, in the second phase of the project.

Floating covers are likely to be appropriate for the dual benefits of increasing minimum temperatures (ie frost control) and excluding pests in transition seasons, especially for leafy vegetables.

The row covers are also likely to increase the quality and consistency of leafy crops. The indicative benefit-to-cost ratio is 2:1 for growing conditions and 3:1 for pest exclusion.

Windbreaks could provide local benefits to all regions where they are not already being used, and a complementary and protective aspect for other LCPC options. Feasibility indicator points suggest that wind protection could have a benefit-to-cost ratio of 12:1 in sites with prevailing moderate to strong wind.

Net houses are generally not suitable due to restricted air flow.

There is potential to improve shade and net houses with engineered ventilation, however this is not considered within the LCPC context of this review.

Fogging could be used to provide an evaporative cooling benefit in hot, dry locations. It could be added to a shade structure.

Rainshelters, tunnels and cloches are unlikely to be suitable. Rainshelters are suitable in wet tropics but present limited benefit for the example vegetable crops and the drier climate of Australia. Low profile greenhouses and cloches are unlikely to be suitable LCPC options because of adverse impacts, particularly from excess heat.

An overview of the suitability of the various protected cropping elements as low cost protected cropping options for Australian vegetable growers are summarised below.

[2] G. Rogers (2013) Understanding and managing impacts of climate change and variability on vegetable industry productivity and profits, Final report VG12041

Suitability of the various protected cropping elements as low cost protected cropping options for Australian vegetable growers

	Shade canopy	Shadehouse	Fogging	Rainshelter	Low profile greenhouse and/or cloche	Floating crop cover	Windbreak
Manjimup	✓	☑				✓	✓
Murray Bridge	✓	☑	✓				
Werribee	✓	☑	✓			✓	
Hay	✓	☑	✓				
Devonport						✓	✓
Gatton	✓	☑				✓	
Bowen	✓	✓				✓	
Carnarvon	✓	✓				✓	✓

Note: Boxed tick indicates that the option may be suitable in some local condition/crop situations

Technical suitability of LCPC options in addressing the five target factors.

	Shade canopy	Shadehouse	Fogging	Rainshelter	Low profile greenhouse and/or cloche	Floating crop cover	Windbreak
High temperatures	✓	☑	✓	✓			☑
Frost and low temperatures	✓	☑	✓	✓	✓	✓	☑
Extreme weather	✓	✓		✓	✓	✓	✓
Impact of light	☑	☑		☑	☑	☑	
Pest exclusion		✓			✓	✓	✓

Note: The boxed ticks indicates that option may have unreliable effects depending on situation and conditions

Recommendations

The review makes the following recommendations:

1. ***Shade canopies*** should be field tested and performance monitored with a full economic evaluation conducted at locations such as Carnarvon (WA), Murray Bridge/Virginia (SA), Mildura/Dareton – Hay (Vic/NSW), Werribee/Gippsland (Vic) and Bowen (Qld).

   A shade level of 50% (30% and 70% as extra options) should be considered. Retractable versus fixed shade. Addition of fogging could also be considered under shade canopy.

Target benefits: Increasing reliability of supply by minimising the effects of temperature extremes, improved water use, longer production season and improved quality.

2. ***Floating crop covers*** be field tested and performance monitored and have a full economic evaluation conducted for locations such as Manjimup (WA), Murray Bridge/Virginia (SA), Mildura/Dareton – Hay (Vic/NSW), Werribee/Gippsland (Vic) and Gatton (Qld).

Target benefits: Increasing reliability of supply by minimising the effects of temperature extremes, earlier and longer production season, insect control and improved quality.

3. ***Windbreaks*** be field tested and performance monitored and have a full economic evaluation conducted for locations such as Manjimup (WA), Murray Bridge/Virginia (SA), Mildura/Dareton – Hay (Vic/NSW), Werribee/Gippsland (Vic) and Gatton (Qld).

Target benefits: Reducing wind damage, reducing water stress during hot, dry windy conditions, pest and disease management.

4. Develop ***economic feasibility indicators*** for a number of the protected cropping options. This could include longer payback period options, and would help growers to make informed decisions about whether or not to invest in LCPC for a given location and crop.

2 Introduction

2.1 Managing production and marketing risk

Climate related risks have always been a part of agriculture, and both management and marketing practices have been developed and implemented to deal with these challenges. However, the economic imperative to consistently and reliably meet market (buyer) demands coupled with tighter profit margins is increasing the pressure to better manage risks associated with unfavourable growing conditions and occasional extreme weather events, and to prepare for a projected increase in periods of adverse weather during primary growing seasons resulting from a changing climate.

Farm profitability is increasingly dependent on greater regularity in production — both in yield and quality. Product consistency and reliability of supply attract better marketing arrangements and lower costs of selling. Adverse weather conditions reduce growth rates, plant productivity, and crop and product uniformity, while increasing production costs. This increases production and marketing risks.

A broad range of systems are used throughout the world to modify growing conditions. Simple structures lessen the negative effects of specific or seasonal weather extremes and/or pests, more complex systems address numerous environmental constraints of production, and technology intensive systems maintain optimal growing conditions year round.

Protected cropping involves the application of structures, materials and technologies (with appropriate practices) to address a range of issues in the growing environment. It uses artificial structures such as greenhouses (polyhouses and glasshouses), shade houses, screen houses, crop canopy (crop-top) structures and crop covers, and various technologies to influence temperature, humidity and light as well as soilless (hydroponic) growing systems[3].

Protected cropping (PC) can be defined as the production of horticultural crops within, under, or sheltered by artificial structures and/or materials to provide and/or enable modified growing conditions and/or protection from pests and adverse weather. It offers a technological response to adverse growing conditions and is successfully being used to secure reliable production of high quality vegetable products throughout Australia and globally.

The infrastructure costs of protected cropping systems can pose a significant barrier to investment for some farm enterprises.

Low cost protected cropping (LCPC) is a relatively new term that has evolved to define a subcategory of protected cropping which can fill the gap between open field production and controlled environment systems to manage key production risks.

[3] http://www.primaryprinciples.com.au/primaryprinciples_faq1.html

2.2 Defining low cost protected cropping

Low cost protected cropping is a deliberate strategy to address a single (or limited number of) key production factors using one or more protected cropping elements. As a subcategory of protected cropping, LCPC has the distinct objective of a short payback period (less than five years) with minimised capital investment achieved by focussing on a limited objective or factor in the growing environment. A controlled environment is not the intention of an LCPC approach.

The smaller capital investment has been a key driver for adoption of LCPC in developing countries. The use of LCPC can also represent a 'limited risk' step towards investing in more comprehensive protected cropping (PC), and ultimately, controlled environment systems.

Figure 1 presents the concept of LCPC as a subcategory of protected cropping [Figure 1][4].

2.3 Determining suitability

The intention of this review is to investigate the suitability of protected cropping elements as low cost options for field vegetable production in a selection of regions. Temperature is considered the principal production factor due to its impact of current conditions for crop development as well as the projected near term effects of climate change.

The second factor that determines the suitability of protective systems is the impact on light levels. Any structure installed near or above a crop will affect the availability and even quality of light accessible to the crop. (Excess light can be a negative production factor for some crops.)

Water availability is a significant production issue throughout Australia. High temperatures and associated evapotranspiration rates, and the existing as well as projected increase in variability in rainfall in many regions, makes crop water use important. Irrigation efficiency and water use efficiency are important in

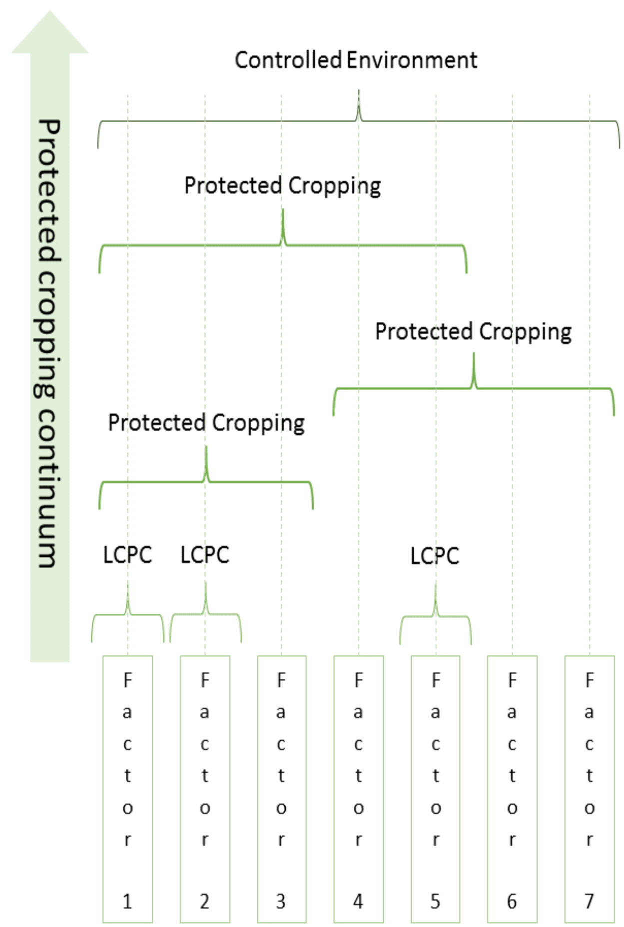


Figure 1: Protected Cropping is a continuum representing different degrees of influence over the growing environment from single factor low cost protected cropping through to fully controlled environments.

[4] http://www.primaryprinciples.com.au/primaryprinciples_low_cost_protected_cropping.html

sustaining a horticultural enterprise and can be influenced with protective systems.

A fourth factor that can inform the suitability for protected cropping is the impact of severe weather. Heavy rain, strong winds, and hail are reasons to provide crop protection. Severe weather events are generally projected to increase as an effect of climate change and this can alter the risk management assessments of vegetable farms.

Finally, pests are also an important production factor that informs the suitability of a protected cropping element.

All these factors interrelate, and the suitability of a protected cropping element should be assessed on the accumulative benefits and impacts on crop production and the economic implications.

The technical suitability of protected cropping elements is matched with environmental factors then a selection of single benefit-to-cost scenarios is used to create indicator points as to likely feasibility. This defines the recommendations for further assessment.

3 What can protected cropping achieve?

There are a multitude of factors in a growing environment that may be modified or mitigated with the use of protected cropping — protective structures, technologies and appropriate practices. The number of factors being addressed reflects the level of protected cropping and is typically proportional to the investment and/or operating costs. Low cost protected cropping (LCPC) focuses on just one or a few factors, while controlled environment systems aim to influence all factors. Depending on the situation, the resources available and the enterprise objectives, protected cropping can encompass a wide range of approaches.

Temperature, humidity, light, carbon dioxide concentration, and nutrient and water supply can all be modified with protective structures, materials and technologies. Planting periods, harvest periods and harvest duration can also be influenced. The impacts of adverse and extreme weather conditions, pests, diseases and weeds can be lessened through protective production systems that reduce plant stress, contain crop losses or improve product quality by reducing damage and/or contamination.Protected cropping can facilitate the production of specific or specialised crops in situations where they otherwise could not be grown.

For this reason, it is important to clearly define the objectives the protected cropping (including LCPC) system is aiming to achieve. Secondary effects of protective structures also need to be identified and considered as all factors in a growing environment are closely interrelated and any intervention to address one factor can have repercussions elsewhere.

3.1 Types of low cost protected cropping structures

There are several types of low cost protected cropping structures. The structure must:

- focus on a primary or specific production constraint
- require a comparatively small investment (that is, be low cost) and therefore facilitate a short payback period
- generate a suitable growing environment for target crops.

Although there can be significant variation in design, materials and costs within a category, protected cropping structures can be grouped as greenhouses, low profile greenhouses (tunnels), screenhouses, canopy (crop top) systems, cloches, floating covers (fleeces) and windbreaks. Portable or moveable structures can provide more versatile and therefore more suitable options in some circumstances.

3.1.1 Greenhouse

A greenhouse is an enclosed structure clad with a material that permits light to enter but restricts the movement of air and moisture. A basic greenhouse can be a feasible low cost option. Tunnel structured greenhouses (described below) tend to be used as a cheaper entry point into protected cropping.

Greenhouses per se are not generally considered an LCPC option, and although in some circumstances they may provide an appropriate low cost fit in an enterprise, this category of protective structures is excluded as an LCPC option in this review.

Greenhouses

3.1.2 Low profile (tunnel) greenhouse

Tunnels are low profile greenhouses that are also known as hoop houses, cold frames, igloos or quonsets. These are semi-circular or dome shaped structures 2 to 3.5 metres high at the highest point with plastic cladding material over a simple frame. Low profile greenhouses are often an entry point for growers into protected cropping.

This type of structure can be used to modify several elements of a growing environment. The most common applications include increasing temperatures and providing protection from rain, hail and pests. Tunnels can protect from frosts, snow and storms, modify the light spectrum and extend a growing season.

Table 1: Benefits and limitations of low profile greenhouses.

Production constraint addressed	Limitation
Low temperatures	High temperatures
Low humidity	Excess humidity
Excess or heavy rain	Insect pests
Frost	Diseases
Storms and strong wind	Condensation
Hail and snow	Insufficient radiation (light)
Cold soils	Poor light quality
Excess radiation (light)	Poor airflow
Poor light quality	Equipment access
Insect pests	Reduced production area
Vertebrate pests	Poor pollination
Excess evapotranspiration rates	

Along with the advantages of using tunnels, there are also some significant limitations, depending on the crop and situation. Tunnels can readily overheat and produce high humidity conditions generating unsuitable growing environments.

A range of improvements can be made to tunnels to recover the growing environment, but these structures can be readily over-capitalised, with growers facing rapidly diminishing returns on investment. Venting capacity is generally the main modification worth considering but needs to be appropriate to the situation in which it is being used.

Tunnels are a useful LCPC option. They will not, however, provide a benefit in terms of adaptation to increased temperatures, and will exacerbate problems arising from extreme daytime temperatures and heat wave conditions. Low profile greenhouses would however offer a reasonable strategy for mitigating an extended frost window and protect from heavy rain and storm events.

A portable or moveable tunnel structure could offer a more versatile option, though at a higher cost.

Low profile greenhouse

Cucumber under low profile greenhouse

3.1.3 Screenhouse (shadehouse, nethouse)

A screenhouse is a fully enclosed structure. It is similar to a greenhouse but has a covering material that is permeable to air and moisture, such as shade cloth (known as shadehouse) or insect screening (known as screenhouse or nethouse).

Screenhouses can be used to modify several elements of a growing environment in a similar way to a greenhouse, and are commonly seen as alternatives to greenhouses in warm to hot climates. The most common application of a screenhouse is to reduce daytime temperatures through shading.

Shadehouse vegetables in NT

Screenhouses are commonly used to protect from wind and exclude pests. They can protect from frost[5], hail and heavy rain, reduce solar radiation/light levels and exclude vertebrate pests. A screenhouse will also maintain higher minimum temperatures by intercepting radiation from the cropping area and through reduced rates of air exchange which can provide a strategy for mitigating frost.

The reduced light levels resulting from the screening material can impose significant limitations when ambient radiation levels are low.

To effectively exclude pests, screening material must have a pore size appropriate to the smallest target pest. Pore size affects airflow through the material, which impacts internal temperature and humidity.

[5] M. Teitel, U. Peiper and Y. Zvieli (1996) Shading screens for frost protection. *Agric. For Meteorology* 81:272–286

Table 2: Benefits and limitations of screenhouses.

Production constraint addressed	Limitation
Low temperatures	Excess heat
Extreme high temperatures	Excess humidity
Low humidity	Insufficient radiation (light)
Heavy rain	Light quality
Frost	Insect pests
Strong wind	Diseases
Hail	Insufficient airflow
Excess radiation (light)	Low transpiration rate
Light quality	Condensation
Insect pests	Cooler soil
Vertebrate pests	Equipment access
Weeds	
Excess evapotranspiration rates	

3.1.4 Crop canopy

A crop canopy, also known as a crop-top structure, consists of a covering material suspended (usually at height) over a large cropping area while the sides remain open. Materials used depend on the desired protective element and include plastic (known as a rainshelter), shadecloth, hail-net and bird-net.

Crop canopies can be used to modify several elements of a growing environment. The most common applications include shading to reduce daytime temperatures, or providing protection from rain, hail or birds. Crop canopies can protect from frosts, snow and storms, and modify the light spectrum.

In contrast to screenhouses and low profile greenhouses, crop canopy structures avoid much of the problem of the build-up of excess heat. With open sides, airflow through the cropping area is less impeded so while the canopy can reduce incident radiation (and/or rain), ventilation is maintained. This reduces temperatures under extreme conditions without creating unsuitable conditions at other times.

While there are advantages to using canopies, reduction of light levels can impose significant limitations when ambient radiation levels are low.

Table 3: Benefits and limitations of crop canopies.

Production constraint addressed	Limitation
Extreme low temperatures	Insufficient radiation (light)
Extreme high temperatures	Poor light quality
Excess humidity	Insect pests
Excess or heavy rain	Diseases
Frost	Condensation
Storms and strong wind	
Hail	
Snow	
Excess radiation (light)	
Poor light quality	
Vertebrate pests (birds)	
Excess evapotranspiration rates	

Lettuce (hydro) under shade canopy

3.1.5 Cloches

A cloche, also known as a low tunnel, is a semi-circular or dome shaped structure less than 2 metres high at the highest point. A cladding material, usually a net or fine plastic, is fastened over a simple or light frame.

Cloches are commonly used to increase minimum temperatures or provide protection from rain, frost or pests. They can increase humidity, raise soil temperature (enabling earlier planting), create shade and modify the light spectrum. The cladding material used will have a direct impact on the internal environment and —similarly to screenhouses and low profile greenhouses— a reduction in airflow will result in temperature and humidity exceeding suitable levels under some ambient conditions. Available carbon dioxide could also become a limiting factor.

Cloches can be used as portable structures, delivering many of the benefits while avoiding some negative impacts. Early crop establishment achieved through warmer soil and frost protection are key opportunities as well as providing protection from heavy rain and pests.

Net cloche

Plastic cloche

Table 4: Benefits and limitations of cloches.

Production constraint addressed	Limitation
Extreme low temperatures	High temperatures
Cold soils	Insufficient radiation (light)
Low humidity	Poor light quality
Excess or heavy rain	Insect pests
Frost	Diseases
Storms and strong wind	Condensation
Hail and snow	Poor equipment access
Excess radiation (light)	Poor access to crop
Poor light quality	Poor airflow
Insect pests	Poor pollination
Vertebrate pests	Increased labour costs
Excess evapotranspiration rates	

3.1.6 Floating crop cover

Floating covers (also known as fleeces and nets) are lightweight, permeable materials that are lain over a crop without a supporting structure.

Floating covers can be used to modify elements of a growing environment with the most common applications being to increase minimum temperatures and/or provide protection from frost and pests. Fleeces can help increase humidity, raise soil temperature, reduce the impact of heavy rain and provide shading.

Crop covers have been shown to increase the growth of cucumber by reducing wind speed, and preventing desiccation and physical abrasion. However, in very strong winds, the covers can damage growing points. Floating crop covers can be used to protect against pests though there is a danger of pests overwintering in the ground.

If pests get into the covered area and breed, they can be more difficult to manage than if there was no covering. Weed control can also become a problem.[6]

[6] O. Wells and B. Loy (1993) Rowcovers and high tunnels enhance crop production in the North-eastern United States. Production and Marketing report. *HortTechnology* 3(1):92-95

Floating crop cover

Production constraint addressed	Limitation
Extreme low temperatures	High temperatures
Cold soils	Excess humidity
Low humidity	Insufficient radiation (light)
Excess or heavy rain	Insect pests
Frost	Diseases
Storms and strong wind	Condensation
Hail and snow	Poor equipment access
Excess radiation (light)	Poor access to crop
Insect pests	Poor airflow
Vertebrate pests	Poor pollination
Excess evapotranspiration rates	

Table 5: Benefits and limitations of floating covers.

As with other enclosing structures such as screenhouses and cloches, floating crop covers reduce airflow and intercept radiation thus producing some of the desired benefits, but also creating limitations under some ambient conditions. Similarly to cloches, floating covers can be used as portable structures, to deliver many of the benefits while avoiding some negative impacts. Covers can help with early crop establishment through warmer soil and frost protection, and provide protection from heavy rain and pests.

3.1.7 Windbreaks

Windbreaks should be considered an LCPC option where strong wind and/or high evapotranspiration rates are experienced. Trials of various crops have shown that windbreaks can increase yield. Strong, hot winds increase evapotranspiration, causing moisture stress. Cold, dry winds cool the soil and plants, slowing growth and delaying crop maturity. Wind also reduces the activity of insect pollinators.

Wind can affect plants directly and indirectly. Air movement influences transpiration as well as evaporation from the ground surface. Strong winds can directly damage plant structures and also influence evapotranspiration rates and plant growth rates. Vegetables generally have a low tolerance to wind compared to other plants[7]. Wind speeds greater than around 14 $km.h^{-1}$ can have physiologically harmful effects on many vegetables[8]. Strong winds can physically damage plant tissues particularly through lodging and stripping of leaves, flowers and fruit. Wind speeds above 40 $km.h^{-1}$ have been shown to desiccate vegetable crops and cause physical damage from sand and grit hitting the plant tissues[9]. Abrasion and 'sandblasting' of crops can occur when wind blows dirt through a cropping area. Windbreaks can reduce the incidence of broken stems, stripped leaves and lodging of plants. It is also likely that wind can increase the carriage and spread of pests and diseases into and within crops.

Specific data on the impacts on yield attributed to wind damage is scarce, though anecdotally it is always considered to have an impact. Trials in Nebraska found that capsicum yields doubled, melon yields increased 70% and cabbage yields were up to 18% higher in crops that were protected from wind[10]. In other trials, yields of snapbeans increased 37% and tomatoes rose 30%[11] when wind speeds are reduced in the cropping area.

Lettuce under net shadecloth windbreak

[7] S. Finch (1988) Field windbreaks. Design criteria. *Agriculture, Ecosystems and Environment* 22:215-228

[8] C. Baldwin (1988) The influence of field windbreaks on vegetable and speciality crops. *Agriculture, Ecosystems and Environment* 22:191-203

[9] J. Dainello and R. Roberts Texas Vegetable Growers' Handbook, accessed online: https://aggie-horticulture.tamu.edu/vegetable/guides/texas-vegetable-growers-handbook/chapter-iv-cultural-practices/

[10] L. Hodges and J. Brandle (2006) Windbreaks for fruit and vegetable crops. EC1779. University of Nebraska.

[11] W. Bagley and A. Gowen (1960) Growth and fruiting of tomatoes and snapbeans in the shelter areas of a windbreak. Proceedings 5th World Forestry Congress 3:1667-1670

Table 6: Benefits and limitations of windbreaks.

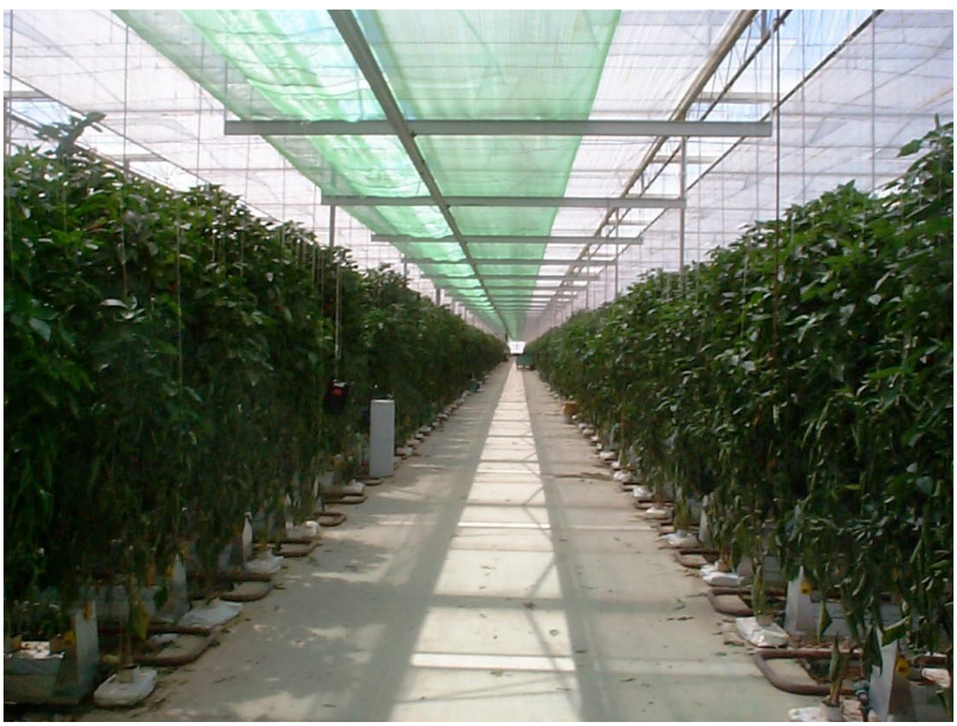
Production constraint addressed	Limitation
Storms and strong wind	Reduced airflow
Excess evapotranspiration rates	Reduced pollination
Insect pests	Pest habitat
Disease	Increased temperature
Physical damage	Reduced transpiration

3.1.8 Moveable structures

Portability of structures can be considered an LCPC option, though adding portability usually increases costs. Cloches and floating crop covers are ordinarily considered to be portable because of their light and simple characteristics. They can be moved into and out of a production area as required.

Plastic tunnels and other structures such as screenhouses and crop canopies can all be made moveable to better manage negative impacts of temperature and light during the cropping period.

Retractable covers and screening materials offer a versatile protected cropping element. Automated retractable rooves and screens in greenhouses are relatively expensive and would generally exclude this as an LCPC option but the capacity to retract screens in a screenhouse and crop canopy can offer a flexible lower cost protected cropping strategy.



Capsicum under retractable shade

3.1.9 Fogging systems

Technologies, as well as structures can address key production issues or enhance control in the growing environment. Fogging is an element commonly installed in greenhouses to provide additional cooling and humidity control. It could be utilised as an LCPC option to offset adverse growing conditions in the field.

Fogging systems deliver a micro-mist of water above the cropping area which is evaporated to create a cooling effect. The amount of cooling attained is dependent upon the air temperature and particularly the relative humidity of the air (Table 7). This element could provide a significant opportunity in mitigating excess heat. It can potentially be installed on its own or in conjunction with a screenhouse or crop canopy structure. Wetting of a shading screen such as with misting can double the cooling benefit of the screen[12].

Table 7: Potential cooling effect of a fogging system. Example illustrated: At an air temperature of 30°C and a relatively humidity of 67%, 5°C cooling could be attained.

Air temp. °C	Potential cooling effect in degrees (°C) at different levels of relative humidity (%)																			
	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10
10	94%	88%	82%	77%	71%	65%	60%	54%	49%	44%	39%	34%	29%	24%	19%	14%	9%			
15	95%	85%	85%	80%	75%	71%	66%	61%	57%	52%	48%	44%	40%	36%	31%	27%	24%	20%	16%	12%
20	96%	87%	87%	83%	78%	74%	70%	66%	62%	59%	55%	51%	48%	44%	41%	37%	34%	30%	27%	24%
25	96%	88%	88%	84%	81%	77%	74%	70%	67%	63%	60%	57%	54%	50%	47%	44%	41%	38%	36%	33%
30	96%	89%	89%	86%	83%	79%	76%	73%	70%	67%	64%	61%	58%	55%	52%	50%	47%	44%	42%	39%
35	97%	90%	90%	87%	84%	81%	78%	75%	72%	70%	67%	64%	61%	59%	56%	54%	51%	49%	47%	44%
40	97%	91%	91%	88%	85%	82%	80%	77%	74%	72%	69%	67%	64%	62%	60%	57%	55%	53%	51%	48%

[12] D. Willits and M. Peet (2000) Intermittent application of water to an externally mounted greenhouse shadecloth to modify cooling performance. ASAE 43(5):1247-1252

Retractable shade and fogging

3.2 Managing climate extremes with protected cropping

Weather impacts vegetable crops and can affect crop productivity and quality. Protected cropping elements can be used to modify or mitigate a range of factors. The more common applications of protective structures include influencing temperature, reducing radiation (light), lowering wind speed, protecting crops from heavy rainfall, frost, hail (and snow) as well as pest exclusion.

Although there has been significant research into the technical performance and technology of greenhouses, the awareness and research into low cost protected cropping elements is much more limited. To develop a clearer understanding of the scope of LCPC for Australian vegetable enterprises, five factors previously identified[13] as likely challenges for the industry – currently, and as a result of a changing climate – will form the context for reviewing what LCPC options could offer.

Screenhouses and floating crop covers are already commonly used internationally as protected cropping alternatives to greenhouses. A key challenge for Australian vegetable growers is the use of protected cropping technologies as a low cost option on a relatively large production scale.

More frequent and longer heatwaves as well as a larger frost window have been identified as the primary production issues resulting from climate change that are likely to occur across key vegetable growing regions in Australia[10]. Management of crop water use is another issue that derives from the increase in extreme temperature, predicted variability in rainfall and subsequent extended dry periods. More frequent and severe storm events

Target factors:

1. Excess heat
2. Frost and low temperatures
3. Crop water use
4. Extreme weather
5. Pest exclusion

[13] G. Rogers (2013) Understanding and managing impacts of climate change and variability on vegetable industry productivity and profits, Final report VG12041, AHR

(including strong wind, heavy rain and hail) can also significantly impact the vegetable industry.

The incidence and/or range of some pests may also be impacted by changes in the climate and warrants consideration in the application of protected cropping structures.

3.2.1 Managing high temperature

Temperature is an extremely important factor in all aspects of horticultural production. All crops have a temperature range within which they can survive, grow actively and produce. Conditions above and below this temperature range constrain crop productivity and can negatively impact the growth, yield and health of a plant.

Increasing daytime temperature is one of the most certain outcomes identified in climate change modelling, as well as more frequent and extended heatwaves[14].

Screening materials and plastic cladding can be used to reduce incoming solar radiation levels. Air, soil and leaf temperatures can all be lowered by screening. Plastic cladding used on low profile greenhouses, cloches and rain shelters reduces light levels. Generally, a greenhouse cladding is selected for high light transmission for a given budget and cropping situation, while screening materials are designed to reduce light transmission.

Plastic cladding typically reduces incident radiation by 15 to 45% and impacts the total energy reaching the crop and ground surface within the structure. However, the accompanying restriction of airflow in such a structure reduces the rate at which heat energy can escape and so generates the warmer growing environment associated with a greenhouse.

Some plastic films are being developed with particular properties, for example specifically reflecting or absorbing infrared radiation. This reduces temperature under the cover, with a greater impact during hot sunny conditions when it is most needed. While specialised films are typically more expensive, the use of plastic cladding material such as a rain shelter as a composite rain protection and shading strategy to reduce temperatures could lower costs.

Screens can be broadly grouped as shade, insect and energy (thermal) screens. Shade screens are typically knitted or woven. The tightness (porosity) of the fibres determines the level of light transmission (degree of shading) and air restriction. There is a broad range of colours which impact the proportion of light reflected, transmitted and absorbed. Insect screens are especially fine materials designed to prevent entry of insects of specific body sizes. The finer the screen, the greater the range of insects that are excluded and the higher the restriction to air flow. Thermal screens are designed to reflect rather than absorb more of the radiation. The porosity of the energy screen influences the level of light and energy transmission and air flow.

A study in Hawaii found that a 15% shading reduced maximum air temperature by 1°C and did not affect minimum temperature[15]. Product claims for a 52% shading polyester

[14] G. Rogers (2013) Understanding and managing impacts of climate change and variability on vegetable industry productivity and profits, Final report VG12041, AHR

[15] X. Wolff and R. Coltman (1990) Productivity of 8 leafy vegetable crops grown under shade in Hawaii. *J. Amer. Soc. Hort*. Sci 115(1) 182-188.

diffusing screen suggest that air temperature is reduced by close to 2°C while plant temperature decreases by 8 to 10°C with ambient conditions of full sun (up to 1000 W/m^2) and 31 – 32°C. Without a screen under these conditions, plant leaf temperature was 6 to 8°C higher than air temperature. The screen reduced air temperature by around 4°C and plant temperature dropped 8°C[16].

During cloudy and low light conditions, the temperature of the plant is similar to the air temperature, however in bright sunlight, plant leaf temperature can be up to 12°C warmer than the air[17]. Plant leaf temperature has a direct effect on transpiration and the rate of photosynthesis and in this regard, is more important than air temperature. In warm to hot conditions under full sun, plant leaf temperature could be reduced by 8 to 10°C with 30 to 50% shading.

Although quite significant temperature reductions are possible with shading, the cooling effect is influenced by the ambient conditions of temperature, humidity and insolation, sources of radiant heat, evapotranspiration levels in the cropping area and amount of air movement. A 30 to 50% shading could be expected to offer at least a 4 to 6°C reduction in temperature in warm to hot conditions, under full sun.

However, a proportion of light energy is converted to heat when it is absorbed by materials and surfaces. This heat can then be re-radiated to surrounding objects and the air. Screening materials will reflect, absorb and transmit varying proportions of radiation depending of the type of material, the colour and its porosity. Colour is a primary determinant of net transmittance and absorbance, with porosity being the second key element[18]. Wetting of shading materials can double the cooling benefit of a shade screen[19].

Absorption and re-radiation of heat from screening materials can reduce the net cooling benefit of shading in some situations. Black knitted shadecloth rated 60% shade has been found to provide no cooling benefit in a greenhouse, while reflective materials showed a 30% decrease in heat gain in a greenhouse[20]. In other trials, shadecloth has been found to generally be about 50% efficient in terms of the shade rating. Trials have shown that a material with a nominal shading effect of 50% reduces temperature by 25%[21]. These studies used black shadecloth and concluded that a primary reason for this inefficiency is that a proportion of the intercepted energy is absorbed by the material and this energy is then radiated as heat into the cropping area.

Brighter colours transmit and reflect more light than dark colours though colour will also impact the level of photosynthetically active radiation (PAR) transmitted. In one study investigating the impact of different colours of shade nets (40% nominal shading), red net resulted in almost 60% transmittance of PAR compared with no net; pearl-coloured net transmitted 53.6%; while black shade net resulted in 52.5% of PAR being transmitted to

[16] Svensson product information. Based on trials using 'SLS 50F Harmony' in Almeria, Spain. Ludvig Svensson.
[17] J. Badgery-Parker and L. James (2010) Commercial greenhouse cucumber production. NSW Department of Primary Industries
[18] I. Al Helal and A. Abdel-Ghany (2010) Responses of plastic sheeting nets to global and diffuse PAR transfer: optimal properties and evaluation. Elsevier 57(2) 125-132.
[19] D. Willits and M. Peet. (2000). Intermittent Application of water to an externally mounted greenhouse shade cloth to modify cooling performance. NSCU. ASAE 43(5):1247-1252.
[20] D. Wittis Research Summary, NCSU. Accessed online (2014): http://www.bae.ncsu.edu/people/faculty/willits/res_sum.html
[21] D. Wittis Research Summary, NCSU. Accessed online (2014): http://www.bae.ncsu.edu/people/faculty/willits/res_sum.html

the crop[22]. Black shade cloth will produce lower transmittance overall, but have proportionally less impact on transmittance of PAR[23]. Dark colours and decreasing porosity result in a greater level of absorption. Flat strip textured materials transmit more light than knitted materials[24]. The brightness of a material has greater impact on reflectance than porosity.

Under cloudy conditions, there is more diffuse light. Bright colours and high porosity[19] transmit a greater level of diffuse light than dark materials .

As well as affecting the amount of radiation that can penetrate the screen, the porosity of a material impacts airflow and determines the range of pests which may be excluded. Installing structures of any kind above or around a crop influences air movement within a cropping area and air exchange with the ambient environment. This influences evapotranspiration and the removal of heat energy.

The porous nature of a screening material facilitates more air exchange and reduces the build-up of excessive heat within the structure compared with an equivalent greenhouse (clad in plastic or glass). However, overheating can still occur under some conditions[25]. Reduced ventilation and air movement within a crop may result in excess temperatures and higher humidity[26]. Under conditions of low wind speed, a screenhouse can reduce ventilation rates by up to 71%[27]. Under cold conditions, sealing a shadehouse can lead to colder conditions inside because of a lack of air mixing with ambient air.[28]

Consequently, a key consideration in the use of low cost protected cropping is the effect on airflow. Airflow through a material is proportional to the porosity of that material.

Similarly, air temperatures under a floating crop cover are higher than in uncovered areas[29], though this difference can be more pronounced at the beginning of the cropping cycle[30]. Soil temperatures at night can be increased by up to 3°C[31]. This effect can be used to facilitate earlier crop establishment or even frost protection. The shading effect can increase moisture retention and provide up to 3°C reduction in peak summer temperatures[28.] However, build-up of excess heat under floating covers during periods of

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[22] Z. Ilic, L. Milenkovic, M. Durovka and N. Kapoulas (2011) The effect of colour shade nets on the greenhouse climate and pepper yield. In Proceedings of the 46th Croatian and 6th International Symposium on Agriculture. Croatia, pp529-532.

[23] E. Holcman and P. Sentelhes (2012) Microclimate under different shading screens in greenhouses cultivated with bromeliads. *Agric. Met. Climate* in Rev.bras. eng. agric.ambient 16(8).

[24] I. Al Helal and A. Abdel-Ghany (2010) Responses of plastic sheeting nets to global and diffuse PAR transfer: optimal properties and evaluation. Elsevier 57(2) 125-132.

[25] G. Desmarais and G. Raghavan (1996) Thermal characteristics of screenhouse configurations in a West-African tropical climate. *Acta Horticulturae* 443http://www.actahort.org/books/443/index.htm

[26] Teitel, M., D. Dvorkin, Y. Haim, J. Tanny, I. Seginer. 2009. Comparison of Measured and Simulated Flow through Screens: Effects of Screen Inclination and Porosity. *Biosystems Engineering*, 102: 162-170

[27] J. Tanny, S. Cohen and M. Teitel (2003) Screenhouse microclimate and ventilation: an experimental study. *Biosystems Engineering* 84:331–341

[28] R. Stamps, S. Natarajan, L. Parsons and J. Chen (2011) Cold protection of foliage plants in shadehouses and greenhouses. Uni of Florida, IFAS extension

[29] D. Rekika, K. Stewart, G. Boivin and S. Jenni (2008) Floating rowcovers improve germination and reduce carrot weevil infestations in carrot. *HortScience* 43(5):1619-1622

[30] C. Gimenez, R. Otto and N. Castilla (2002) Productivity of leaf and root vegetable crops under direct cover. *Scientia Horticulturae* 94:1-11

[31] R. Munton (2013) The production of baby-leaf lettuce under floating crop covers, Final report VG09188, Horticulture Australia

high temperature can have an adverse effect, with heavier materials having a greater effect on increasing temperature[32].

The height at which a screening material is installed will influence how much of the energy absorbed by a screen is subsequently re-radiated and will affect temperature within the protected area. Height also directly impacts the air volume within the protected area and the amount of air mixing that will occur in the space between the crop and the covering material. Installation heights in the nursery industry in Australia (which is the largest current user of screenhouses) is generally 3.5m[33]. Nets for hail protection and screenhouses in the orchard industry are generally erected at 3.5 to 4.5m and up to 5m depending on pruning structure. The hydroponic lettuce industry has tended to install light shade/hail screens at up to 5m. Screenhouse temperature increases and absolute humidity decreases with increasing height[34].

3.2.2 Managing crop water use

Extended dry periods and an increase in variability of rainfall are two predicted effects of climate change that can significantly impact vegetable growing enterprises. Reduced cloud cover associated with dry periods may produce greater frost risks and higher day temperatures. The availability and irrigated cost of suitable water are important components in farm decision making and risk management. Improved irrigation efficiency has been a long standing focus of the vegetable industry, though the strategy has generally been on improving the application efficiency of irrigation water. Another aspect to managing water supply risk is crop water use efficiency.

Crop water use is primarily a factor of the atmospheric growing conditions. The demand for water is the combination of evaporation and transpiration which are affected by radiation (sunshine) levels, temperature, windspeed and relative humidity. Protected cropping elements can be used to influence these environmental conditions and reduce levels of evapotranspiration.

Measured water consumption of capsicum in a nethouse in Israel was found to be one third of the potential evapotranspiration of a comparable open field crop[35]. Similar results are being reported from trials conducted in Griffith which show that screenhouses could reduce radiation levels by 40% and cut water use by more than a third[36]. In other work, reductions in radiation level, wind speed and vapour pressure deficit within a nethouse were the main factors in reducing transpiration rates and consequently crop water use. During this work, transpiration rates inside the screenhouse were approximately 1.8 to 2.1mm.day^{-1} during the most active stage of growth, while simulated rates for a similar crop grown outside were 4.5 to 5.3mm.day^{-1} on average[37].

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[32] D. Rekika, K. Stewart, G. Boivin and S. Jenni (2008) Row covers reduce insect populations and damage and improve early season crisphead lettuce production. *Intl J. Vegetable Science* 15:71-82

[33] R. Clough (2014) Living Shade, pers comm.

[34] J. Tanny, S. Cohen and M. Teitel (2003) Screenhouse microclimate and ventilation: an experimental study. *Biosystems Engineering* 84:331–341

[35] M. Möller, J. Tanny, S. Cohen, Y. Li and A. Grava (2004) Water consumption of pepper grown in an insect proof screenhouse. *Acta Horticulturae* 659:569–575

[36] Sun shield reduces water needed to grow vegetables: southern NSW trial. NSW DPI Science and Research newsletter, 2007.

[37] M. Möller, J. Tanny, Y. Li and S. Cohen (2004) Measuring and predicting evapotranspiration in an insect-proof screenhouse. *Agric For Meteorology* 127:35–51

Floating covers were found to reduce crop water use, with evapotranspiration higher in uncovered crops[38]. Trials in Australia demonstrated a 30% increase in soil moisture retention and suggest that floating covers could reduce irrigation requirements by 30 to 50% depending on the time of the year[39].

3.2.3 Managing extreme weather events

More frequent and severe weather events such as storms and strong winds, hail and heavy rain are a predicted result of climate change[40]. These conditions would impact all regions and expose an enterprise to acute production and economic risk.

Screenhouses, crop canopy, cloches, floating covers and low profile greenhouses can protect crops from heavy rain. Screening materials such as shadecloth and floating crop covers break up heavy rain and large droplets, allowing a mist to fall to the crop. The same amount of water will reach the ground but it will not be physically damaging. Low profile greenhouses and plastic cloches are impermeable to rain and can be used to manage excess water in the cropping area and improve efficiency of water capture.

All these protected cropping elements can provide protection from wind damage, though a crop canopy can be less effective against wind than the other structures. Floating crop covers used under very windy conditions[41] may need to be held off the crop a little to avoid plant damage, particularly for crops such as capsicum which have exposed growing points[42]. A windbreak can be used to mitigate strong winds and raise minimum temperatures slightly.

The impact of extreme weather events on the protected cropping structure itself must also be considered in financial assessments. Structural supports must be sufficiently sized, posts must be well anchored and cladding materials properly fastened. Wind deflectors or other windbreaks can be used to reduce wind damage on the structures.

3.2.4 Frost and low temperatures

The likely impact of frost on the vegetable industry is high[43].The acute nature of frost damage may have a greater economic impact than higher average temperature, as temperature changes are more gradual, enabling various strategies to be implemented such as the development of new varieties and even farm relocation.

The main concern regarding frost in a region is an extension of the frost window which can adversely affect the length of the cropping season and increase production and economic risks. Crops with a short growing season may be less affected[39], though the accumulative

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[38] E. Suarez-Rey, T. Soriano, F. Quesada, M. Morales, and N. Castilla (2001) Effect of different covers on growth and nitrate accumulation in iceberg lettuce (*Lactuca sativa* L.) and escarole (*Cichorium endive* L.) Intl Symposium on irrigation of horticultural crops; Physical control methods in plant protection. *Acta Horticulturae* 792:215-223

[39] R. Munton (2013) The production of baby-leaf lettuce under floating crop covers, Final report VG09188, Horticulture Australia

[40] G. Rogers (2013) Understanding and managing impacts of climate change and variability on vegetable industry productivity and profits, Final report VG12041 AHR

[41] G. Dickerson (2009) Row cover vegetable production techniques, Guide H-251. Cooperative extension service, New Mexico State University.

[42] J. Howell and R Hazzard (editors) (2014) *Slitted and floating row covers*, New England Vegetable Management Guide, University of Massachusetts.

[43] G. Rogers (2013) Understanding and managing impacts of climate change and variability on vegetable industry productivity and profits, Final report VG12041 AHR

impacts of changing climate may need to be considered; for example, extreme high temperatures occurring in the mid to late season may require earlier establishment which in turn would expose even short season crops to frost risk. Conversely, increasing frost risk may necessitate a later planting of sensitive crops exposing them to adverse hot conditions towards the end of the growing season.

Frost protection can, to some extent, be achieved with a screenhouse, crop canopy, cloche, floating cover or low profile greenhouses, while a windbreak may exacerbate frost risk. Floating crop covers can achieve up to a 2°C[44, 45] increase in minimum temperatures while heavier plastic covers could deliver an increase of up to 4°C[41].

3.2.5 Impact on light levels

Reducing the level of incident radiation (sunshine) is the most commonly used means of reducing temperature and will also affect the light available to the crop. A minimum light requirement exists for all crops. The impact of protected structures on light levels on a daily, seasonal or annual basis has to be considered. Some crops also have upper light thresholds, for example lettuce quality can be adversely affected at moderate light levels and capsicum fruit is susceptible to sunburn. Subsequently, shading is used to reduce light intensity as a primary objective in some cropping situations. For particular crops such as lettuce and capsicum, protective shading can offer a double benefit of reducing light and temperature.

In greenhouses, the potential impact on light from structural components above a crop and the cleanliness of cladding material can account for more than 10% reduction in transmission. Condensation can reduce light transmission by 8%[46]. Because cladding materials further reduce light reaching the crop they must be carefully selected and the production system closely managed to optimise light transmission. A single layer, clean, new plastic film cladding will generally have a light transmission of 80%.

The same factors apply to other cladding and protective covers including shadecloth, insect screen and floating crop covers. The transmission of photosynthetically active radiation under a floating cover is around 80%[41] but can vary from 85 to 65% (compared to no covering) depending on the level of dust on the covering material and condensation on the inner surface[47]. Shadecloth is specified according to its nominal light transmission[48] with a 50% shade material being designed to transmit half of the incoming radiation.

Floating covers also provide a shading effect and can protect sensitive crops from sunburn[41]. Heavy covers are only used for overnight frost protection as they exclude more light[49] and may have insufficient light transmission for suitable crop growth[50]. Some of the heavier covers have transmission levels as low as 30 to 40%[51].

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[44] R. Munton (2013) The production of baby-leaf lettuce under floating crop covers, Final report VG09188, Horticulture Australia

[45] J. Dainello and R. Roberts *Texas Vegetable Growers' Handbook*, accessed online: https://aggie-horticulture.tamu.edu/vegetable/guides/texas-vegetable-growers-handbook/chapter-iv-cultural-practices/

[46] *Greenhouse covering materials*, NSW Department of Primary Industries. Accessed online (2014): http://www.dpi.nsw.gov.au/agriculture/horticulture/greenhouse/structures/covers

[47] C. Gimenez, R. Otto and N. Castilla (2002) Productivity leaf and root vegetable crops under direct cover. *Scientia Horticulturae* 94:1-11

[48] Assumes light transmission impacting on a horizontal surface

[49] G. Dickerson (2009) *Row cover vegetable production techniques*, Guide H-251. Cooperative extension service, New Mexico State University.

The impact of light cannot be underestimated. Trials growing tomato in South Africa demonstrated the interaction of light and temperature. Forty percent (40%) shade achieved an improved temperature regime in a summer of high temperatures but the reduced light levels resulted in low yield, while a level of 15% shade over a milder season gave the highest yields. Yet the same level of 15% shade during the lower light conditions of winter produced poor yields[52]. Moderate shade levels of 30% and 47% are recommended as best for peppers[53] .

3.2.6 Exclusion of pests

The incidence and severity of some pests and diseases, and their incursion into new regions is expected to occur as a result of changing climate, in particular with warmer temperatures. Pests are consistently a significant production concern in all cropping situations.

Screen houses and floating crop covers can be used to exclude pests. The porosity and sealing of the materials determines the range of pests that can be kept out. Reduced air flow is a key effect of fine pore sizes needed to prevent pest entry and this can have an adverse impact on the growing environment; increasing temperature and humidity and reducing air speed and evapotranspiration.

Trials looking at the protection afforded by floating covers on zucchini targeting whiteflies (and virus) found just ten adult whiteflies under the covers compared with 6425 adults in the control area. The difference in yield was equally dramatic. Yield of the protected zucchini was 20 times greater.[54] Melon production in Mexico found that row covers completely excluded a number of pests including beetle, leaf miner, whitefly and aphid.[55]

In carrot, floating crop covers reduced carrot weevil damage by an average of 70% over two years.[56] Work in Australia with floating covers has been limited to date, however reductions of insect populations of 89% have been demonstrated in baby leaf crops.[57]

3.2.7 Recognition of interactive effects

Any protected cropping arrangement, even if it is focussed on a specific factor, will impact other conditions in the growing environment. For example, installing a shadehouse to reduce incident solar radiation in order to mitigate extreme daytime temperatures will

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[50] *Row covers*, Pennsylvania State University extension. Accessed online (2014) http://extension.psu.edu/plants/plasticulture/technologies/row-covers

[51] J. Howell and R Hazzard (editors) (2014) *Slitted and floating row covers*, New England Vegetable Management Guide, University of Massachusetts.

[52] P. Mills, I. Smith and G. Marais (1990) A greenhouse design for a cool subtropical climate with mild winters based on microclimate measurements of protected environments. *Acta Horticulturae* (ISHS) 281:83-94

[53] J. Diaz-Perez (2013) Bell pepper (Capsicum annum L) crop as affected by shade level: Microenvironment, plant growth, leaf gas exchange and leaf mineral nutrient concentration. *HortScience* 48(2):175-182

[54] E. Natwick and A. Durazo (1985) Polyester covers protect vegetables from whiteflies and virus disease. *California Agriculture*, July-August; 21-22

[55] M. Orozco-Santos, O. Perez-Zamora and O. Lopez-Arriaga (1995) Floating row cover and transparent mulch to reduce insect populations, virus diseases and increase yield in cantaloupe. *Florida Entomologist*, September: 493-501

[56] D. Rekika, K. Stewart, G. Boivin and S. Jenni (2008) Floating row covers improve germination and reduce carrot weevil infestations in carrot. *HortScience* 43(5):1619-1622

[57] R. Munton (2009) The production of baby-leaf lettuce under floating crops covers. Project VG09188. Final report Horticulture Australia.

influence light levels, airflow and humidity and could also affect pollinating insects or pests.

3.3 Design of low cost structures

Protected cropping structures vary in performance according to design. The shape, height and materials used all influence the environment within a protected cropping structure. The architecture, or shape, of a structure and the porosity of the covering material have the greatest influence on internal temperature[58]. A multispan roofline generates greater negative air pressures than a flat roof screen house. The lower wind speeds within the structure lead to higher temperature and higher relative humidity[59].

The size of a structure also has a significant bearing[60]. The height has a direct influence on the internal environment and is a key performance indicator of greenhouses in terms of air temperature, humidity and uniformity of the growing environment. A similar benefit of increasing structure height has been observed in screen houses[61].

Orientation

In a screenhouse, all surfaces have some degree of air exchange with the outside, so the surface area is critical in a similar way to the ventilation area of a greenhouse. Understanding the impact of air pressures along the surface of the screening materials can be used to improve ventilation. When wind is moving parallel to the long side of a screenhouse, temperatures are cooler[57].

Light transmission

Tunnels, cloches and rainshelters may be clad in a plastic film which is impermeable to air and moisture and has an influence on the transmission of light. All materials —even a basic, clear cladding material —will reduce total light transmission. Light diffusion, alteration to the colour spectrum and the blocking of particular wavelengths such as ultraviolet or infrared are all possible with different materials.

Screening materials can be used as a screenhouse, on a cloche or as a crop canopy. Although permeable to air and moisture, screens affect light transmission and air flow and subsequently the cropping environment. The colour and type of the material influences the amount of radiation that is absorbed, reflected or which passes through to the crop and the degree to which the light that passes through is scattered (diffused). A screenhouse also influences the radiation that is emitted from the cropping area.

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[58] G. Desmorais and G. Vigaya Raghoven (1996) Thermal Characteristics of screenhouse configurations in a West-African tropical climate *Acta horticulturae*. 443: 39-46.

[59] Flores-Velazquez, J, Mejia, E, Lopez, I, Rojano, A, Montero, J, Hernandez, M, Kamfener, O and Mendoza, M (2013) 3-Dimensional Thermal Analysis of a Screenhouse with Plane and Multispan Roof by Using Computational Fluid Dynamics (CFD) *Acta horticulturae*. (ISHS) 1008:151-158

[60] J. Tanny, M. Teitel, M. Barak, Y. Esquirra, R. Amir (2008) The effect of height on screenhouse microclimate. *Acta horticulturae*, (ISHS) 801:107-114.

[61] Tanny, J., Haijun, L. and Cohen, S. 2006. Airflow characteristics, energy balance and eddy covariance measurements in a banana screenhouse. *Agricultural and Forest Meteorology*, 139(1-2):105-118.

More diffuse radiation under a screenhouse is likely to be a key factor in improved crop performance[62].

Porosity

Protected cropping structures also influence the crop environment by altering airflow. While screening materials can influence many of the same factors as plastic or glass cladding, the primary difference is that screening materials — being permeable to air and moisture — can create a very different environment. A primary characteristic of screening is the pore size— the size of the gap between the fibres or strips of the screen material. A larger pore enables greater air exchange and intercepts a smaller proportion of radiation.

Pore size impacts the type of pests that can be physically excluded. A larger hole size permits a wider range of insects and weed seeds to enter the structure, yet enables greater airflow. An insect screening material (used to create a nethouse) has holes sized to prevent target insects gaining access. A finer mesh restricts smaller species.

Although the usual assumption is that the screening material is a type of fabric, screenhouses can also be constructed from other materials including timber and vegetation. The same principles apply irrespective of the material.

[62] E. Kitta, A. Baille, N. Katsouas, N. Rigakis and M. Gonzalez-Real (2014) Effects of cover optical properties on screenhouse radiative environment and sweet pepper productivity. *Biosyst Eng* 122:115–126

4 Evaluation of LCPC for Australian vegetable growing regions

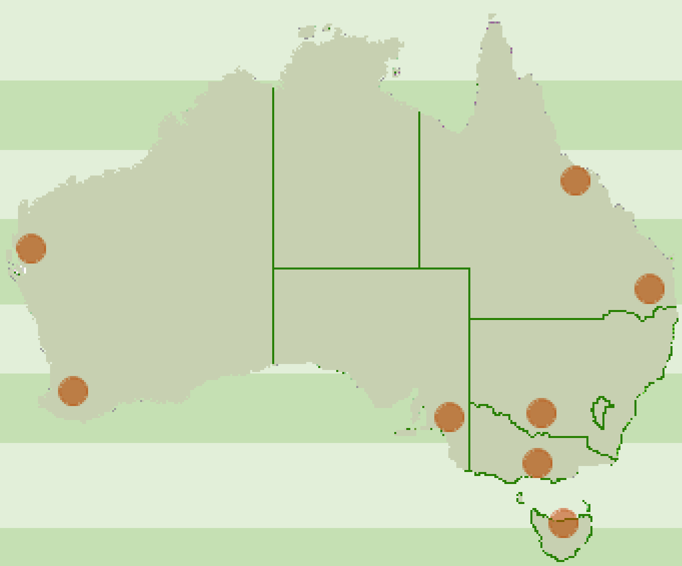
The scope to feasibly use low cost protected cropping options can differ between locations and cropping situations. Rogers[63] detailed six vegetable production regions (Manjimup, WA; Murray Bridge, SA; Hay, NSW; Werribee, Vic; Devonport, Tas.; and Gatton, Qld.) as a handy representation of the production of key levy crops, a spread of geographical areas and a range of growing conditions, and discussed the projected changes in climate of these regions.

This provides a useful structure to evaluate the merits of different low cost protected cropping options described previously (Section 3) for each location and their suitability for managing high temperatures, crop water use and extreme weather events, frost mitigation, impacting light levels and exclusion of pests. Two other regions (Carnarvon, WA and Bowen, Qld) have been added to enable an assessment of the merits of LCPC in more northern production areas.

A number of vegetable crops are produced across some or all of these regions, (Table 8) providing a framework to illustrate the contribution protected cropping elements could offer across the Australian vegetable industry.

Table 8: Representative regions and crops for review of protected cropping options

	Regions	Crop sensitivities
Lettuce		Heat, Frost, Excess light
Baby-leaf (spinach, rocket)		
Broccoli		Heat
Cauliflower		Heat
Capsicum		Frost, Heat, Sun damage
Sweet Corn		Heat, Frost
Bean		Heat, Frost
Cucurbits (cucumber , melon)		Frost, Sun damage
Carrot		Heat



[63] G. Rogers (2013) Understanding and managing impacts of climate change and variability on vegetable industry productivity and profits, Final report VG12041 AHR

4.1 Crop sensitivity to temperature extremes

Light and temperature — two of the most important parameters of the growing environment for all crops —need to be key considerations in the use of [low cost] protected cropping. All types of protected cropping can affect temperature and light levels in some way within a cropping area. Additional parameters to be considered are the physical impacts of environmental elements including heavy rain, hail, strong wind (>45 $km.h^{-1}$), still air (<0.2 $km.h^{-1}$) and extreme evapotranspiration.

4.1.1 Lettuce

Lettuce has an optimal growing temperature of between 12°C and 21°C and will tolerate temperatures from 7°C to around 28°C, above which development and quality declines sharply. Yield declines by as much as half when temperatures exceed 32°C[64]. Much of this loss is attributed to premature bolting and tipburn, though water stress and wilting associated with high temperatures can also produce bitterness in leaves. Conversely, temperatures below 0°C can reduce yields by as much as 35%[62]. The length of the growing period is also affected by temperature. Warmer conditions can reduce the period to harvest while cooler conditions will result in slower rates of growth.

Lettuce has a relatively low light requirement of 400 to 600 $\mu mol.m^{-2}.s^{-1}$ [65]. The daily light integral (DLI) of lettuce is reported to be in the range of 11 to 17 $mol.m^{-2}.day^{-1}$ (2.4 – 3.7 $MJ.m^{-2}.day^{-1}$)[66] of photosynthetically active radiation (PAR) with the range generally reflecting different varieties.

Lettuce is a low light crop and is sensitive to excess light, heat and frost.

4.1.2 Baby-leaf

Several crops can be included in this group which are produced as baby-leaf and salad greens. Spinach and rocket are two common crops. Similarly to lettuce, leafy crops tend to have lower light requirements, with these baby-leaf crops needing at least 14 to 17[67] $mol.m^{-2}.day^{-1}$ (~3 – 3.7 $MJ.m^{-2}.day^{-1}$) of photosynthetically active radiation. Optimum growing temperatures of these crops are in the narrow range 15 to 18°C, though they are fairly temperature tolerant with 5°C considered the lower temperature threshold and 30°C the threshold above which produce quality declines.

Baby-leaf crops generally have a lower light requirement and are sensitive to heat.

[64] G. Rogers (2013) Understanding and managing impacts of climate change and variability on vegetable industry productivity and profits, Final report VG12041 AHR

[65] W. Fu, P. Li, Y. Wu, J. Tang, 2012. Effects of different light intensities on anti-oxidative enzyme activity, quality and biomass in lettuce. *Hort. Sci.* 39: 129–134.

[66] Conversions between units of measurement of light are not consistent. The conversion used to estimate $MJ.m^{-2}.day^{-1}$ from 1 $\mu mol.m^{-2}.s^{-1}$ is equivalent to 4.57 $MJ.m^{-2}.day^{-1}$ based on K. McCree (1981) Photosynthetically Active Radiation in Encyclopaedia of Plant Physiology vol12A Springer-Verlag 41-55

[67] M. Brechner and D. de Villiers (2013) Hydroponic spinach production handbook. Cornell University.

4.1.3 Brassica crops

There is a wide range of brassica crops grown throughout Australia. Broccoli and cauliflower are examples of crops that may be affected by changes in growing conditions in key production areas due to climate change[68].

A wide assortment of varieties of broccoli and cauliflower facilitate selections for cool and warm seasons though specific varieties generally have narrow optimal temperature ranges, making these crops quite temperature sensitive. The optimal warm season conditions for broccoli are 21 to 22°C, while 4 to 5°C suits cool season varieties. The upper threshold for broccoli is 30°C beyond which poor quality results. Higher day temperatures can be tolerated if the night temperatures are below 15°C. Temperatures below 4°C also affect quality, reducing yield by 25%[66].

Cauliflower has a slightly cooler optimum of 15 to 18°C and temperatures over 32°C severely impact yields[66]. Cauliflower can tolerate temperatures down to freezing.

Brassica crops have a reasonable tolerance to lower light conditions, though can also thrive in higher light conditions provided temperature and water supply are suitable. A minimum daily light integral (DLI) of just 10 $mol.m^{-2}.day^{-1}$ has been reported for *Brassica rapa*[69] though light requirements in the range of 15 to 20 $mol.m^{-2}.day^{-1}$ (3.3 to 4.4 $MJ.m^{-2}.day^{-1}$) of photosynthetically active radiation are more appropriate for these crops. Net photosynthesis in Chinese cabbage[70] has been found to be at a light integral of 1500 $\mu mol.m^{-2}.s^{-1}$ which approximately corresponds to 43 $mol.m^{-2}$.8h day^{-1} and roughly converts to 4.7 $MJ.m^{-2}.day^{-1}$ PAR.

Brassica crops generally have a moderate light requirement and are sensitive to heat.

4.1.4 Capsicum

Capsicum has an optimum temperature range of 20 to 25°C. Temperatures above 32°C can reduce yield by 20%[66] due to problems with pollination and sunburn of fruit, though adverse effects on pollination have been found at temperatures above 27°C[71] which lowers fruit set. Late season production of capsicum in Carnarvon, WA results in 78% reduction in marketable fruit, primarily due to sunburn damage[72].

Capsicum is a cold sensitive crop. Conditions below 8 to 10°C can cause misshapen fruit and diminish yields by as much as 35%[71]. Once retarded by cold weather, capsicum does not usually regain its vigour and lower yield results.

Although capsicum is commonly grouped with crops such as tomato and cucumber in terms of its light requirement, a daily light integral of 14 $mol.m^{-2}.day^{-1}$ (3 $MJ.m^{-2}.day^{-1}$)

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68 G. Rogers (2013) Understanding and managing impacts of climate change and variability on vegetable industry productivity and profits, Final report VG12041 AHR

69 I. Tarakanov and J. Wang (2009) Light trophic and signal roles in the control of morphogenesis of the Brassica plants developing storage roots. *Rus. J. Plant Physiology* 56(2):232

70 X. Wolfe and R. Coltman (1990) Productivity of eight leafy vegetable crops grown under shade in Hawaii. *J. Amer. Soc. Hort. Sci*. 115(1):182-188

71 *Production of sweet bell peppers*, Ministry of Agriculture and Rural Development, Alberta. Accessed online (2014): http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/opp4523

72 V. Kesavan (2002) Sustainable production of quality capsicums in Carnarvon. Project VG99013 Final report. Horticulture Australia.

PAR has been reported as suitable. Fruit quality declines when temperatures exceed around 30°C and additionally, fruit can be sunburnt under hot, sunny conditions.

Capsicum has a moderate light requirement and is sensitive to frost and heat.

4.1.5 Sweet corn

Sweet corn is a warm season crop with an optimum growing temperature range of 24 to 30°C; however temperatures above 32°C adversely affect pollination and can reduce yield by 30%. Corn is also frost sensitive and temperatures below 12°C can reduce yield by half due to poor germination and seedling emergence. Sweet corn has a high light requirement with a minimum DLI expected to be 20 $mol.m^{-2}.day^{-1}$ (~4 $MJ.m^{-2}.day^{-1}$) of photosynthetically active radiation.

Sweet corn has a high light requirement and is sensitive to frost and heat (above 32°C).

4.1.6 Beans

Beans have a high light requirement expected to be at least 20 $mol.m^{-2}.day^{-1}$ (~4 $MJ.m^{-2}.day^{-1}$) of photosynthetically active radiation and an optimal temperature range of between 15 and 21°C. Temperatures above 28°C affect pollen viability and reduce pod quality and can result in a 35% decline in yield, while a halving of yield can occur at temperatures below 10°C[73].

Beans have a generally high light requirement and are sensitive to frost and heat.

4.1.7 Cucumbers

Cucumber is a common cucurbit crop produced in Australia. Cucurbits are warm season crops with an optimal growing temperature range of 21 to 27°C. Temperatures exceeding around 30°C will adversely affect plants and yield may decline by 25% or more[74]. These crops are also cold sensitive and temperatures below 15°C will result in yield decline.

Cucumber is a high light crop with minimum DLI around 20 $mol.m^{-2}.day^{-1}$ (~4 $MJ.m^{-2}.day^{-1}$)[75] of photosynthetically active radiation.

Cucumbers have a high light requirement and are sensitive to frost and heat.

4.1.8 Carrots

Carrot has an optimum temperature range of 15 to 18°C with an upper threshold of 27°C, above which yield may be reduced by as much as 30%. Higher temperatures can be tolerated provided night temperatures do not exceed 15°C. Temperatures below around 7°C can reduce yield by as much as 20%[76].

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[73] G. Rogers (2013) Understanding and managing impacts of climate change and variability on vegetable industry productivity and profits, Final report VG12041 AHR

[74] J Badgery-Parker (2011) *Cost effective improvements to tunnel houses* [workshop presentation] Extension activity within 'Development of a cost effective protected vegetable cropping system in the Philippines', HORT/2007/066-2, ACIAR.

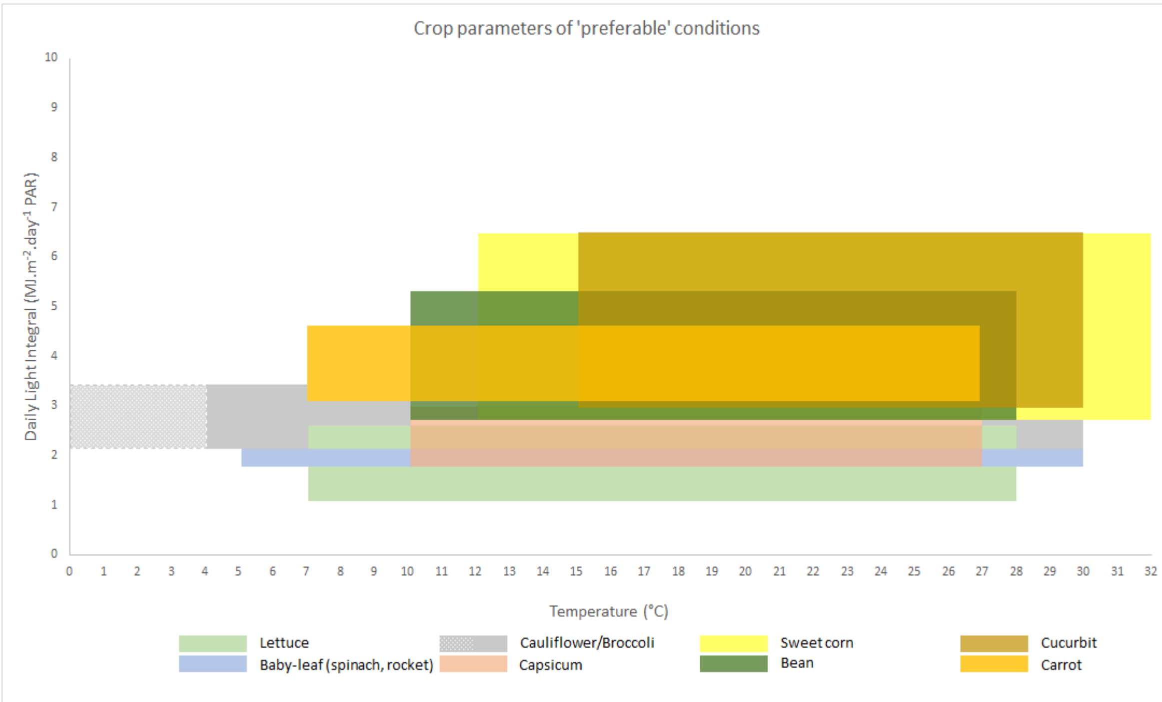
[75] S. Parks and R. Worrall (2005) Greenhouse vegetable production in the Australian climate in Proceedings 2005 National Conference of the Australia Hydroponic and Greenhouse Industry.

[76] G. Rogers (2013) Understanding and managing impacts of climate change and variability on vegetable industry productivity and profits, Final report VG12041 AHR

Carrot has a fairly wide tolerance to light levels and does get grouped as a lower light crop though other reports suggest minimum light levels of 20 to 25 $mol.m^{-2}.day^{-1}$ (~4 – 5.4 $MJ.m^{-2}.day^{-1}$) of photosynthetically active radiation are required for this crop.

Carrot has a moderate to high light requirement and is sensitive to heat.

Figure 2: Crop parameters illustrating generally preferred light and temperature conditions for crops



4.2 Managing extreme weather events

4.2.1 Rain

Variability in rainfall is expected to increase in all regions. There are two aspects to rainfall that can be considered. The first is the impact of heavy or extreme rainfall events and the second is an overall decline in rainfall, and thus the amount of available water for irrigation. Much of Australia already has quite variable rainfall from year to year, so this projected change over the next few decades and beyond means variability is likely to become even more pronounced.

Fewer but more intense rainfall events are predicted. Heavy rain can damage crops directly as well impact negatively on fertiliser efficiency due to excess or additional nutrient leaching. Disease pressure may also increase in heavy and/or extended periods of rain. A decline in rainfall coupled with extended dry periods increases the water management risk, putting more pressure on security of supply as well as the need for irrigation efficiency and improving crop water use efficiency.

Protective structures over cropping areas minimise physical damage of crops from heavy rain, and water-permeable covers such as shade cloth, netting and floating crop covers can improve infiltration rates by breaking up and spreading large droplets and slowing the rate of fall. Protected cropping options using plastic covering materials can be used to redirect rain, improving storage and overall water and fertiliser efficiency.

The impacts and potential benefits are similar in all regions. The key considerations in assessing the suitability of an LCPC option will be the influence it has on the day-to-day growing environment.

4.2.2 Wind and storms

Prevailing windspeeds vary between regions and even within a region. While wind is considered within the context of temperature management under each region, strong wind can directly damage plants as well as effect growth rates making this a potential production factor that could be mitigated with low cost protected cropping. Windbreaks, floating crop covers, low profile greenhouses, cloches and shadehouses can all be used to provide protection from wind.

The impacts and potential benefits are similar in all regions, though will be more pronounced in locations with stronger prevailing winds and wind events. Carnarvon, Bowen and Devonport tend to experience stronger winds than the other example locations. Windbreaks can be used to provide protection without affecting crop light levels and can also provide a slight rise in minimum temperatures.

Low profile greenhouses, cloches and floating crop covers offer a double benefit — increasing minimum temperatures and providing wind protection. Shadehouses and crop canopies can reduce windspeeds in the cropping area.

All low cost protected cropping options offer some protection from storms and heavy rain, but need to be assessed at an enterprise level.

A primary factor to consider in all regions with respect to strong wind and storm events is the structural integrity of any protected cropping element installed. There can be additional costs in meeting specific wind risk levels. Windbreaks can also be used to protect protected cropping structures.

4.3 Exclusion of pests

The use of protected cropping elements to exclude pests from a cropping area is unlikely to be regionally specific.

Protective structures can physically prevent pest entry and some cladding and netting materials can deter specific pests. The impacts and potential benefits are similar in all regions. The key considerations in assessing the suitability of an LCPC option will be the influence it has on the day-to-day growing environment.

Floating covers can significantly reduce if not fully exclude pests. Shadehouses and nethouses directly impact pest entry according to the pore size of the screening material. The net benefit of pest exclusion is linked to the temperature and light levels attained within a protective structure and this will influence the degree to which an LCPC option can be feasibly used to exclude pests. High temperatures are a common factor to all but one of the regions and light levels are potentially low during winter in all the southern regions.

In all regions, the value of using a floating crop cover to exclude pests will be tempered by the period of time that the cover can be used before daytime temperatures become too hot. Light levels may also be limiting in winter in southern regions.

For screenhouses, there are two primary constraints for all regions except Carnarvon, WA. Light levels in winter and during transition periods are likely to be limiting and low wind speeds can be insufficient to provide adequate air exchange within an enclosed structure during hot weather.

5 Regional analysis

5.1 Manjimup

5.1.1 Overview

A number of crops are grown in the Manjimup area. Lettuce and baby leaf crops to supply the local WA market are traditionally harvested over summer although high temperatures can adversely affect yield and quality. Broccoli and cauliflower are traditionally harvested year round with the dominant production period from November to June.

The projected increase in temperature attributed to climate change in this region could result in a range of effects, from a slightly reduced growing cycle through to reduced product qualityand summer crop failure which could force a move to transitional and winter production only.

5.1.2 Managing high temperature

High summer temperatures are the primary production factor that could be mitigated with protected cropping in this region.

Mean daily maximum and minimum temperatures and the temperature range over the past 15 years are presented in Figure 3. The mean temperatures demonstrate a generally suitable growing environment, however unfavourable daytime temperatures can occur on any day between mid-November and April.

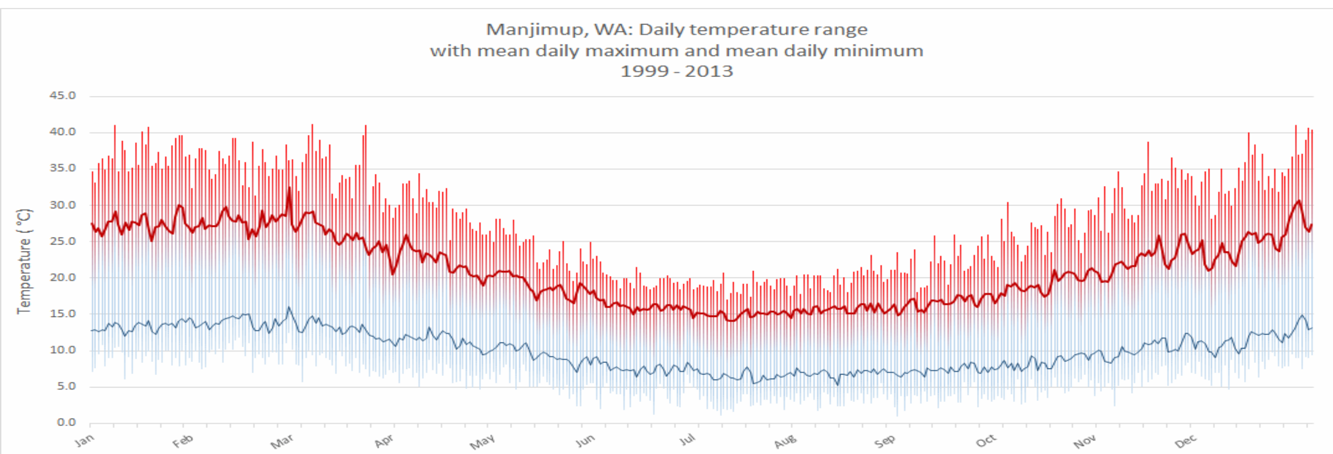


Figure 3: Mean daily temperatures and range for past 15 years at Manjimup, WA.

Lettuce is grown all year round in this region. Baby-leaf crops (rocket and spinach) as well as broccoli and cauliflower are also grown and harvested year-round. Figures 4 – 6 illustrate the optimal growing conditions of lettuce, baby-leaf crops and broccoli respectively, in relation to the Manjimup climate and the extended conditions that these crops tolerate with minimal disruption to yield or quality. Cauliflower shares a similar upper threshold as broccoli, though tolerates temperatures as low as 0°C.

During summer, daytime temperatures routinely exceed the thresholds for these crops and would be adversely affecting yield and quality. The climate change projections for

Manjimup are that maximum temperatures will further increase by between 0.6 and 1.0°C[77]. Increases in day temperatures and particularly extreme temperatures and heatwaves are likely to exacerbate the adverse effect on summer-grown leaf vegetables in this region.

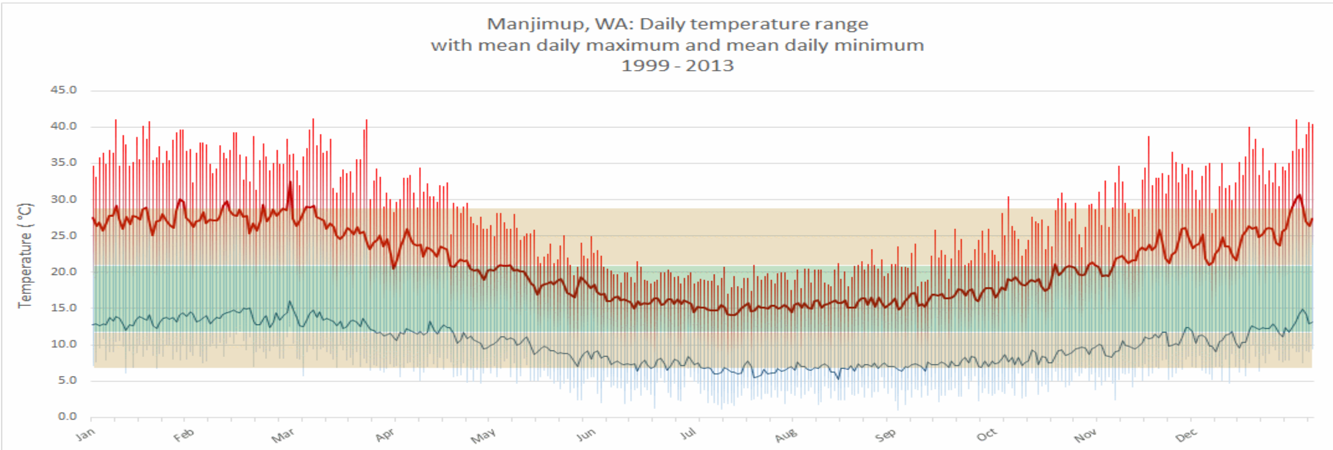


*Figure 4: Mean daily temperatures and range for past 15 years at Manjimup, WA with overlay of suitable (green) and tolerable (tan) growing conditions for **lettuce**.*

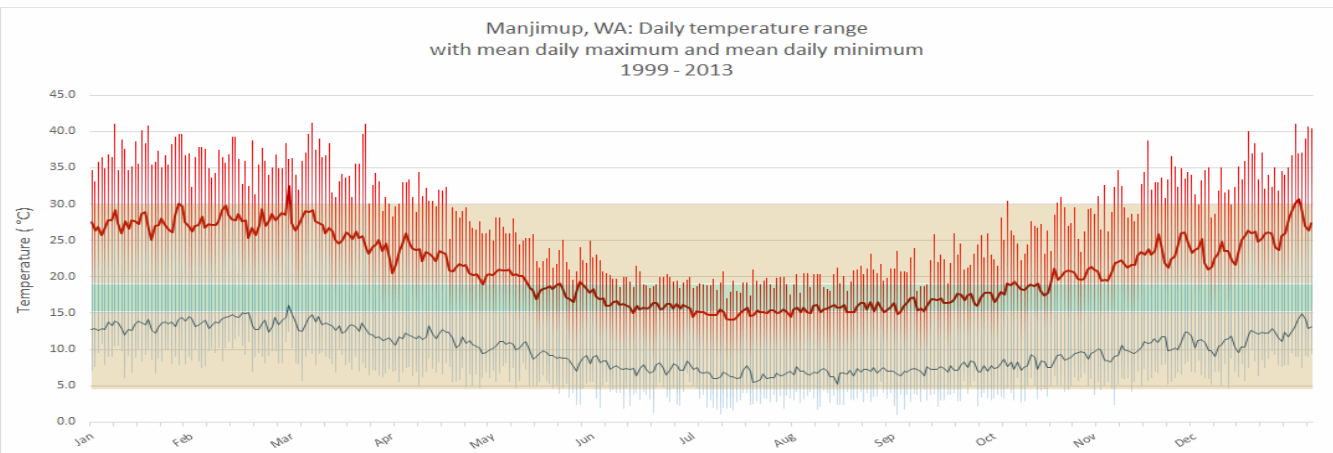


*Figure 5: Mean daily temperatures and range for past 15 years at Manjimup, WA with overlay of suitable (green) and tolerable (tan) growing conditions for **baby-leaf (rocket, spinach)**.*

[77] G. Rogers (2013) Understanding and managing impacts of climate change and variability on vegetable industry productivity and profits, Final report VG12041 AHR

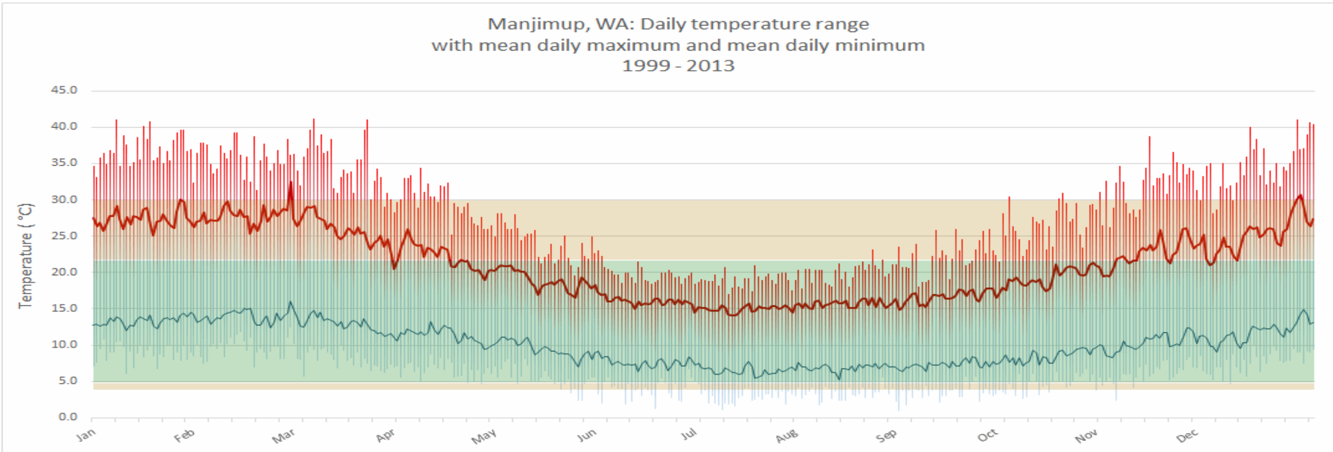


Figure 6: Mean daily temperatures and range for past 15 years at Manjimup, WA with overlay of suitable (green) and tolerable (tan) growing conditions for ***brassica crops such as broccoli****.*

Figures 7, 8 and 9 illustrate the potential growing temperatures at Manjimup for lettuce with a cropping area modified by screening, floating cover and tunnel or plastic cloche, respectively. An effective decrease in maximum temperatures by 6°C and a small increase in minimum temperatures are used in the screening example. The floating cover provides a 2°C increase in minimum temperatures. A tunnel or plastic cloche is expected to provide a 10°C lift in minimum temperatures and over summer an adverse 5°C rise in maximum temperatures for a vented tunnel or 10°C rise in a plastic cloche or poorly vented tunnel have been illustrated, however the increase in maximum temperatures could be by more than 20°C.

Screening in this situation (Figure 7) would substantially reduce the overall number of days that exceed the threshold for the crop and enable yield and quality to be better maintained.

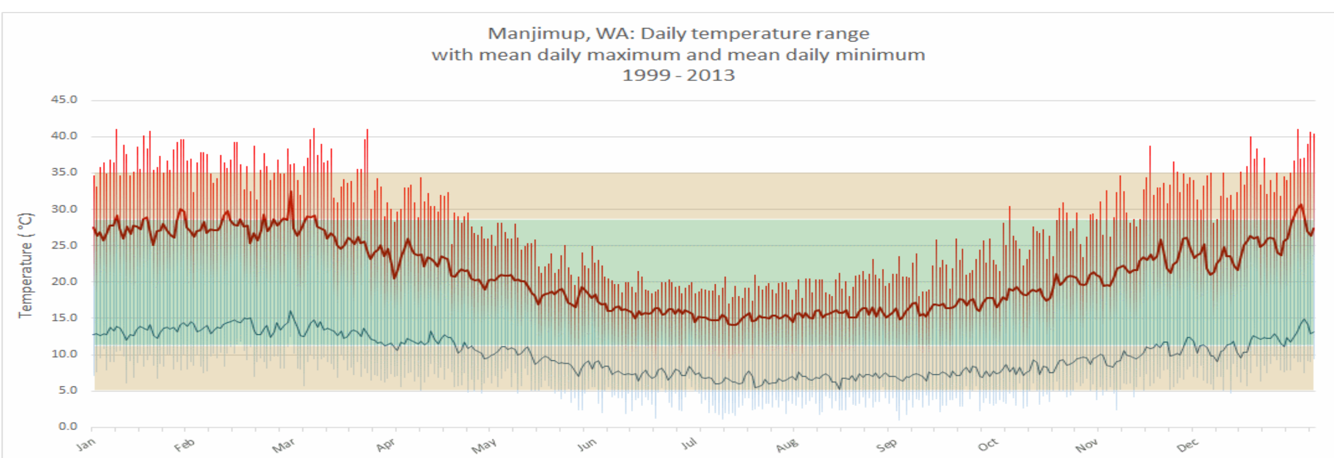


Figure 7: Mean daily temperatures and range for past 15 years at Manjimup, WA with overlay of suitable (green) and tolerable (tan) growing conditions for ***lettuce extended with screening****.*

A floating crop cover would provide a significant improvement with respect to mean minimum temperatures over winter (Figure 8) and although it would eliminate most frost risk, it would not fully compensate for lowest minimum temperatures which would slow plant development during this period. A floating cover could provide a minor benefit in the transitional seasons.

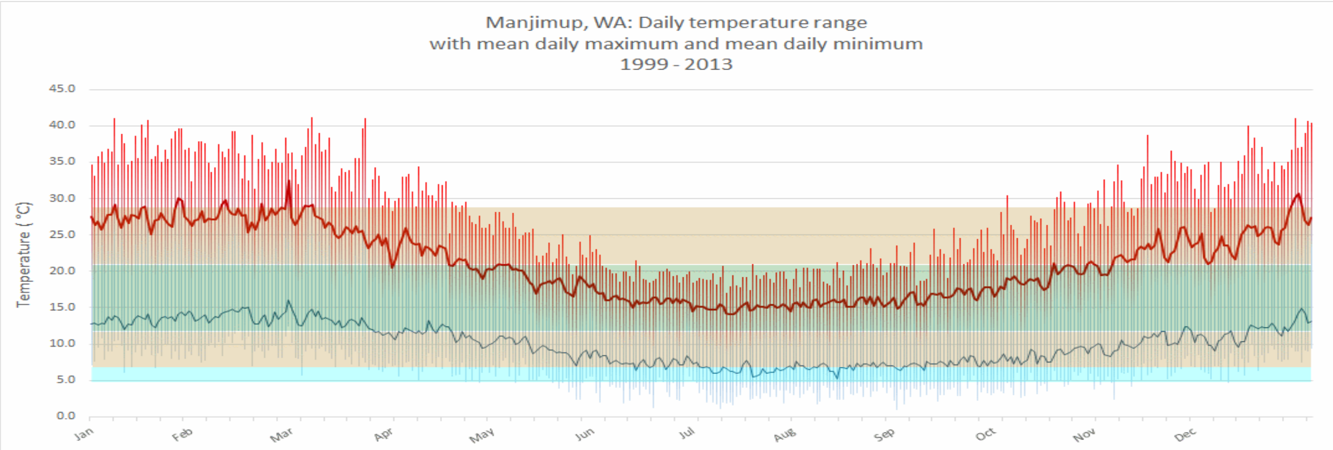


*Figure 8: Mean daily temperatures and range for past 15 years at Manjimup, WA with overlay of suitable (green) and tolerable (tan) growing conditions for **lettuce extended with floating cover** (blue).*

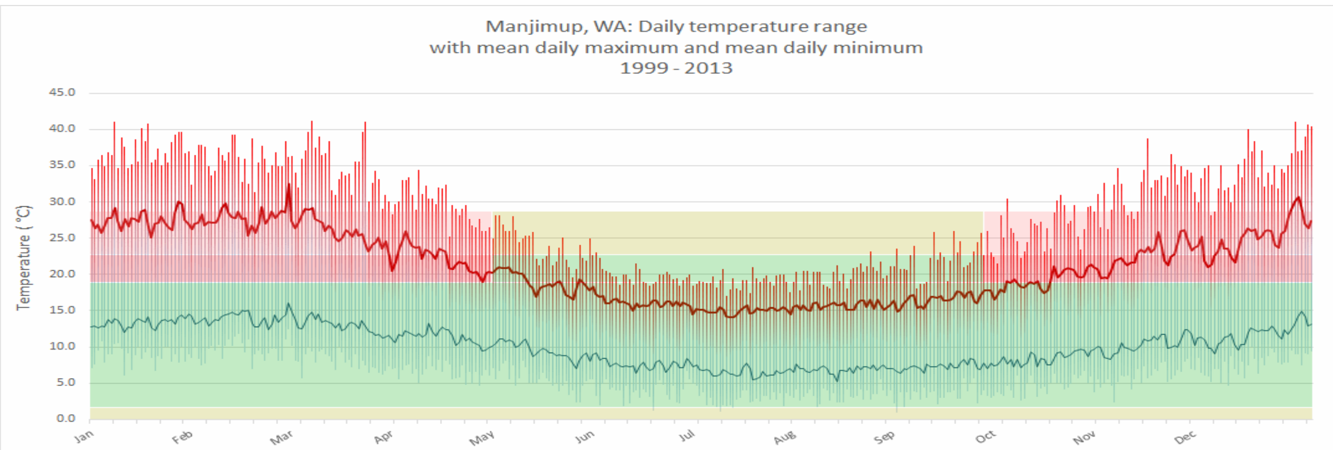


*Figure 9: Mean daily temperatures and range for past 15 years at Manjimup, WA with overlay of suitable (green) and tolerable (tan) growing conditions for **lettuce extended with plastic tunnel house or cloche**. An adverse increase in maximum temperature over summer is indicated for a vented tunnel (light red) and a poorly vented tunnel or cloche (red).*

The use of a low profile greenhouse or cloche (Figure 9) would have a benefit during winter and in the transitional seasons producing warmer, more suitable growing conditions. However, for approximately eight months of the year, an adverse increase in maximum temperatures would necessitate removal of the protected cropping structure.

For other crops, such as baby-leaf spinach and rocket, screening could generate a slightly better situation compared with lettuce due to the wider temperature tolerance. Similarly, the variety selection in brassica crops facilitates a fairly wide temperature range which could potentially be extended with screening (Figure 10).

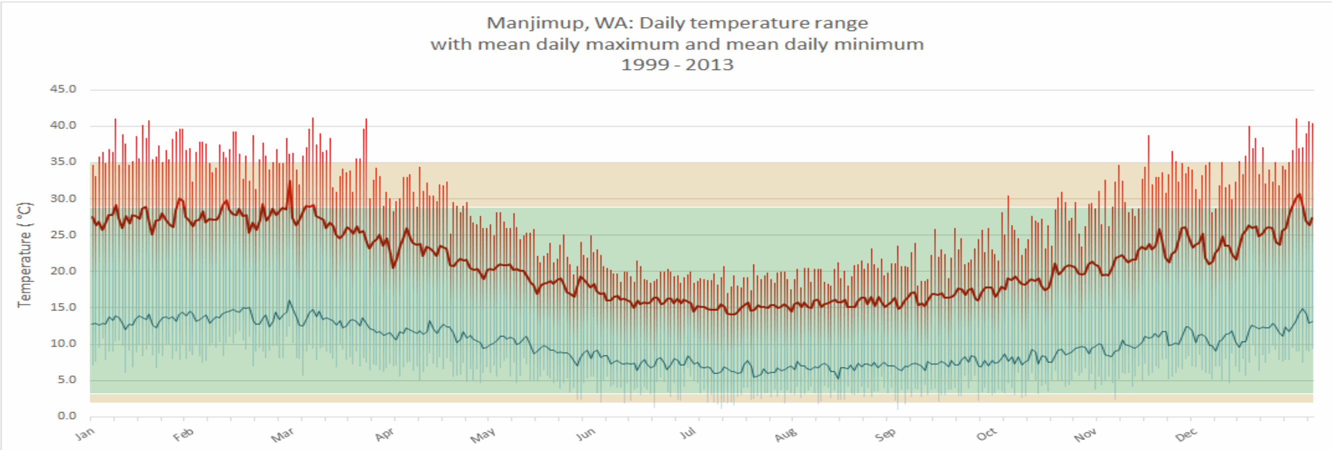


Figure 10: Mean daily temperatures and range for past 15 years at Manjimup, WA with overlay of suitable (green) and tolerable (tan) growing conditions for ***broccoli extended with screening****.*

The anticipated suitable temperature range would fully encompass the mean temperatures throughout the year.

An alternative means of assessment can be made by reviewing the expected number of days that will typically exceed the high temperature threshold. For lettuce (and many other crops) this is 28°C. The number of days that might typically exceed this threshold can be represented by assessing the median number of days over the threshold (Figure 11) for the past 15 years. In any year, a farm manager could expect at least three and as many as thirteen days over summer to have an adverse impact on the crop. With a predicted 1°C rise in temperature by 2035, across summer almost one in every two days would be detrimental to this crop. The insert in Figure 11 illustrates the potential cooling effect of a screen. Assuming a 6°C reduction in maximum temperatures, a screen could limit extreme temperatures in the crop to just two days per month in summer.

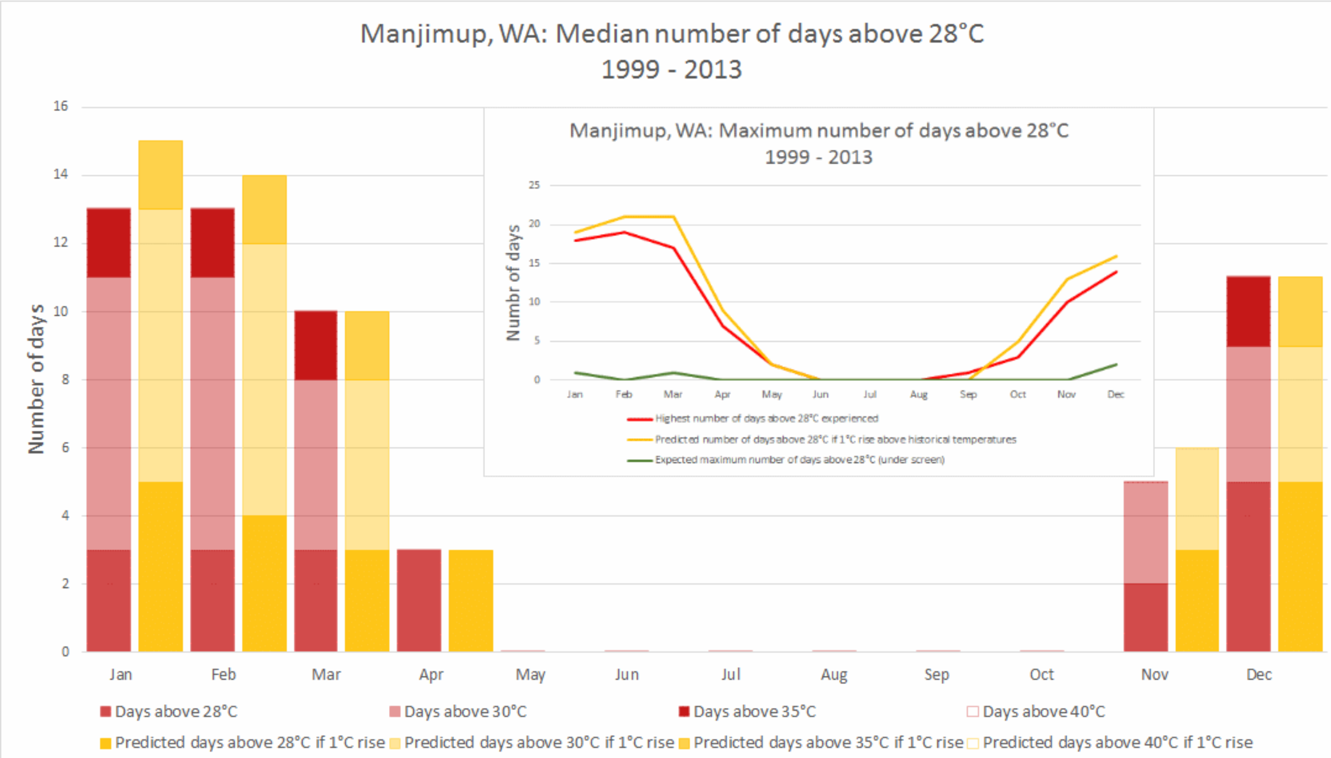


Figure 11: Median number of days above 28°C (red) for last 15 years at Manjimup, WA and with a 1°C predicted rise in temperature (yellow). Insert figure shows the maximum number of days above 28°C including expected maximum under screening (green).

Although crops such as spinach, rocket, broccoli and cauliflower have a higher temperature threshold (~30°C) at which yield and quality are adversely affected, the weather data shows that typically as many as one in three days across summer will have a negative impact. A protective screen reducing maximum temperatures by approximately 6°C would remove this impact.

Two additional effects of screening are a reduction in light levels (discussed below in the subsection *Impact on light levels*) and a reduction in airflow.

A screenhouse is likely to intensify the heat gain in the cropping area in this region. Screening materials restrict airflow. The impact of reduced air exchange is exacerbated under conditions of low wind speed. Low volumes of air exchange limit the amount of heat energy that can be removed from the cropping area and can reduce plant transpiration, affecting the level of evaporative cooling.

In Manjimup, warmer days are typically characterised by light to moderate wind speeds (Figure 12). Consequently, installation of a protected cropping element needs to consider the effect on air exchange during periods that cooling would be beneficial.

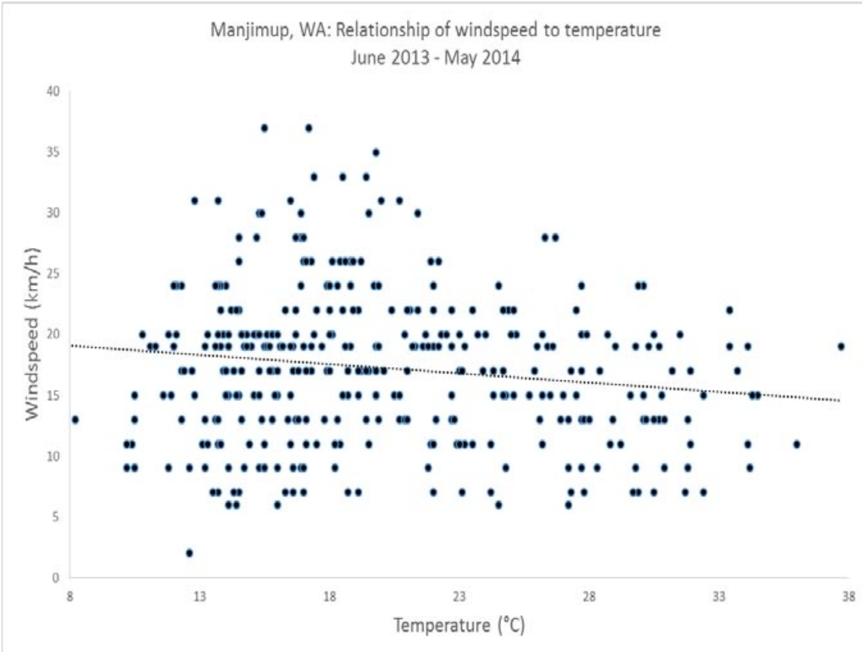


Figure 12: Warmer days are typically associated with lower wind speeds.

Under these conditions, reduced air movement in the cropping area could lead to increased temperatures. This means that enclosed protected cropping options such as screenhouses and floating crop covers that reduce ventilation would negate some or all of the benefits of shading.

Screening installed as a crop canopy would provide the shading effect with a lesser impact on airflow due to the open sides.

Additional cooling to manage high temperatures could be achieved in this region with an ancillary protected cropping option — fogging. Fogging creates evaporative cooling which could further improve growing conditions during days of excess heat. Higher temperatures are associated with lower relative humidity levels in this area which means that fogging could deliver significant temperature reductions and more than 7°C during excess heat days (Figure 13).

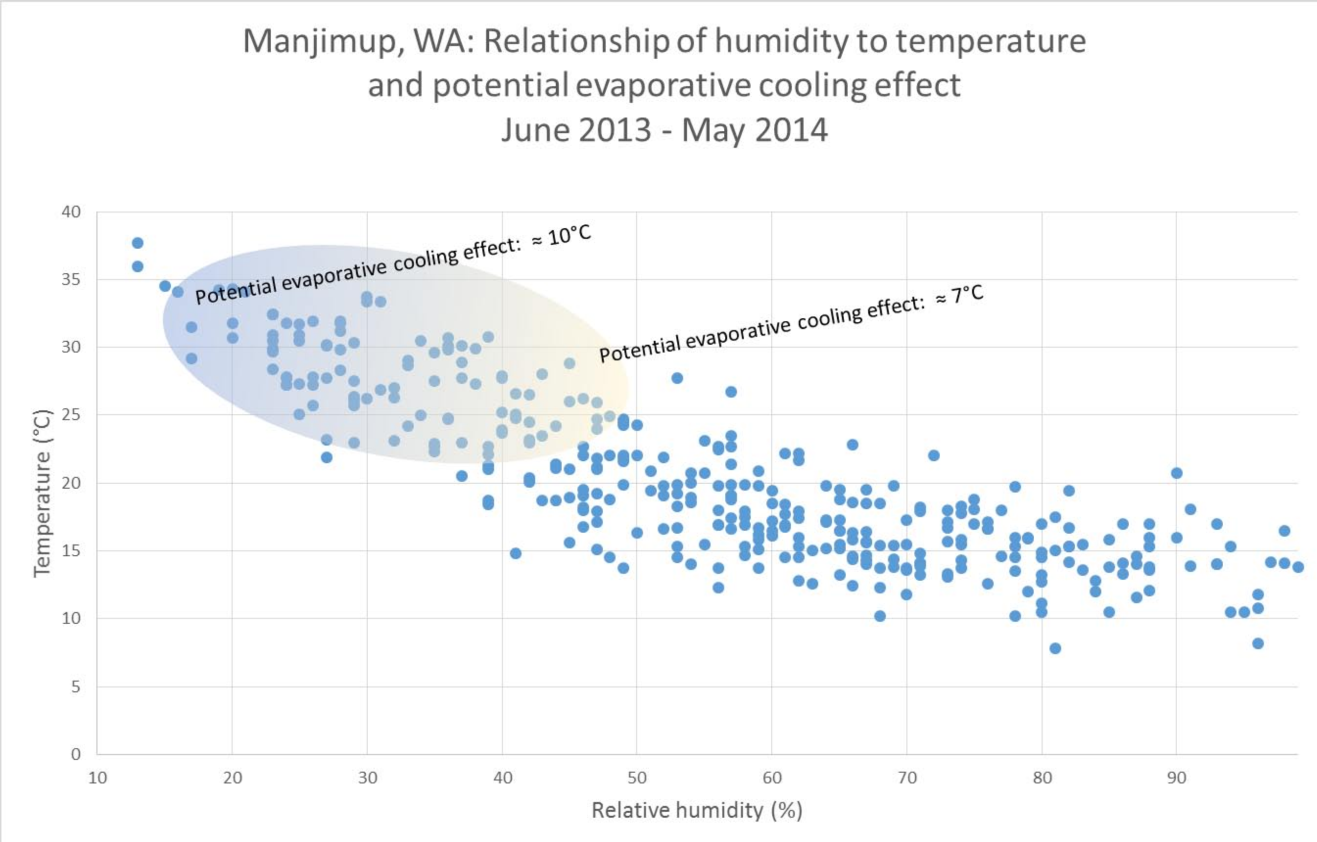


Figure 13: Warmer days are associated with lower relative humidity enabling significant evaporative cooling potential.

Coupled with screening, suitable conditions could be achieved year-round. Figure 14 illustrates the potential conditions for lettuce extended with screening and fogging.

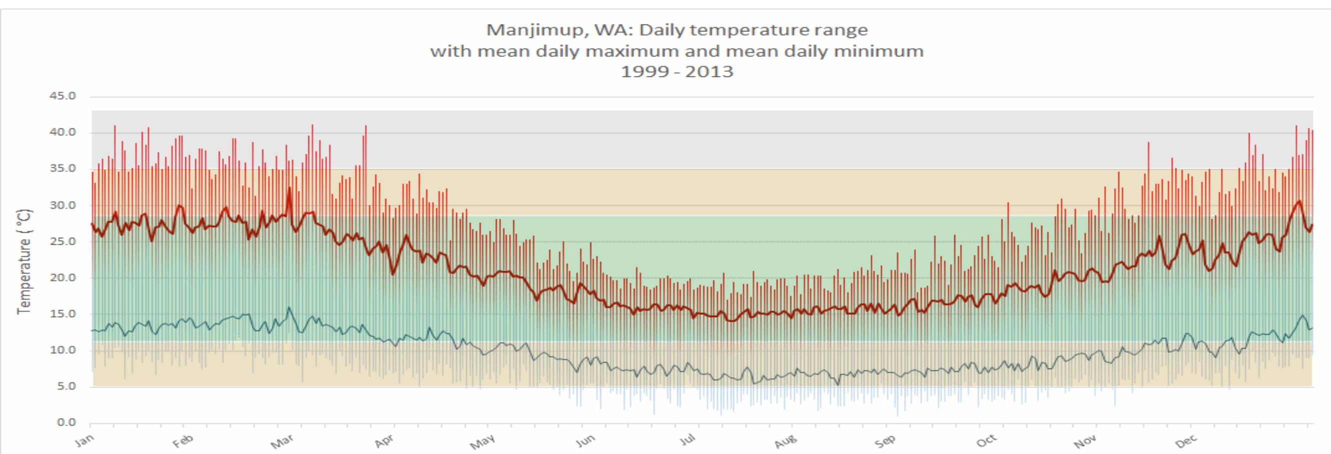


Figure 14: Mean daily temperatures and range for past 15 years at Manjimup, WA with overlay of suitable (green) and tolerable (tan) growing conditions for ***lettuce extended with screening with addition of fogging*** *(grey).*

5.1.3 Crop water use

Vegetable production in this region is based on local capture and storage of rainfall. Projections are that the observed 15% decrease in rainfall over the past 20 years will continue over the next 20 years with annual rainfall expected to decline by up to a further 9% by 2035[78].

Although rainfall follows a fairly consistent seasonal pattern, a dominant characteristic of this region is that the quantity of rain is quite variable year to year. Figure 15 illustrates the mean monthly rainfall for the past 15 years displayed against the monthly range, that is, the highest and lowest monthly falls over the same period.

This variability creates a high level of water risk. Low rainfall levels impact on availability of water for crop needs while high rainfall events can damage crops, decrease fertiliser efficiency and also lead to increased disease pressure.

Increasing variability in weather is likely to exacerbate this wide range in monthly falls, adding to the overall water management task. Additionally, the annual rainfall is projected to decrease by up to 9%[75].

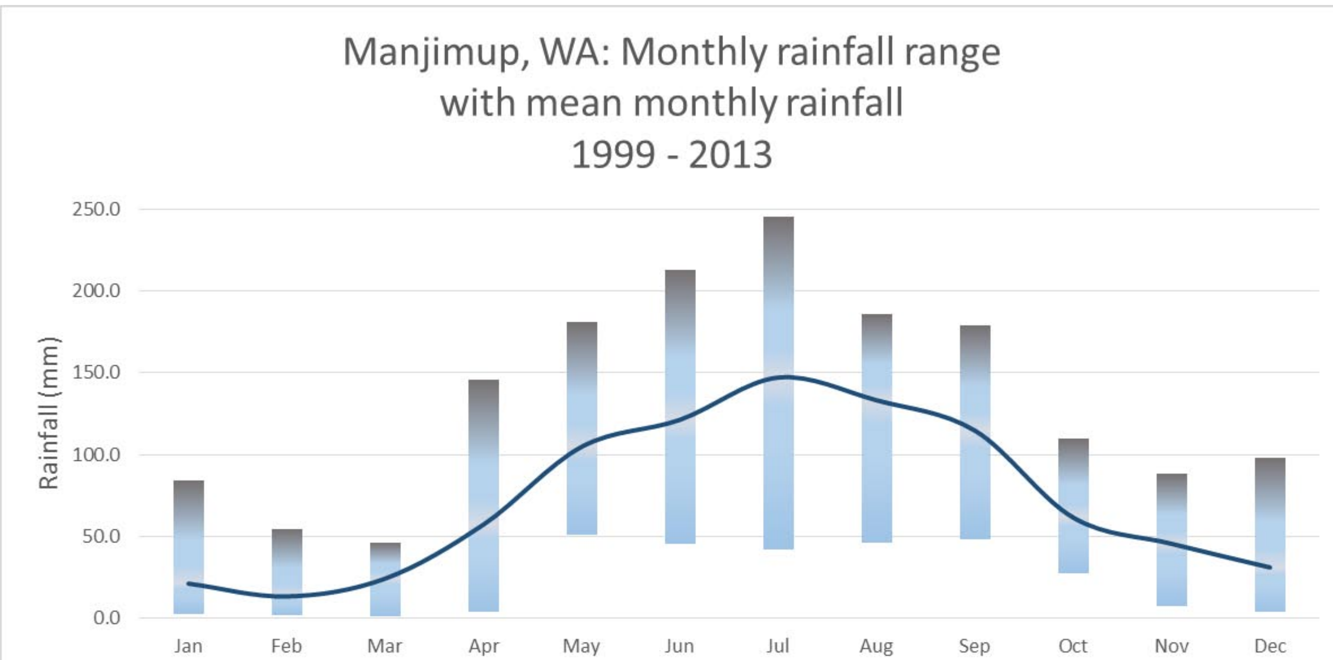


Figure 15: Mean monthly rainfall and range for past 15 years at Manjimup, WA.

Reducing crop water use and/or enhancing water capture are opportunities for which screenhouses and crop canopies could be utilised. Both options can be used to reduce incident radiation, lowering maximum temperatures and light levels which can reduce crop water demand. Reducing air movement and lowering wind speed can further impact on

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[78] G. Rogers (2013) Understanding and managing impacts of climate change and variability on vegetable industry productivity and profits, Final report VG12041 AHR

evapotranspiration rates. A crop canopy rainshelter could also be used to improve water capture and more tightly manage irrigation.

Crop water use is a key production factor that can be influenced with protected cropping. The historical monthly rainfall and approximate evapotranspiration[79] (in megalitres per hectare) is presented in Figure 16. The shaded part of the evapotranspiration columns indicates a potential reduction in crop water use that could be attained with some form of shade screening. In this region, during summer, the volume of the water that might be conserved exceeds the mean monthly rainfall for the same period.

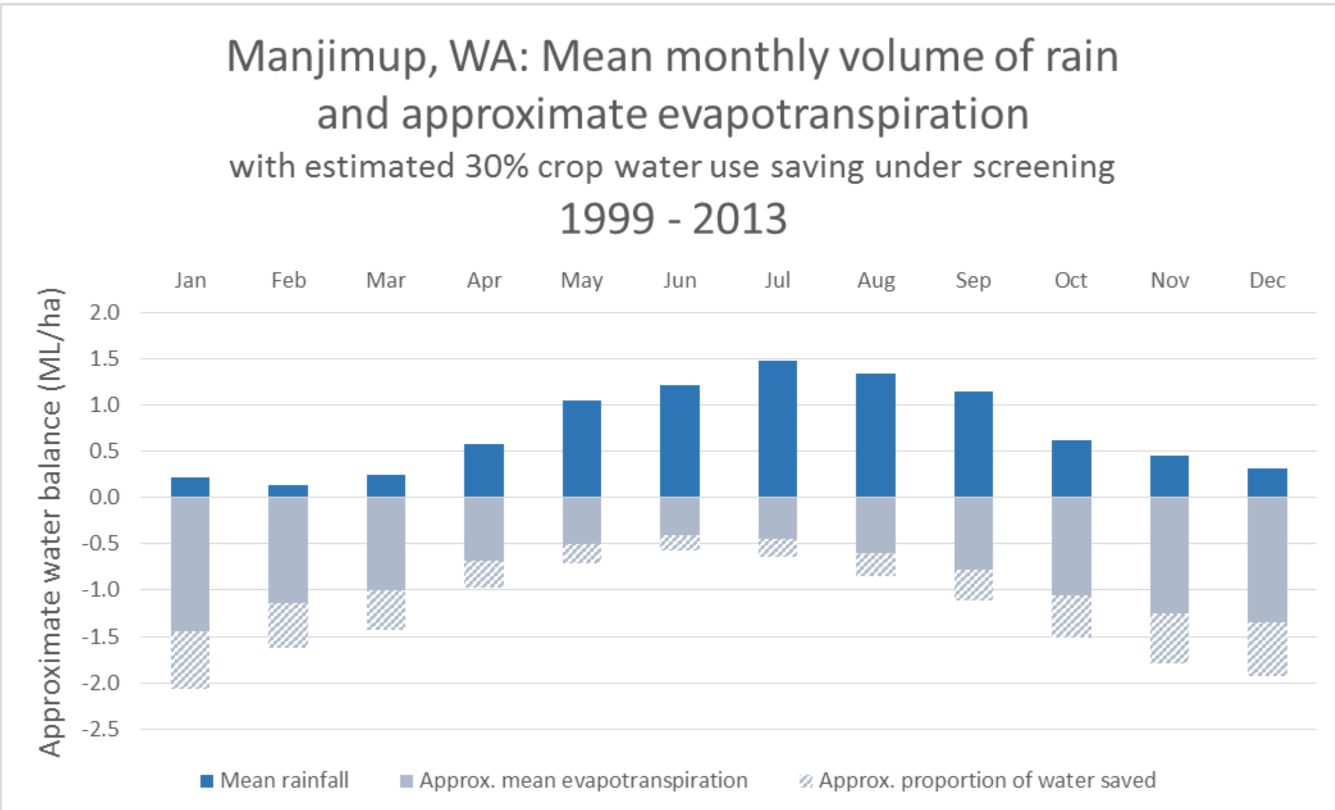

Figure 16: Approximate monthly rainfall and evapotranspiration for past 15 years at Manjimup, WA.

5.1.4 Frost and cool temperatures

Frost is an uncommon and minor production threat as the winter is fairly mild in this region. Although frost can occur, it is only within the winter months, posing little risk in the shoulder seasons (Figure 17).

Expectations of climate change in some regions are that the frost window will be extended, however this is not likely to result in an increased problem in this region.

[79] Evapotranspiration values used are an approximation (Hargreaves method) and a crop coefficient of 1 (lettuce, spinach). The full impact of crop water use is not only influenced by sunshine, but also temperature, windspeed and relative humidity.

Subsequently, frost is not a production constraint warranting investment attention, nor is increasing of minimum temperatures likely to be a priority for the target crops

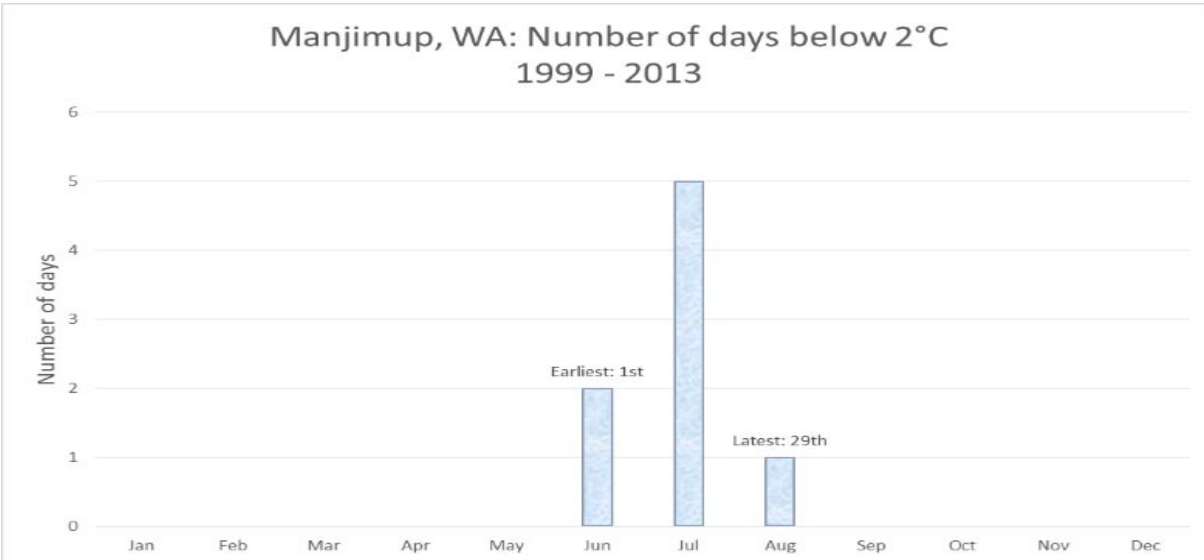

Figure 17: Highest number of days below 2°C per month (approximating the number of frosts) for the past 15 years at Manjimup, WA. Including earliest and latest occurrence.

5.1.5 Impact on light levels

Light is a critical growth parameter for all plants, and all plants have a minimum required amount of light to survive and grow. Plants that have a lower minimum light requirement also have upper thresholds beyond which damage can occur.

The impact on light levels has two important implications for protected cropping. In the first instance light levels can be reduced in order to protect crops that would otherwise be damaged by high light levels. Levels of tipburn in lettuce can increase when photosynthetically active light levels exceed around 17 $mol.m^{-2}.day^{-1}$ (depending on variety) and are further influenced by temperature, windspeed and relative humidity. This corresponds to approximately 3.5 $MJ.m^{-2}.day^{-1}$ which is below the mean monthly sunshine levels experienced in this region (Figure 18) indicating that crop quality could be improved by reducing light levels. The increased band of ‘suitable’ light levels is displayed in Figure 19 which assumes a screening material reduces radiation getting to the crop by 50%.

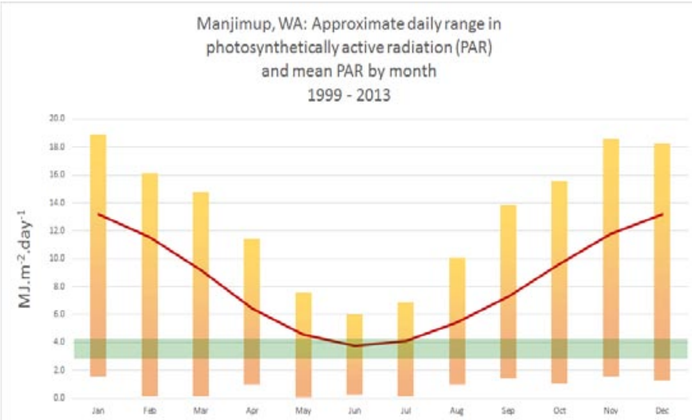

*Figure 19: Approximate levels of photosynthetically active radiation (PAR) for the past 15 years at Manjimup, WA with overlay of suitable light levels for **lettuce** (green).*

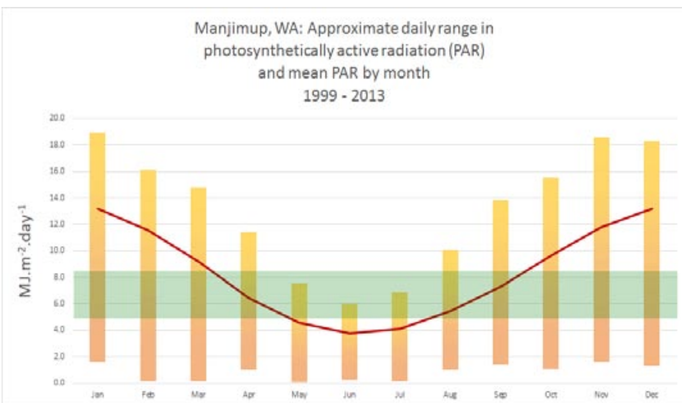

*Figure 18: Approximate levels of photosynthetically active radiation (PAR) for the past 15 years at Manjimup, WA with overlay of suitable light levels for **lettuce, extended by shading** (green).*

The second implication of reduced light levels is that any protective structure installed above a cropping area will impact on the amount and quality of light reaching the crop. The use of a screening material to reduce temperatures, for example, will necessarily also affect crop light levels. If light becomes limiting, the benefit of reduced temperatures is negated.

The use of a screening material in Manjimup over lettuce would not adversely affect light levels (Figure 19) and could provide a duplicate benefit of less extreme temperatures and improved light quality.

5.1.6 Manjimup LCPC assessment

The Manjimup region experiences high summer temperatures, mild winter temperatures, high light levels and variable rainfall. Temperatures are expected to rise and rainfall to decline and become more variable as a result of climate change. The primary focus for protected cropping in this region should be on managing extreme high temperatures and extended heatwaves.

Shading of 30 to 50% could decrease maximum temperatures by 6°C or more, containing mean maximum temperatures within crop thresholds, but a more realistic expectation of maximum temperatures indicate a significant number of excess heat days would not be sufficiently moderated. The addition of fogging would have large benefit on excess heat days in this region and would effectively mitigate excess heat days.

The high summer light levels could also enable a greater shading level to be suitable and provide further reduction in maximum temperatures. Reduced crop water use through summer would be expected to be a further benefit of shading. Any reduction in light levels would be detrimental to crops in winter. Crop coverings would need to be moveable or at least installed seasonally to avoid low light conditions.

Light to moderate winds prevail during warm to hot conditions in this region and could result in increased temperatures in a screenhouse due to reduced ventilation and airflow within the crop. Local conditions will need to be assessed. Low profile greenhouses, cloches and floating crop covers are likely to result in a similar problem as the reduction in incident radiation is coupled with significantly reduced ventilation in the cropping area.

A crop canopy structure could provide a shade cooling effect without adversely affecting airflow and subsequently remove heat from the cropping area. Depending on secondary objectives, either a shade screen or a rainshelter form could be used. The latter would enable more efficient collection of rainfall.

Floating crops covers could provide a benefit in the exclusion of crop and contaminant pests, though the adverse impact of higher temperatures for much of the year and reduced light levels in winter are likely to limit the overall benefit for much of the year and would need to be assessed at a local level.

Low profile greenhouses and plastic cloches are not likely to provide any suitable benefit due to the mild winter temperatures and would generate adverse high temperatures from November to April.

Windbreaks could provide some benefit in reducing plant damage resulting from ‘sandblasting’ but the generally light to moderate winds and high summer temperatures could lead to excess heat in the cropping area. Local assessment should be undertaken.

5.2 Werribee

5.2.1 Overview

The Werribee region represents a region producing several of the target crops in this review, including the production of leafy vegetables over summer as well as lettuce and brassica crops in winter.

This region is expected to experience increased variability in weather due to climate change at both extremes — in minimum temperatures throughout the year and maximum temperatures across spring and summer[80]. Higher summer maximum temperatures may adversely impact production as the annual maximum temperatures, across the year, are projected to increase between 0.6 and 1.3°C by 2035 and minimum temperatures are expected to rise 0.5 to 1.0°C. Rainfall is projected to decline by up to 14% necessitating improved water use efficiency in all crops.

Warmer winter temperatures may benefit winter crop development though shortening of the growing season. A wider frost window could affect the start and end of cropping seasons, while higher spring and summer temperatures may adversely impact on summer cropping. Decreasing availability and quality of irrigation water may impact production.

Mean daily maximum and minimum temperatures and the temperature range over the past 15 years are presented in Figure 20. The mean temperatures demonstrate a generally suitable growing environment with fairly distinct summer and winter seasons. This is reflected in the cropping programs in the region, though unfavourable daytime temperatures can occur on almost any day between November and late March.

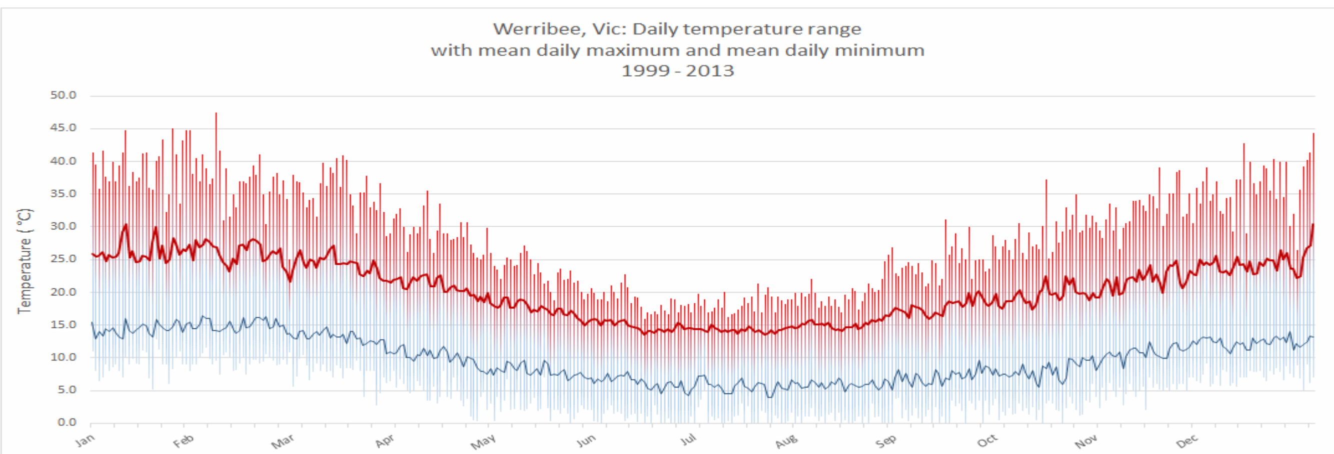

Figure 20: Mean daily temperatures and range for past 15 years at Werribee, Vic.

5.2.2 Managing high temperature

High summer temperatures are a primary production factor that could be mitigated with protected cropping in this region.

[80] G. Rogers (2013) Understanding and managing impacts of climate change and variability on vegetable industry productivity and profits, Final report VG12041 AHR

The mean temperatures demonstrate a generally suitable growing environment, however unfavourable daytime temperatures can occur on any day between late October and April (Figure 21).

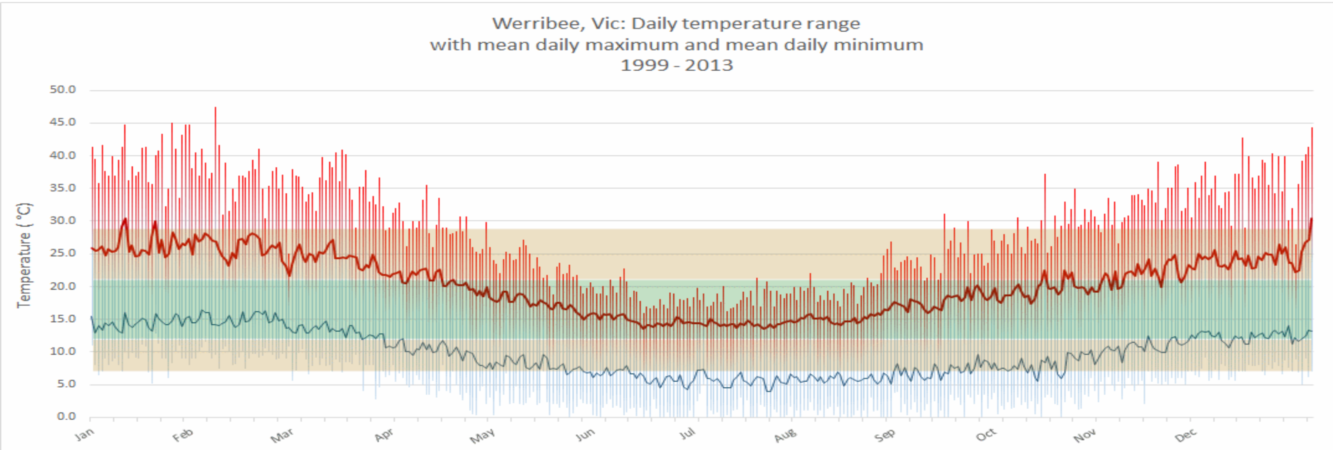

Figure 21: Mean daily temperatures and range for past 15 years at Werribee, Vic. with overlay of optimal (green) and tolerable (tan) growing conditions for ***lettuce****.*

Although screening could fully encompass the mean maximum temperatures to provide

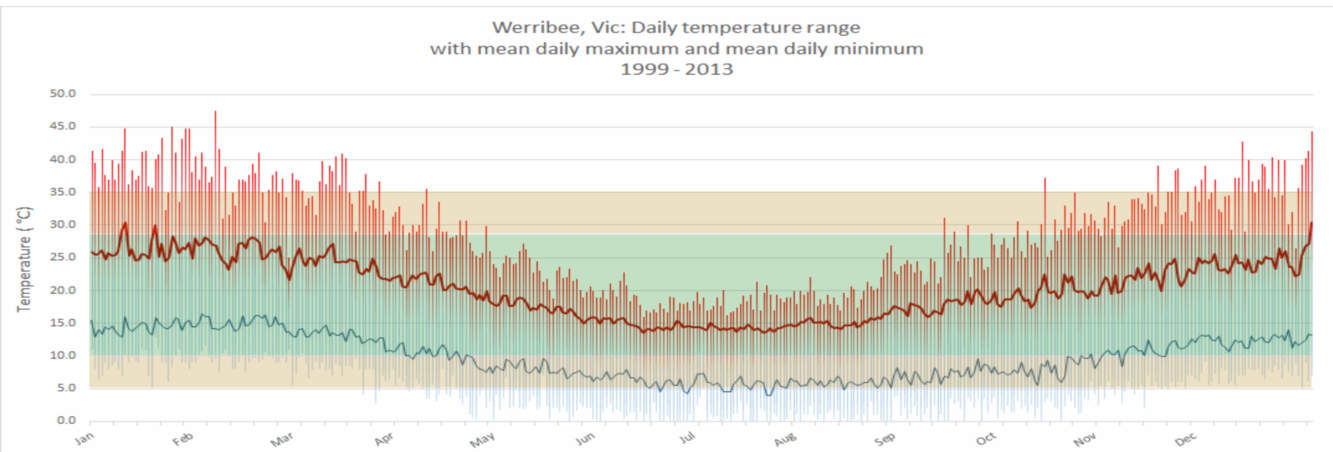

Figure 22: Mean daily temperatures and range for past 15 years at Werribee, Vic. with optimal (green) and tolerable (tan) growing conditions for ***lettuce extended with screening.***

suitable conditions (Figure 22), a substantial number of days in summer will potentially exceed the crop threshold and adversely impact growth and yield. This shortcoming would limit the net benefit of screening.

Some additional temperature reduction could be attained by incorporating evaporative cooling through fogging, however, weather data for the past year indicates that high relative humidity is associated with as many as one third of the excess heat days (Figure 23) in this region. High moisture levels in the air reduce the potential cooling and subsequently limit the overall benefit. A detailed analysis of environmental conditions and costs would be required to determine whether such a protected cropping option would be suitable.

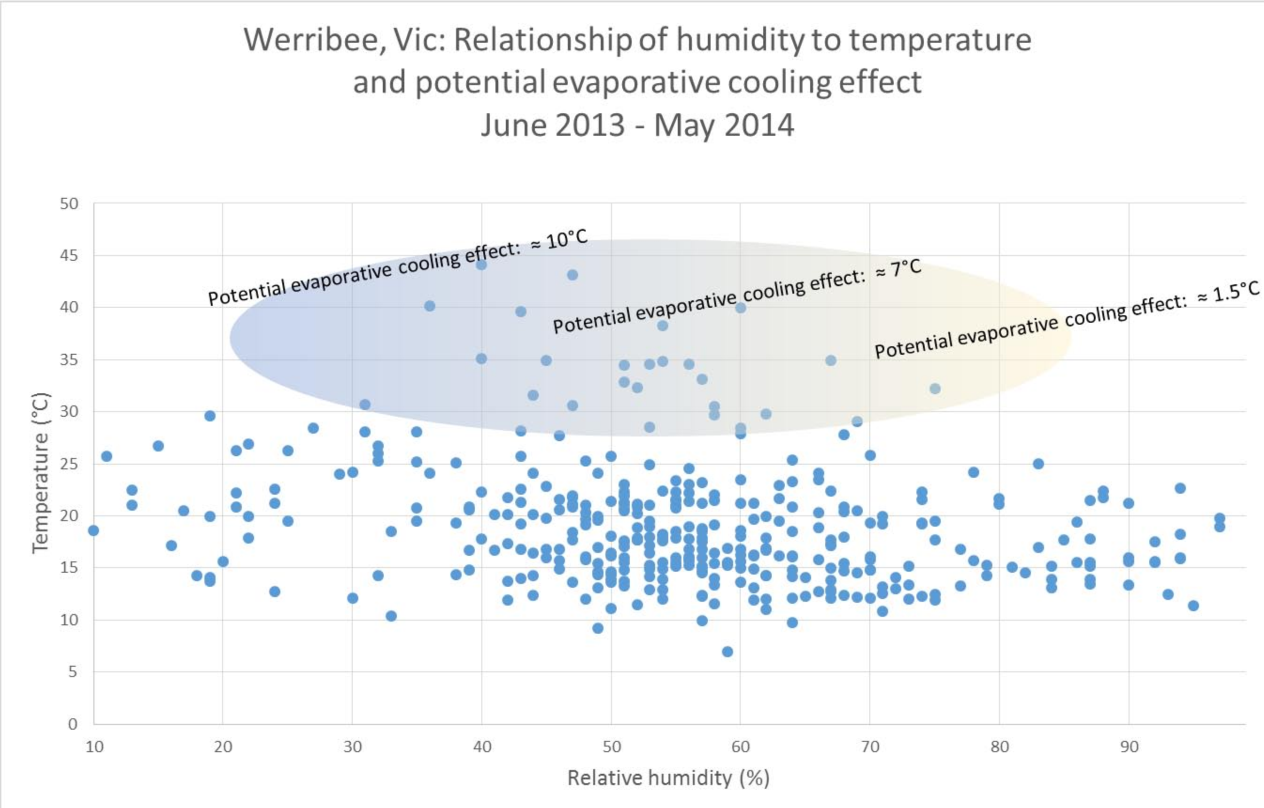

Figure 23: Warmer days are associated with a wide range of relative humidity levels resulting in varied evaporative cooling potential.

In addition to relative humidity considerations, this region is characterised by light to moderate wind speeds (Figure 24). The impact of reduced air exchange needs to be considered. Under warm, humid conditions, reduced air movement in the cropping area could lead to increased temperature and humidity, both of which can lead to crop growth problems. This means that enclosed protected cropping options such as screenhouses and floating crop covers that reduce ventilation would negate some or all of the benefits of shading.

Screening installed as a crop canopy would provide the shading effect with a lesser impact on airflow due to the open sides.

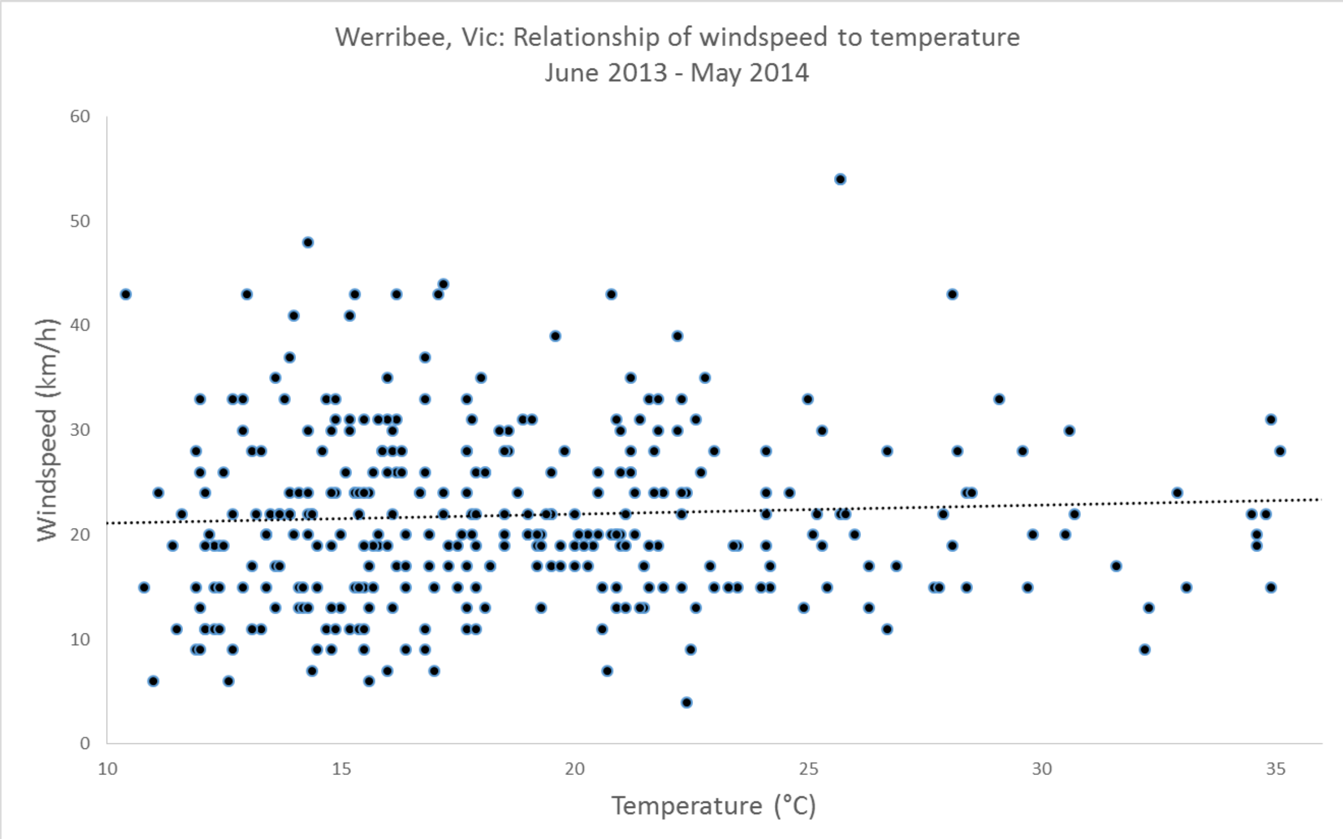

Figure 24: Light to moderate winds prevail in the Werribee region.

Extreme heat days pose an existing and likely increasing impact on vegetable crops in this region. A review of the median number of days over 28°C over the last 15 years (Figure 25) gives an indication of the occurrence of excess heat days that could typically be expected. Based on this data, over summer, farm managers in this region could expect the equivalent of almost two days per week (almost 25% of summer) reaching temperatures that would have a negative impact on crops.

A rise of 1°C on top of historical values would increase the typical number of excess heat days to almost one in three days over summer. A shading cover providing approximately 6°C of cooling could limit the maximum number of excess heat days to the equivalent of one day per week, with the typical number (median) dropping to one in ten days.

Low profile greenhouses and plastic clad cloches would be unsuitable under these conditions. A floating crop cover would worsen the conditions.

As discussed above, fogging to provide evaporative cooling could provide some degree of relief on up to two thirds of the hot days (based on conditions over the past year).

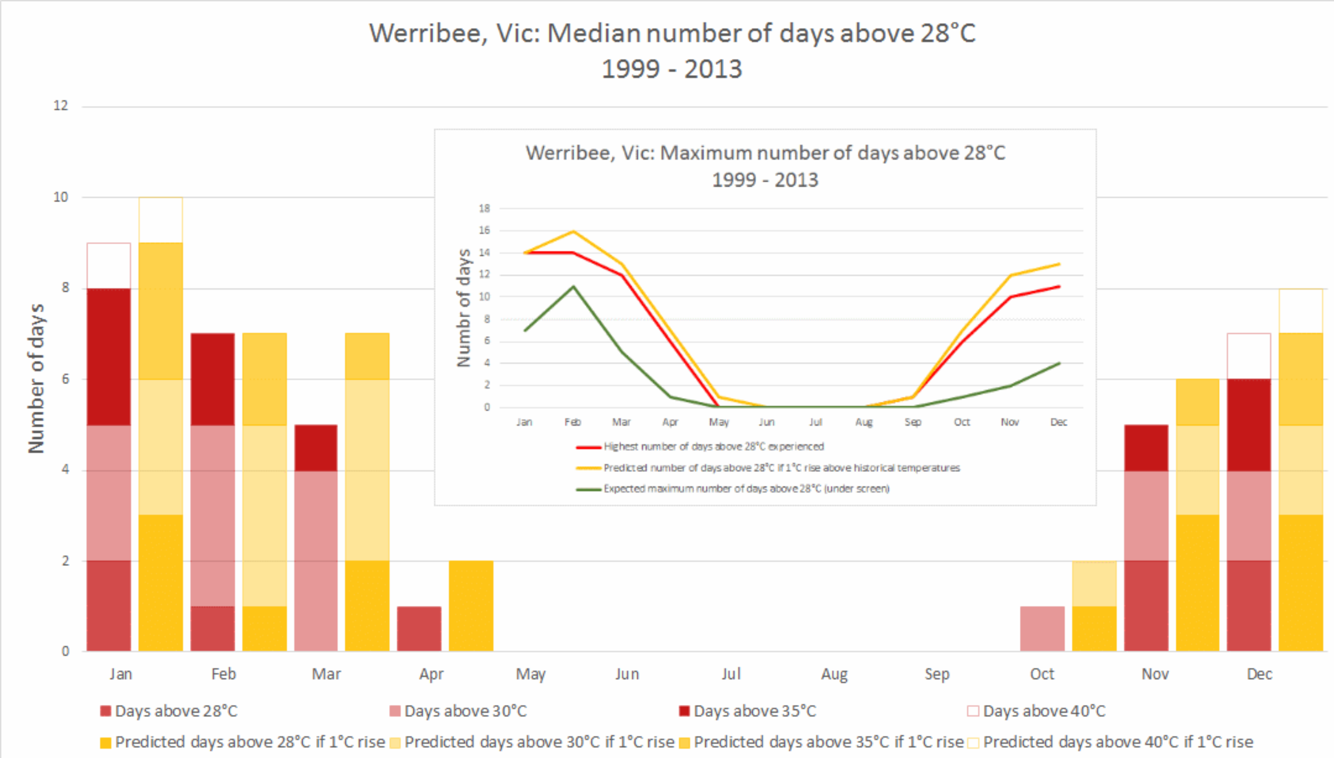

Figure 25: Median number of days above 28°C (red) for last 15 years at Manjimup, WA and with a 1°C predicted rise in temperature (yellow). Insert figure shows the maximum number of days above 28°C including expected maximum under screening (green).

5.2.3 Crop water use

Vegetable production in this region is based on local capture and storage of rainfall and ground water. Projections are that the mean annual rainfall could decline by up to 14% over the next 20 years[81].

Mean monthly rainfall is fairly consistent throughout the year though variability in summer rainfall is quite pronounced. This variability suggests that heavy rain in summer could pose a production constraint. Figure 26 illustrates the mean monthly rainfall for the past 15 years displayed against the monthly range, that is, the highest and lowest monthly falls over the same period.

Increasing variability in weather is likely to exacerbate this wide range in summer falls, adding to the overall water management task. The largest decrease in mean rainfall due to climate change is expected to occur in spring[79] which may create an increased water availability risk through summer.

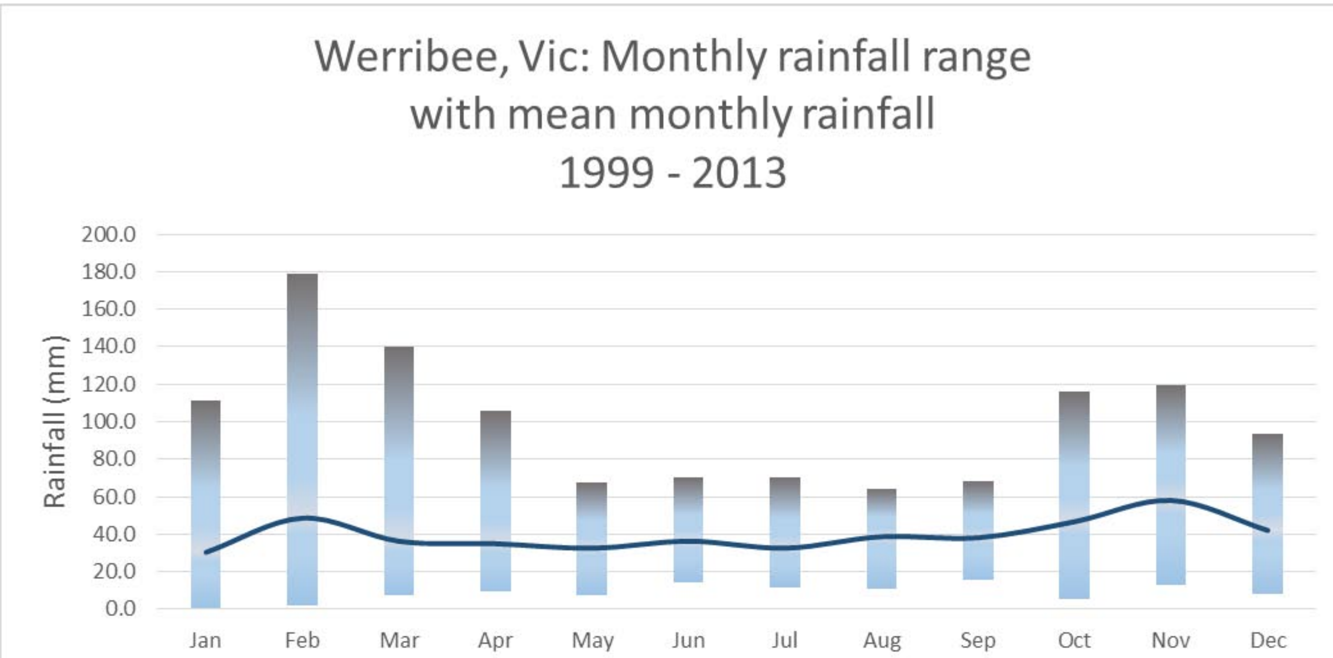

Figure 26: Mean monthly rainfall and range for past 15 years at Werribee, Vic.

Reducing crop water use may be an objective for protected cropping in a region such as this. The historical monthly rainfall and approximate evapotranspiration[82] (in megalitres per hectare) is presented in Figure 27. Evapotranspiration exceeds the mean monthly rainfall.

[81] G. Rogers (2013) Understanding and managing impacts of climate change and variability on vegetable industry productivity and profits, Final report VG12041 AHR

[82] Evapotranspiration values used are an approximation (Hargreaves method) and a crop coefficient of 1 (lettuce, spinach). The full impact of crop water use is not only influenced by sunshine, but also temperature, windspeed and relative humidity.

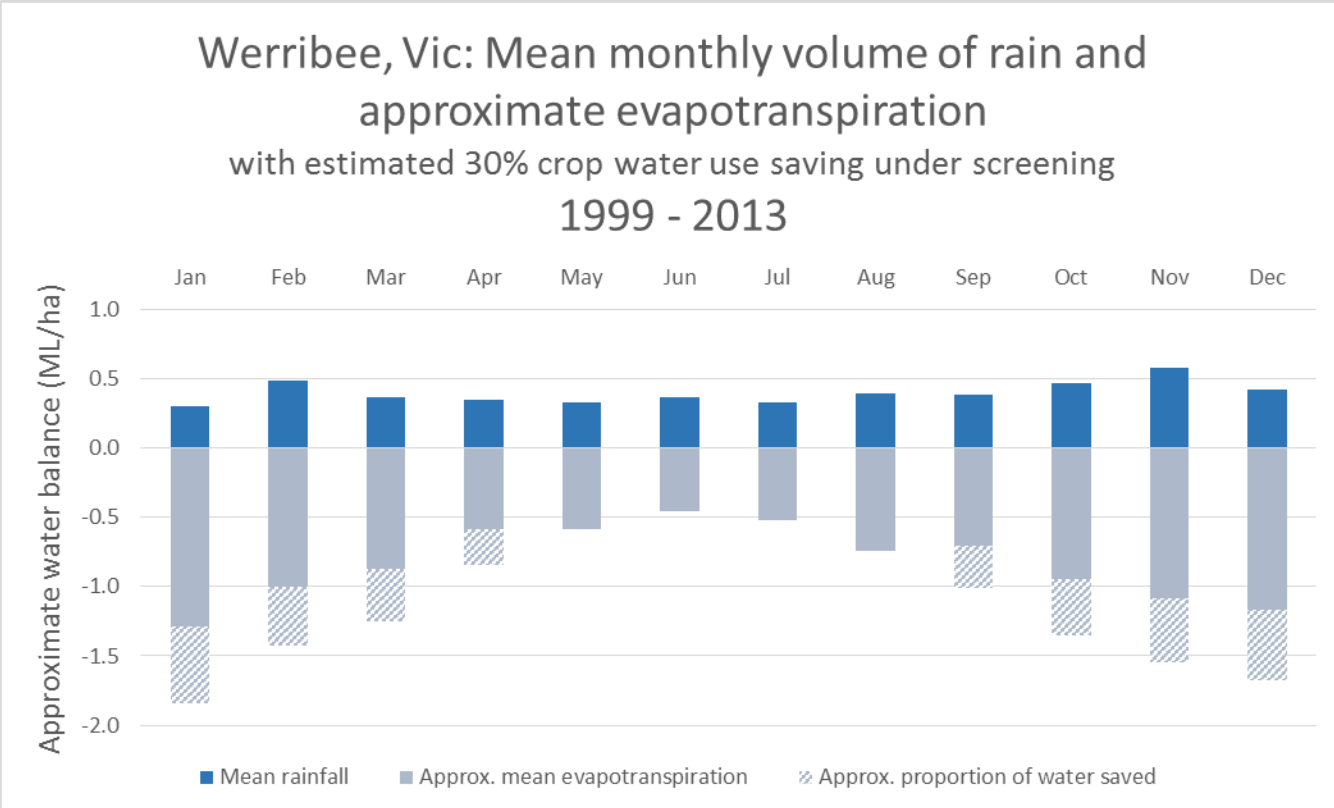

Figure 27: Approximate monthly rainfall and evapotranspiration for past 15 years at Werribee, Vic.

The installation of screenhouses and crop canopies could be utilised to moderate crop water use and/or enhance water capture in the case of a rainshelter. Both options can be used to reduce incident radiation, lowering maximum temperatures and light levels which can reduce crop water demand. The shaded part of the evapotranspiration columns indicate a potential reduction in crop water use that could be attained with some form of shade screening. In this region, during summer, the volume of the water that might be conserved exceeds the mean monthly rainfall for the same period with the exception of years in which high summer rains fall. There would not be a water saving in winter.

Reducing air movement and lowering wind speed can further influence evapotranspiration rates. A crop canopy, rainshelter or a low profile greenhouse could also be used to improve water capture and more tightly manage irrigation.

5.2.4 Frost and cool temperatures

Frost is a common and expected occurrence in winter though late frosts pose a production threat (Figure 28).

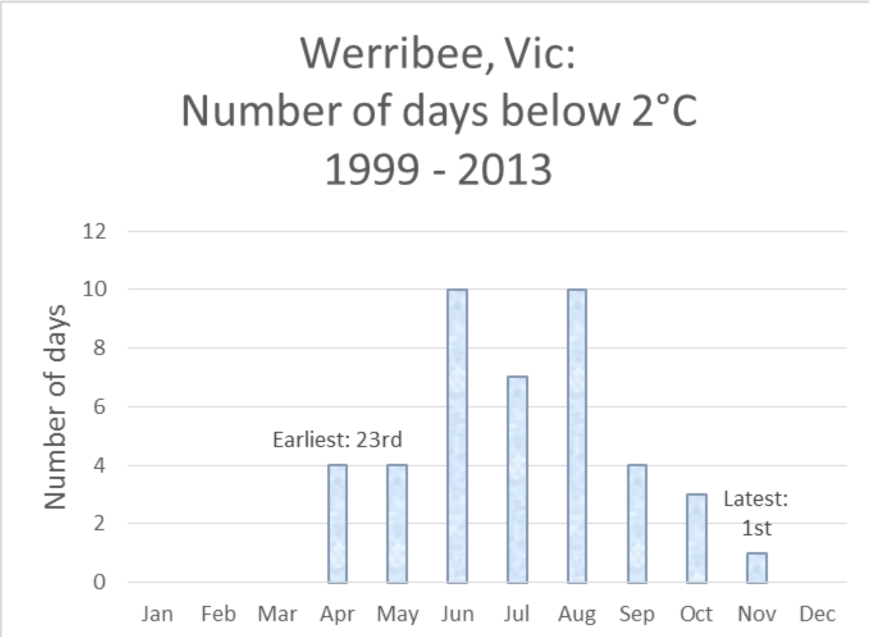

Figure 28: Highest number of days below 2°C per month (approximating the number of frosts) for the past 15 years at Werribee, Vic. Including earliest and latest occurrence.

A widening of the frost window is a projected effect of climate change for this region and could increase risk in establishing summer crops.

An average increase of four frost days each decade has been identified, and later endings for the frost window are occurring across southern Australia[83].

Screening has a minor effect in raising minimum temperatures and would provide suitable conditions in an average year, however, based on the past 15 years, minimum temperatures can register below 2°C on almost any day from May through to November, indicating a frost risk.

This is presented in Figure 29 which shows the suitable conditions for lettuce extended with screening. The red box highlights the days from the past 15 years which could have posed a frost risk. The frost risk in winter is accommodated through crop and variety selection so is not expected to be a production threat, but late spring frosts pose a significant risk for establishing summer crops.

[83] G. Rogers (2013) Understanding and managing impacts of climate change and variability on vegetable industry productivity and profits, Final report VG12041 AHR

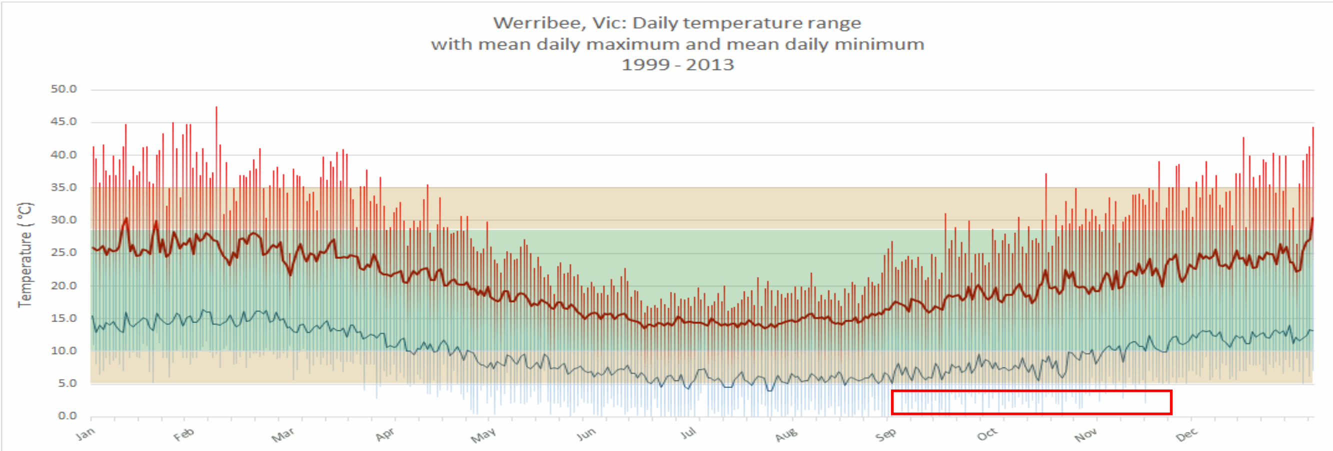

Figure 30: Mean daily temperatures and range for past 15 years at Werribee, Vic. with optimal (green) and tolerable (tan) growing conditions for lettuce extended with screening. Red box highlights potential frost risk in spring.

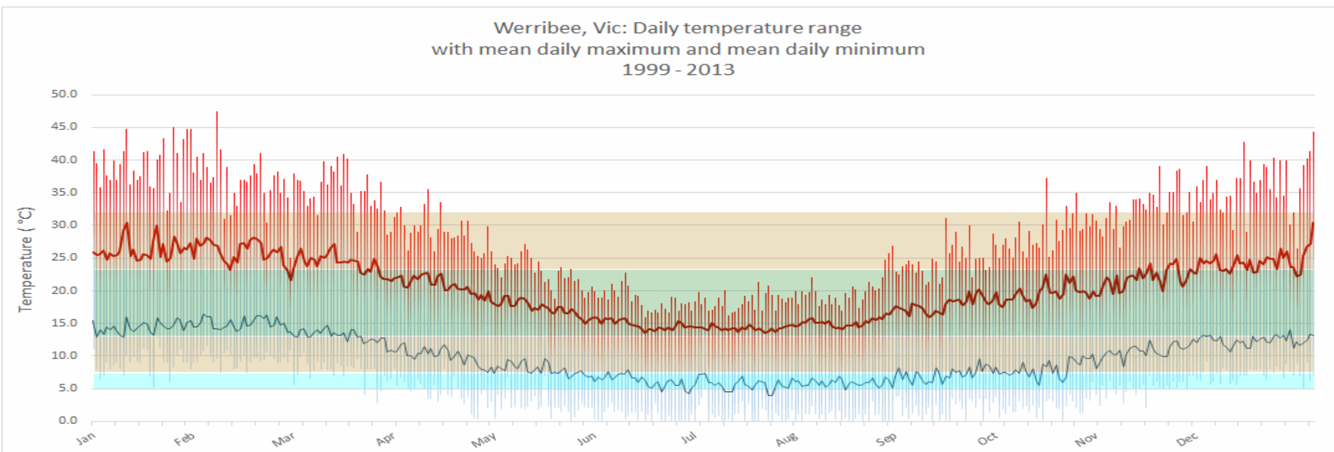

Figure 29: Mean daily temperatures and range for past 15 years at Werribee, Vic. with optimal (green) and tolerable (tan) growing conditions for lettuce extended with floating cover (blue).

A floating crop cover may only raise minimum temperatures by around 2°C[84]. This could provide a marginal benefit (Figure 30) but would not eliminate frost risk in this region. If the benefit of screening and floating cover can be accumulated, the combination of the two protected cropping options may reduce risk sufficiently to be feasible (Figure 31). It is not clear whether the two benefits could accumulate; a field trial would be of value to determine this. Combining a screen with a floating cover would necessitate the screen (at least) be retractable to avoid light deficient conditions during the day. A heavier floating cover can provide a slightly greater temperature rise, up to 3.8°C, making a more suitable option for regions such as Werribee.

[84] J. Dainello and R. Roberts, Texas Vegetable Growers' Handbook accessed online (2014): https://aggie-horticulture.tamu.edu/vegetable/guides/texas-vegetable-growers-handbook/chapter-iv-cultural-practices/

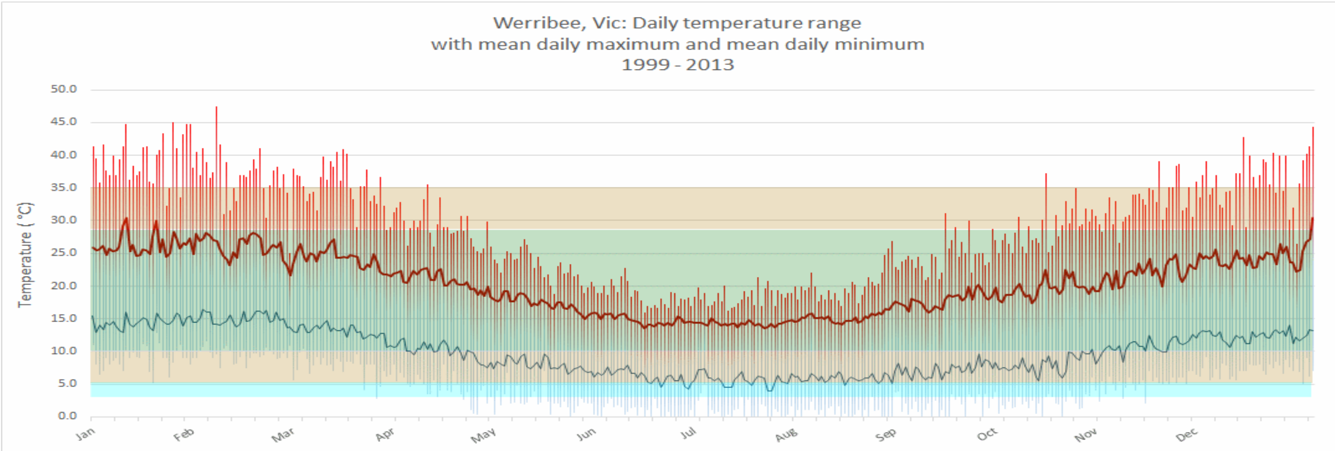

Figure 32: Mean daily temperatures and range for past 15 years at Werribee, Vic. with optimal (green) and tolerable (tan) growing conditions for lettuce extended with screening and with floating cover (blue).

Low profile greenhouses and cloches offer an effective means of raising minimum temperatures. Figure 32 illustrates the potential benefit in minimum temperature when growing lettuce under this type of protective element, however, similar to most areas in Australia, the increase in maximum temperatures across summer are detrimental to most crops.

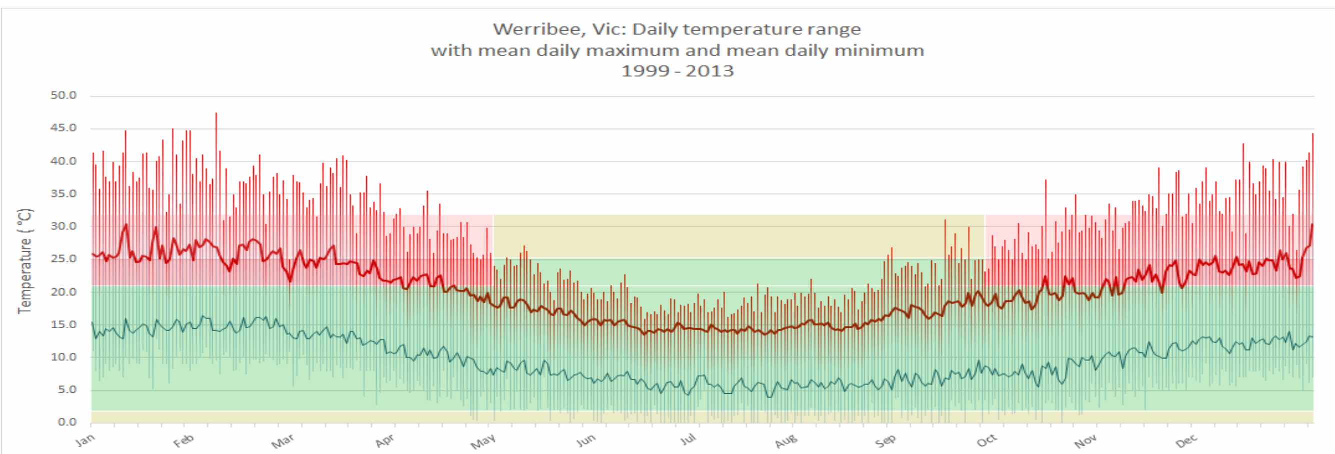

Figure 31: Mean daily temperatures and range for past 15 years at Werribee, Vic with overlay of suitable (green) and tolerable (tan) growing conditions for lettuce extended with plastic tunnel house or cloche. An adverse increase in maximum temperature over summer is indicated for a vented tunnel (light red) and a poorly vented tunnel or cloche (red).

5.2.5 Impact on light levels

During June and July, mean light levels in this region are just sufficient for a low light crop such as lettuce (Figure 33) though maximum light levels exceed the optimum and could be having an adverse impact for the remainder of the year. Figure 34 illustrates the optimal light level for lettuce expanded with shade screening. Using shade for reducing excess heat from November through to April would not be light limiting and could provide the double benefit of lower light intensity and reduced temperatures for summer-grown leafy vegetables. Growing of higher light requiring crops such as beans or capsicum under shade screening would be suitable from November through to April.

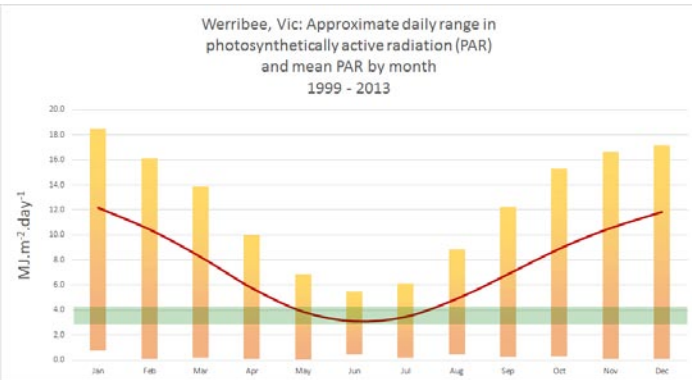

Figure 34: Approximate levels of photosynthetically active radiation (PAR) for the past 15 years at Werribee, Vic [Based on data from www.bom.gov.au] with overlay of suitable light levels for lettuce (green).

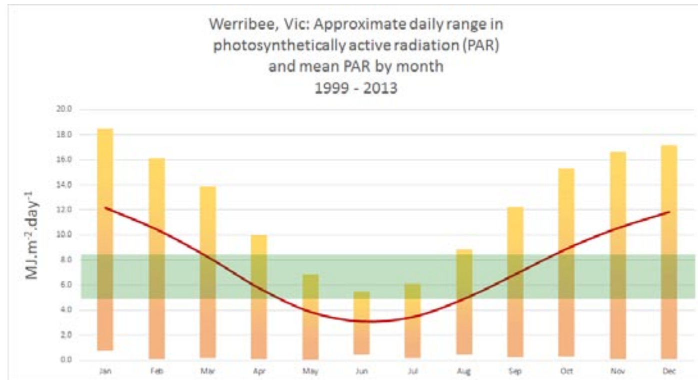

Figure 33: Approximate levels of photosynthetically active radiation (PAR) for the past 15 years at Werribee, Vic [Based on data from www.bom.gov.au] with overlay of suitable light levels for lettuce, extended by shading (green).

However, in this region, installation of screening would need to be seasonal or retractable, firstly because the daily range of sunshine is very large and additional shading during an extended low light period could be detrimental to crops, and secondly, resultant light levels under screening would be deficient through winter even for low light requirement crops such as lettuce.

All protected cropping options that cover the cropping area will reduce light levels. Plastic cladding on low profile greenhouses, rainshelters and cloches will have a shading effect similar to shadecloth rating from 20% up to 50% shade. The reduction in light transmission is not only a factor of the plastic itself, but is also affected by several factors including age of the material, dust/dirt and condensation.

The potential benefit of using tunnel houses or cloches to raise minimum temperatures in winter is likely to be somewhat negated by the growth limit imposed by a light deficiency.

5.2.6 Werribee LCPC assessment

The Werribee region experiences high summer temperatures, cool to cold winter temperatures with several frost days, high light levels in summer and low light levels in winter. Winds tend to be light to moderate. Summer rainfall can be variable.

The primary focus for protected cropping in this region should be on managing extreme high temperatures and extended heatwaves. Some frost protection may be feasible.

Shading of 30 – 50% could decrease maximum temperatures by 6°C or more containing mean maximum temperatures within crop thresholds, but a more realistic expectation of maximum temperatures suggests a significant number of excess heat days would not be sufficiently mitigated. The addition of fogging would have benefit but would be marginal on up to a third of excess heat days.

The high summer light levels could enable a greater shading level to be suitable and provide further reduction in maximum temperatures. Reduced crop water use through summer would be expected to be a further benefit of shading. Any reduction in light levels would be detrimental to crops in winter. Crop coverings would need to be moveable or at least installed seasonally to avoid low light conditions.

Light to moderate winds may result in increased temperatures in a screenhouse due to reduced ventilation and airflow within the crop. Local conditions will need to be assessed. Low profile greenhouses, cloches and floating crop covers are likely to result in a similar problem as the reduction in incident radiation is coupled with significantly reduced ventilation in the cropping area.

A crop canopy structure could provide a shade cooling effect without adversely affecting airflow and subsequently heat removal from the cropping area. Depending on secondary objectives, either a shade screen or a rainshelter form could be used. The latter would enable more efficient collection of rainfall.

Floating crop covers could provide a marginal frost protection benefit in establishing summer crops, though screening would provide a greater overall benefit in terms of temperature management. Exclusion of crop and contaminant pests could be achieved with floating covers, though adverse impacts on the growing environment in this area are likely to limit the overall benefit.

Low profile greenhouses and plastic cloches could significantly improve frost protection and minimum temperatures but need to be moveable or used seasonally to avoid adverse high temperatures from October to May. Low light conditions in winter will need to be carefully managed and high transmission cladding would be required and need to be well maintained. Condensation in winter will reduce light transmission.

5.3 Murray Bridge

5.3.1 Overview

The annual maximum temperature in the Murray Bridge region is projected to increase 0.6 – 1.1°C by 2035 and annual minimum temperatures are forecast to rise by almost as much though the frost window is also expected to increase[85]. Summer maximum temperatures already potentially exceed upper thresholds for most crops on almost every day between mid-November and April. Figure 35 illustrates the mean daily maximum and minimum temperatures and the temperature range over the past 15 years.

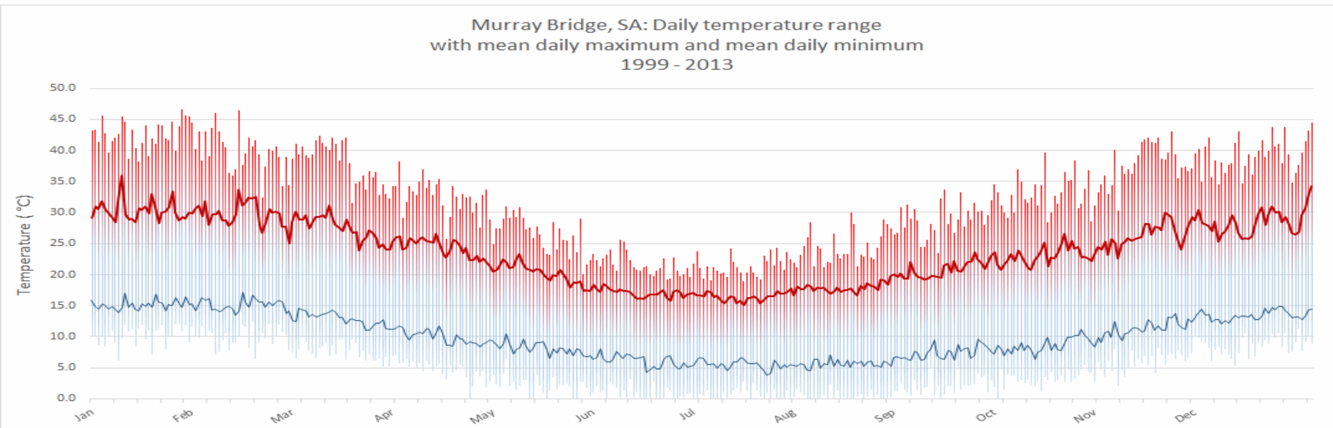

Figure 35: Mean daily temperatures and range for past 15 years at Murray Bridge, SA.

5.3.2 Managing high temperature

The region represented by Murray Bridge currently experiences excess heat days from mid-September through to May and mean maximum temperatures in summer fluctuate around the upper temperature thresholds for most vegetable crops.

Lettuce is traditionally harvested from this region throughout this period, while brassica crops are harvested year-round. Figures 36 and 37 present the suitable conditions for lettuce under ambient conditions and under a shade screen, respectively. Under these conditions, the potential decline in yield could be as much as 50%. Under screening, mean maximum temperatures are generally within the tolerable range, though based on the past 15 years, any day in summer could potentially exceed the upper threshold for lettuce even under shading.

[85] G. Rogers (2013) Understanding and managing impacts of climate change and variability on vegetable industry productivity and profits, Final report VG12041 AHR

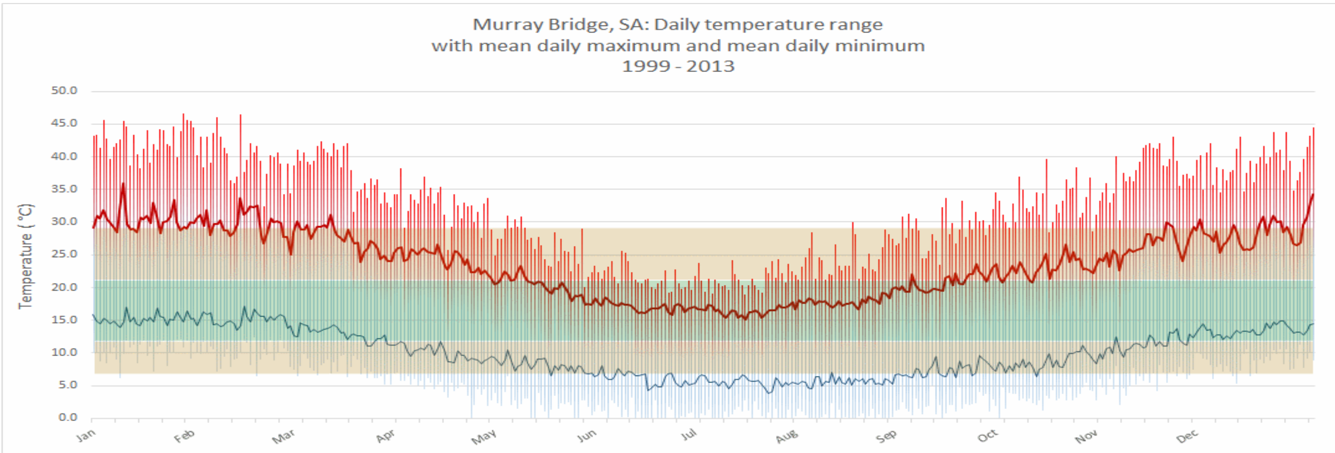

*Figure 36: Mean daily temperatures and range for past 15 years at Murray Bridge, SA. with suitable (green) and tolerable (tan) growing conditions for **lettuce**.*

The situation over summer is little better for brassica crops despite variety selections

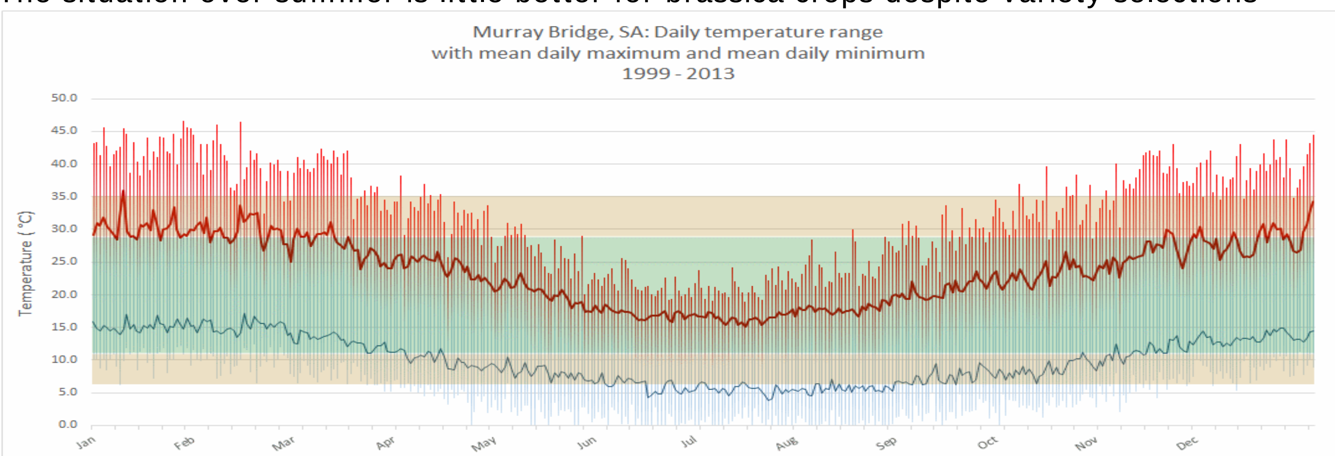

*Figure 37: Mean daily temperatures and range for past 15 years at Murray Bridge, SA. with suitable (green) and tolerable (tan) growing conditions for **lettuce extended with screening**.*

giving a wide temperature band (figure 38). These temperatures are potentially contributing to a significant reduction in yield and quality. Winter conditions are quite suitable for brassicas.

Some additional temperature reduction in summer could be attained by incorporating evaporative cooling through fogging. Weather data for the past year indicates that excess heat days (Figure 39) in this region are strongly associated with low relative humidity facilitating high evaporative cooling potential. Although a detailed analysis of environmental conditions and costs would be required to properly determine whether such a protected cropping option would be suitable, Figure 40 shows the potential conditions that might be attained with shade screening and fogging with reference to broccoli. A similar situation would exist for lettuce and baby-leaf crops.

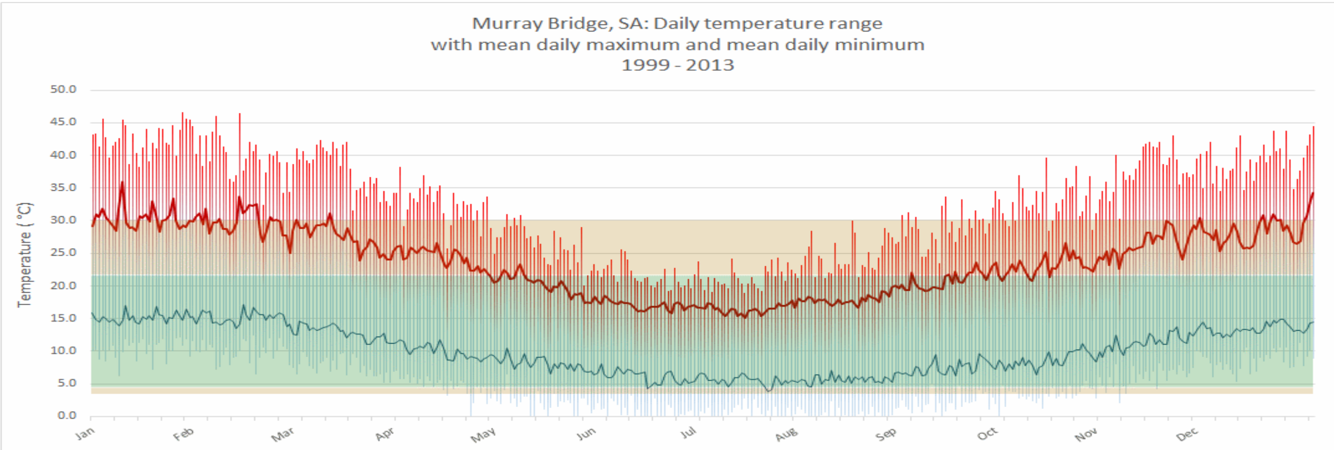

*Figure 38: Mean daily temperatures and range for past 15 years at Murray Bridge, SA. with suitable (green) and tolerable (tan) growing conditions for **broccoli.***

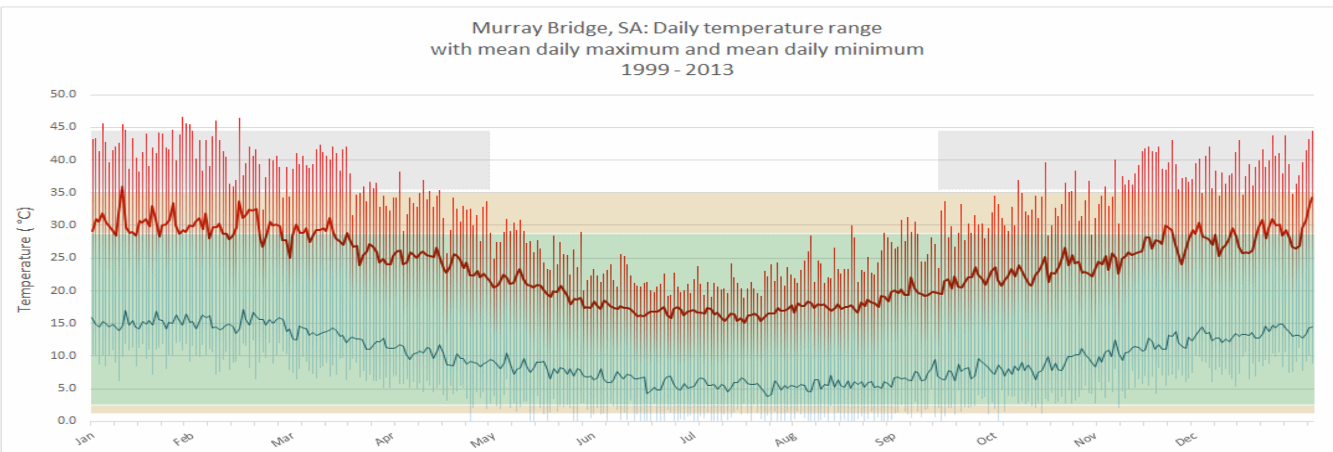

*Figure 39: Mean daily temperatures and range for past 15 years at Murray Bridge, SA with overlay of suitable (green) and tolerable (tan) growing conditions for **broccoli extended with screening with addition of fogging**.*

Combining shade screening and fogging could almost fully offset excess heat days in this area. Low profile greenhouses and plastic clad cloches would not be suitable in this region across summer and would be of marginal benefit in winter.

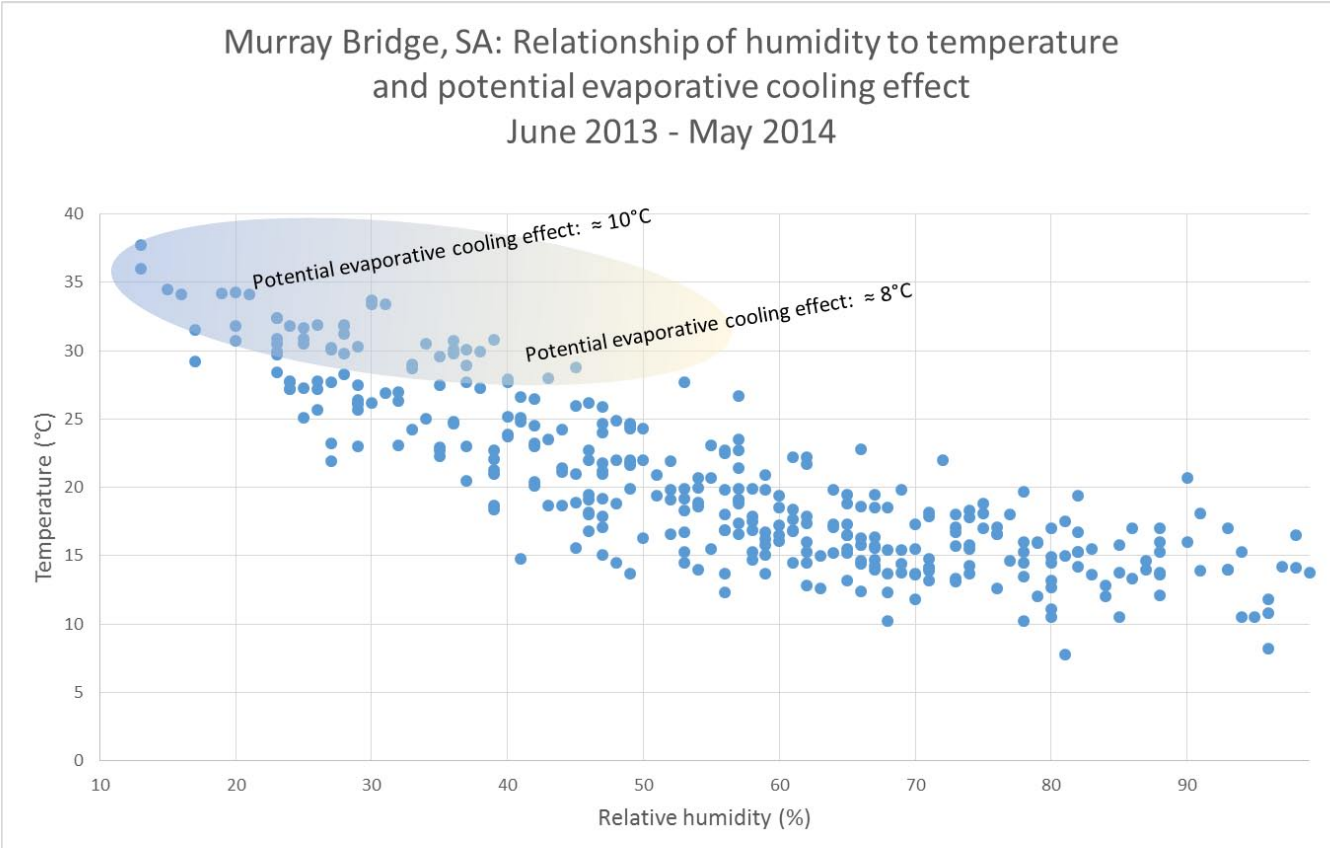

Figure 40: Warmer days are associated with a low relative humidity levels resulting in high evaporative cooling potential.

Light to moderate winds are usual in Murray Bridge (Figure 41) and the effect on air movement from a protected cropping element need to be taken into account. The reduced airflow in a standard enclosed shadehouse under light wind conditions on excess heat days may impact on the crop and a shade canopy could be a more suitable option. However, weather data from the past year show that several strong wind events occurred in this region. Windbreaks integrated with a shade canopy could offer an overall benefit. Reduced air flow and small air volume within a netted cloche is likely to negate any shade cooling benefit from this type of structure.

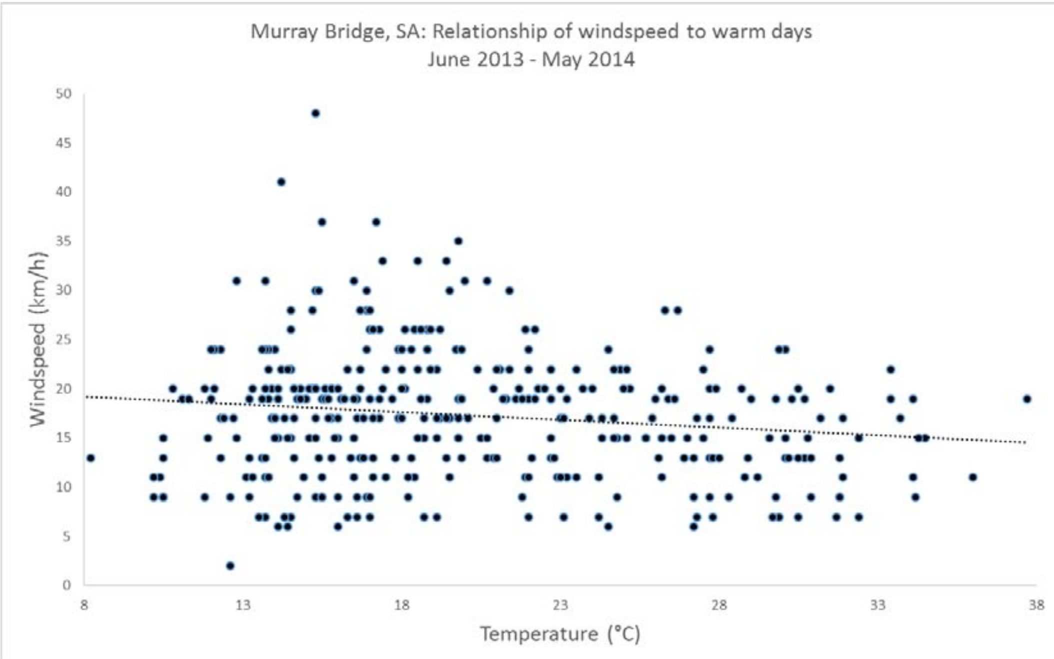

Figure 41: Light to moderate wind speeds dominate in this region, though strong wind events do occur.

Capsicum is being grown in this area as a response to increasing costs eroding profitability of low technology greenhouse crops in the North Adelaide Plains area.

Although capsicum is commonly considered a warm season crop, suitable temperatures for capsicum are quite moderate. The upper threshold for plant growth is around 32°C, however pollination is adversely affected above 27°C and fruit are susceptible to sun damage. Above the upper temperature threshold, yield could decline by as much as 20%[86]. More production could be achieved by offsetting the excess heat days with shade.

Figures 42 and 43 illustrate the suitability of ambient growing conditions and conditions modified with screening and fogging for capsicum in this region. Shading alone could provide suitable conditions in an average season (mean maximum temperatures) but could be insufficient to avoid yield loss in a typical season. The low humidity associated with high temperatures in this area mean that fogging, in addition to shading, could minimise yield decline due to excess heat and sun damage.

[86] G. Rogers (2013) Understanding and managing impacts of climate change and variability on vegetable industry productivity and profits, Final report VG12041 AHR

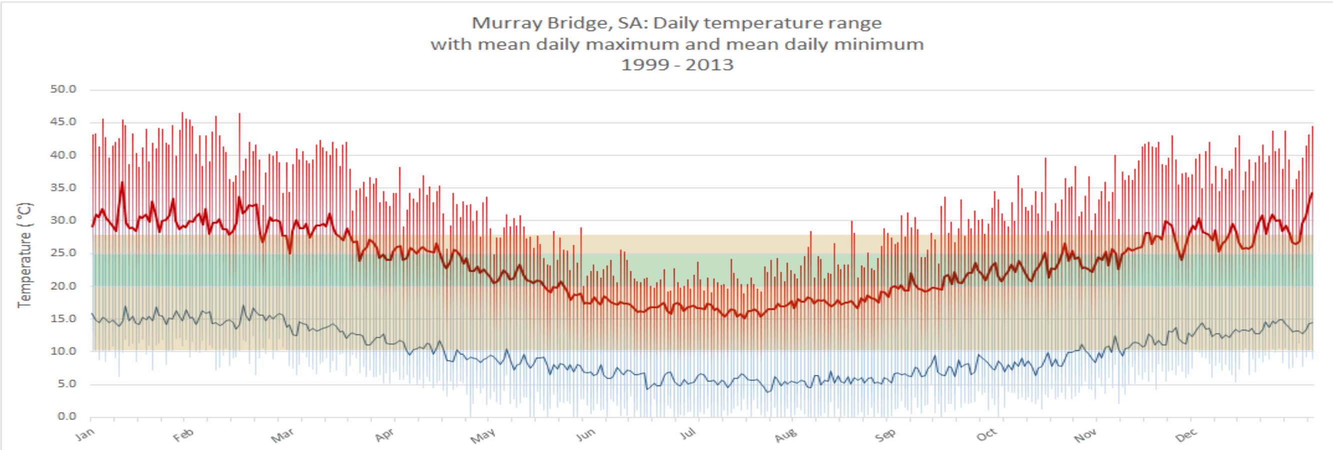

*Figure 43: Mean daily temperatures and range for past 15 years at Murray Bridge, SA with overlay of suitable (green) and tolerable (tan) growing conditions for **capsicum**.*

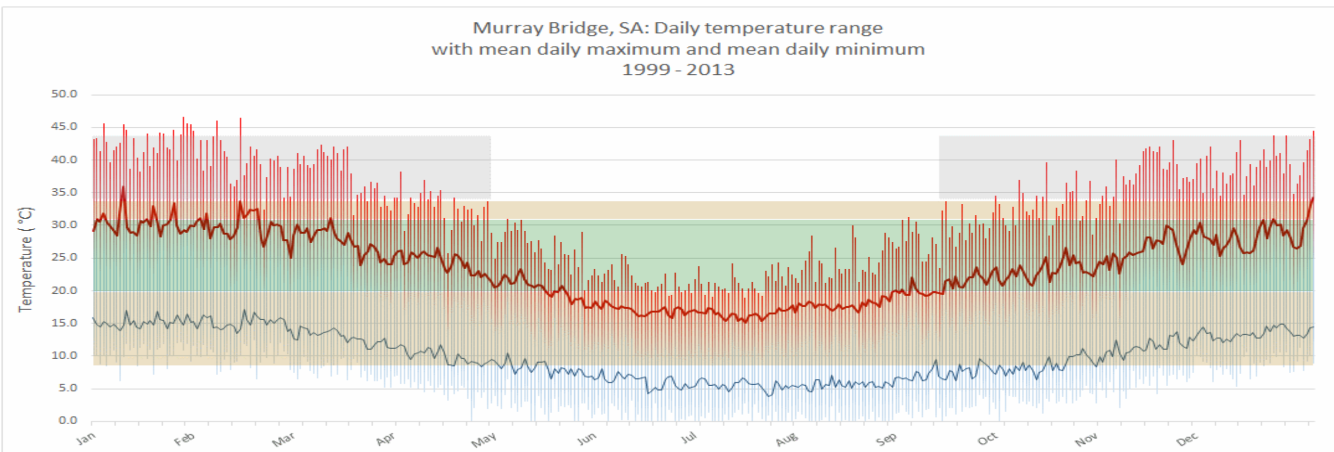

*Figure 42: Mean daily temperatures and range for past 15 years at Murray Bridge, SA with overlay of suitable (green) and tolerable (tan) growing conditions for **capsicum extended with screening with addition of fogging**.*

Excess heat days typically occur one in every two days over summer; illustrated by the median number of days over 28°C over the past 15 years in the Murray Bridge region (Figure 44). The maximum number of excess heat days experienced in the recent past has been as many as two in every three days over summer. The installation of shading could almost halve the maximum number of days that exceed the upper threshold for most crops, though the benefit would be more modest in a typical season.

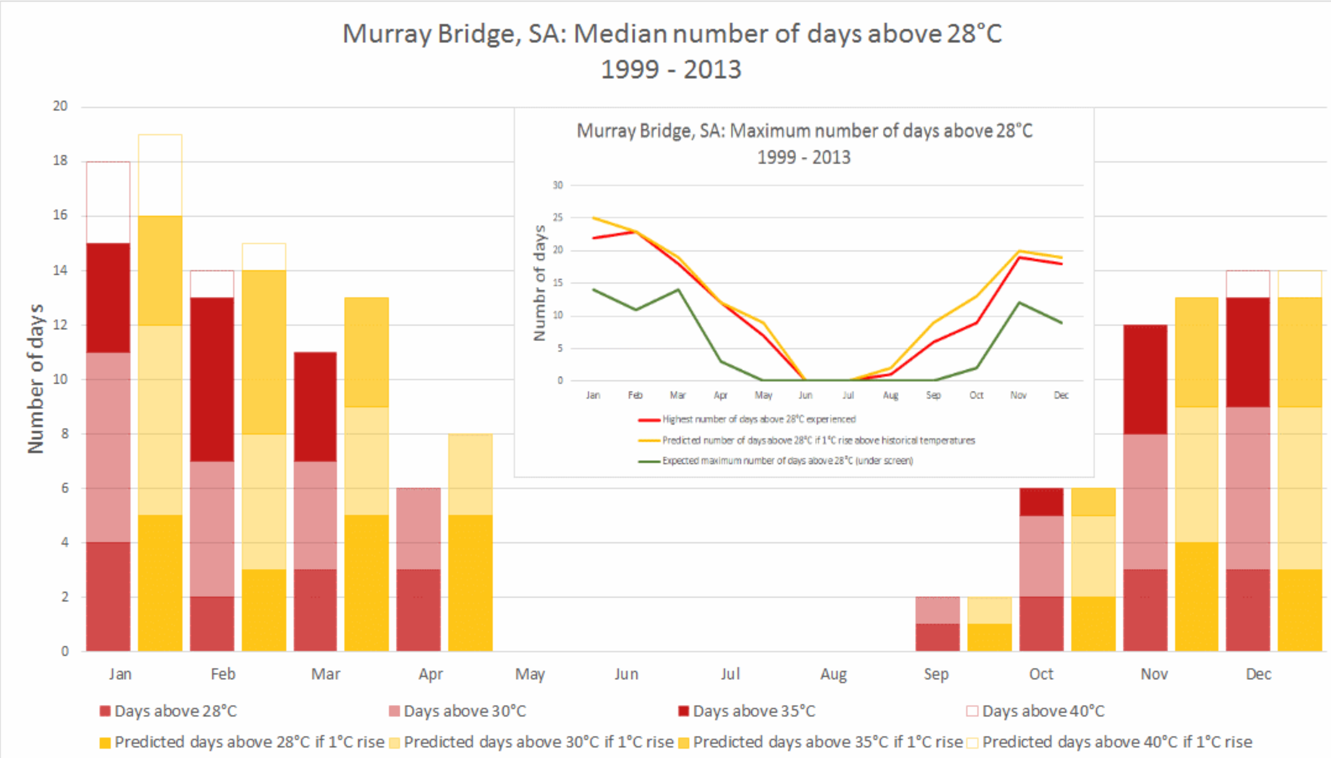

Figure 44: Median number of days above 28°C (red) for last 15 years at Murray Bridge, SA and with a 1°C predicted rise in temperature (yellow). The insert graph shows the maximum number of days above 28°C including expected maximum under screening (green).

5.3.3 Crop water use

Mean rainfall is fairly consistent throughout the much of the year. The mean monthly rainfall and monthly range for the past 15 years is presented in Figure 45. January is relatively dry while quite large amounts of rain are experienced in June. Heavy rainfall events may pose a production risk.

The mean annual rainfall in this area is projected to decline by as much as 15%, with a similar reduction in surface water availability in the Murray River. Crop water use is a significant production factor that could be modified with protected cropping, however with irrigation dependent on river flows, upstream rainfall will have a more significant impact for this region.

Evapotranspiration rates are quite significant, at more than four times mean monthly rainfall for most of the year. Crop shading could have a significant effect in reducing crop water use and/or increasing water use efficiency. Figure 46 illustrates the approximate mean volume of rain and evapotranspiration by month from the past 15 years. The shaded component of the evapotranspiration represents a 30% water saving under shade screens.

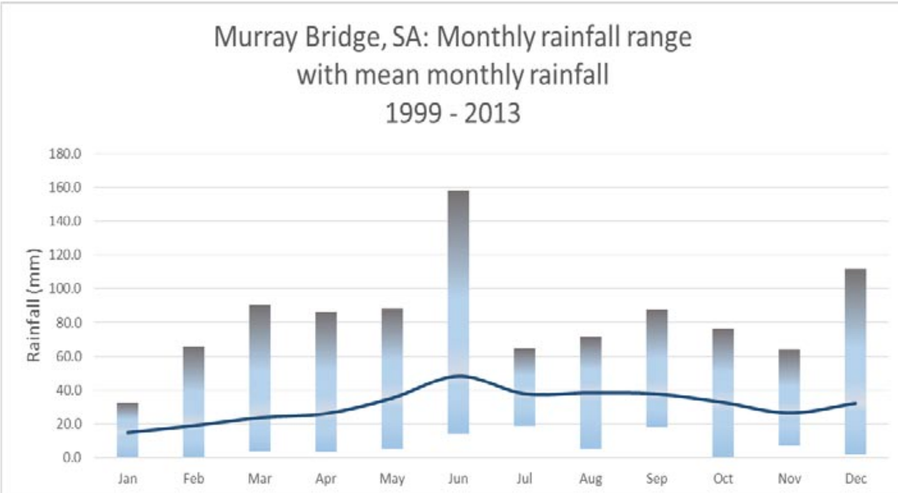

Figure 45: Mean monthly rainfall and range for past 15 years at Murray Bridge, SA.

Windbreaks may also provide some reduction in crop water use by reducing air movement through the crop but unlike shade screening, windbreaks would not have the benefit of reducing maximum temperatures and could result in higher temperatures within the cropping area by reducing the rate at which heat energy is removed.

Other protected cropping elements including tunnels, cloches and floating covers are not likely to provide any benefit in crop water use or from improved water use efficiency due to expected impacts of excessive temperatures which would occur under these options.

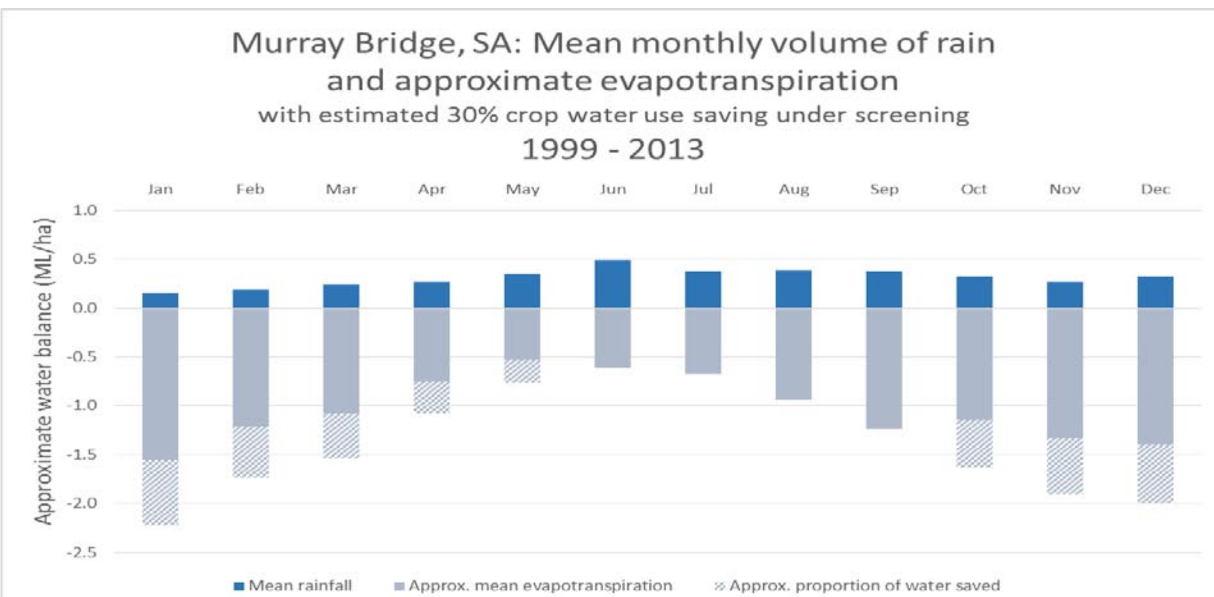

Figure 46: Approximate monthly rainfall and evapotranspiration for past 15 years at Murray Bridge, SA.

5.3.4 Frost and cool temperatures

The frost window is projected to increase in this area as the climate changes. Frost is a common event through winter in this region. The number of frost days over the past 15 years as approximated by the number of days that temperatures fall below 2°C is shown in Figure 47. The current frost window extends from mid-April to mid-October. Later occurring frosts pose a significant risk for establishment of summer crops while early frosts could have a big impact on late finishing summer crops, particularly as daytime temperatures during April and May can still be quite high, with mean maximum temperatures in the mid-twenties providing otherwise suitable conditions for most summer crops.

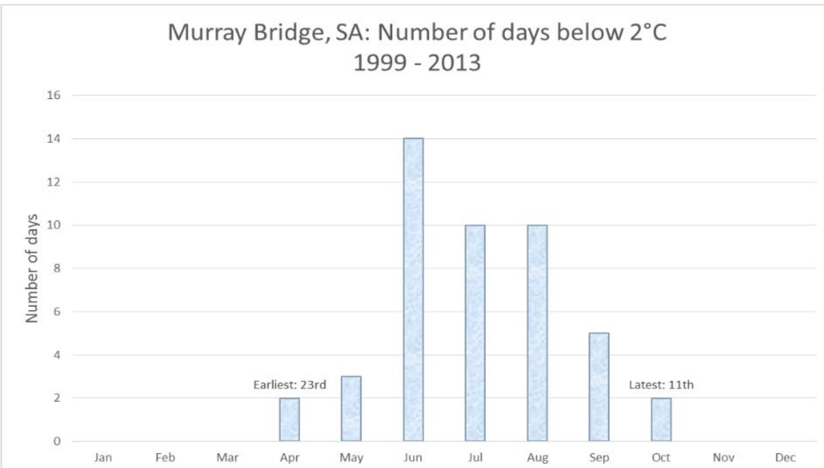

Figure 47: Highest number of days below 2°C per month (approximating the number of frosts) for the past 15 years at Werribee, Vic. Including earliest and latest occurrence. [Based on data from www.bom.gov.au]

Floating crop covers could be suitable to mitigate frost risk to protect warm season varieties in autumn and establishment of summer crops in spring. A more versatile option could be achieved with a retractable shade screen which could offer an equivalent benefit in raising minimum temperatures during the transition periods and help mitigate excess heat during the day. The possible influences of these protective options on the suitability of growing conditions for lettuce are illustrated in Figures 48 and 49.

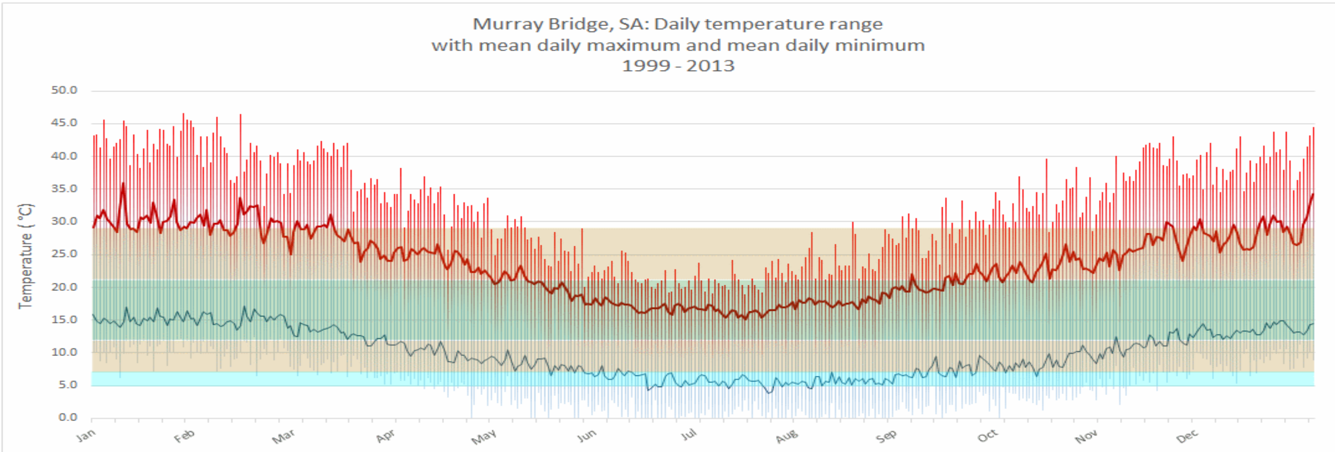

*Figure 49: Mean daily temperatures and range for past 15 years at Murray Bridge, SA. with suitable (green) and tolerable (tan) growing conditions for **lettuce extended with floating cover** (blue).*

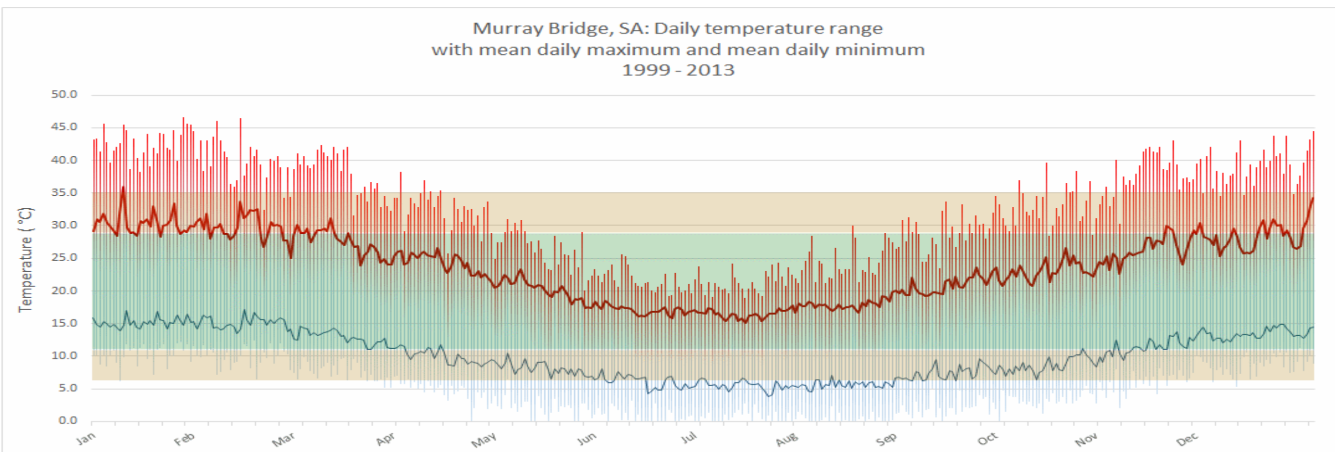

*Figure 48: Mean daily temperatures and range for past 15 years at Murray Bridge, SA with overlay of suitable (green) and tolerable (tan) growing conditions for **lettuce extended with screening**.*

Low profile greenhouse and cloches could significantly improve minimum temperatures and minimise frost risk, however the high maximum temperatures that can occur from early spring through to late autumn would be intensified under these structures. This is illustrated in Figure 50. To be of net benefit, these option would need to be moveable or only used seasonally. Although cloches are moveable, this task would need to be done quite regularly to avoid adverse effects of excess heat and the likely high labour cost of this task will probably make cloches unsuitable for most enterprises.

Improved ventilation in low profile greenhouses would significantly increase the usefulness of this protected cropping option in the transitional periods and through winter but for at least half the year the negative impacts of high temperatures would outweigh any frost protection of low temperature benefit.

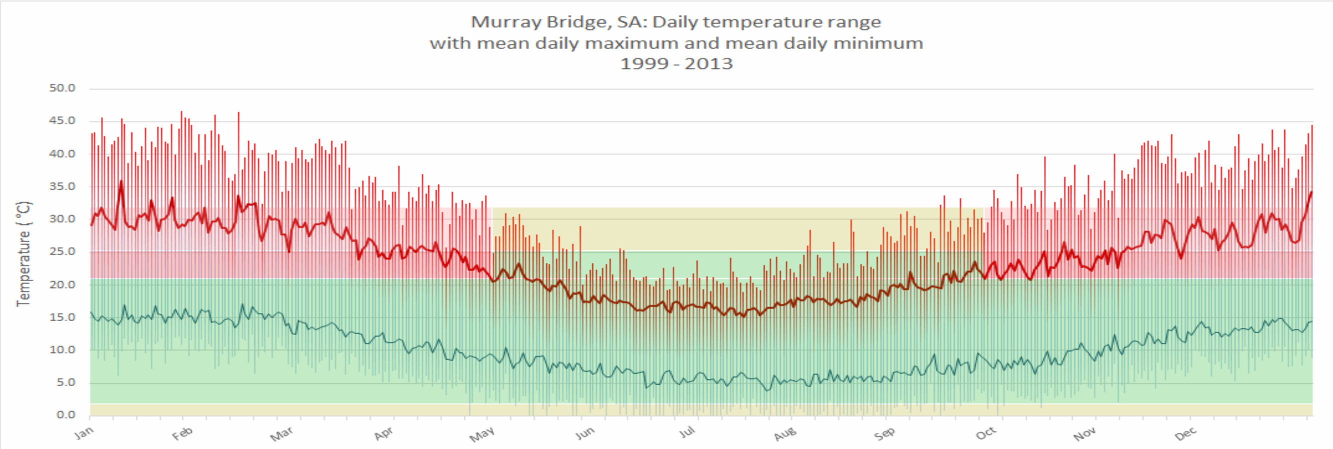

Figure 50: Mean daily temperatures and range for past 15 years at Murray Bridge, SA with overlay of suitable (green) and tolerable (tan) growing conditions for lettuce extended with plastic tunnel house or cloche. An adverse increase in maximum temperature over summer is indicated for a vented tunnel (light red) and a poorly vented tunnel or cloche (red).

5.3.5 Impact on light levels

Any protective structure installed above a cropping area will impact on the amount and quality of light reaching the crop. The use of a screening material to reduce temperatures, for example, will necessarily also affect crop light levels. If light becomes limiting, the benefit of reduced temperatures is negated.

A clean plastic covering material installed as a tunnel house, cloche, rainshelter or floating cover can be expected to transmit around 80% of the light. This is reduced by age, dirt and condensation. Figure 51 shows the approximate daily mean levels and range of photosynthetically active radiation (PAR) for Murray Bridge with an overlay of the suitable light levels for lettuce. The mean daily level has been adjusted to reflect an 80% (pink) and a 50% (blue) transmission level. With 50% transmission, such as under a 50% shade screen or a dirty and wet floating cover, mean PAR levels are almost deficient.

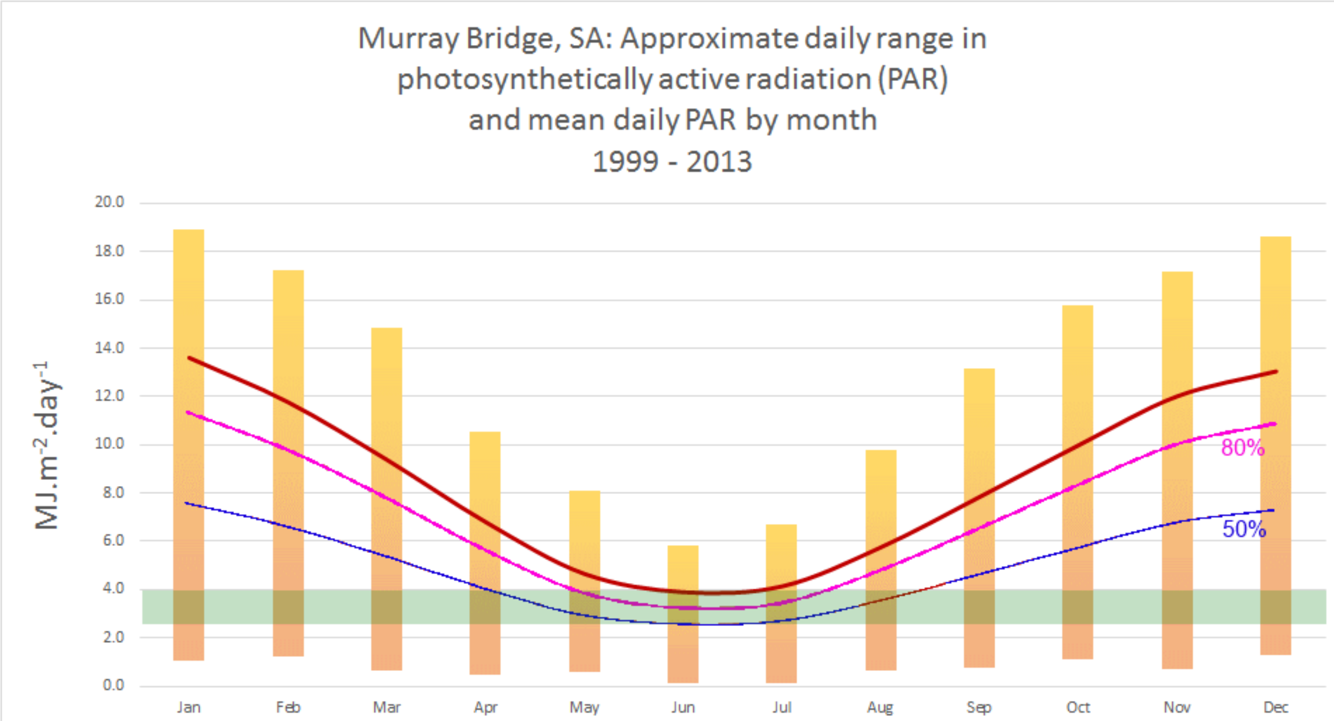

Figure 51: Approximate levels of photosynthetically active radiation (PAR) for the past 15 years at Murray Bridge, SA with overlay of suitable light levels for lettuce and indication of mean daily PAR given 80% (pink) and 50% (blue) transmission rates.

The use of a screening material in Murray Bridge has been discussed previously in '*Managing high temperatures'* and there is a high likelihood that shade screening could provide a beneficial cooling effect to most crops in this region. Figures 52 presents the approximate mean daily level of photosynthetically active radiation by month and the highest and lowest levels experienced over the past 15 years with an overlay of the 'suitable' light levels for lettuce under screening (Figure 52).

This example assumes a screen provides 50% shading. Any screening or covering over the crop would need to be moveable or at least installed seasonally otherwise mid-winter light levels could be deficient even for a low light requirement crop such as lettuce. With a retractable screen, light levels would not be deficient for lettuce (Figure 53). Similarly, capsicum, which has a higher light requirement than lettuce, would experience deficient levels of light in winter under a fixed covering, but a retractable or moveable option would overcome this (Figure 54).

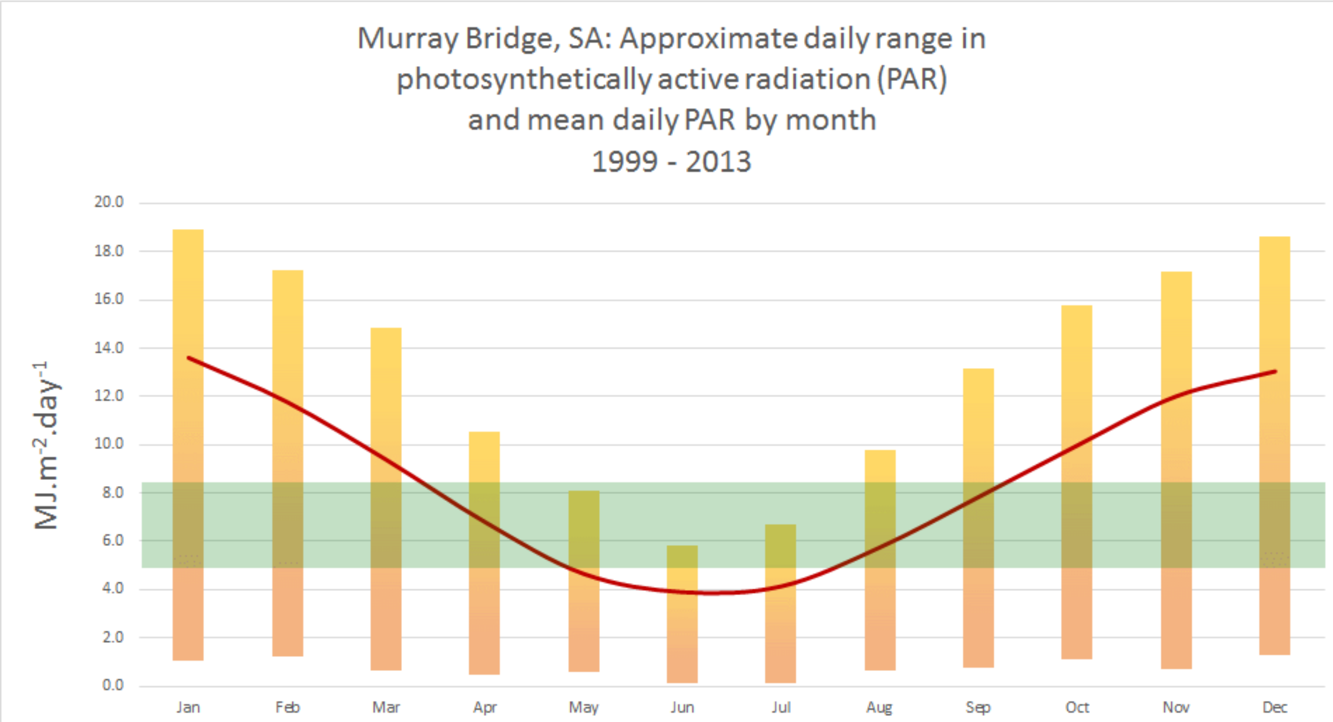

*Figure 52: Approximate levels of photosynthetically active radiation (PAR) for the past 15 years at Murray Bridge, SA with overlay of suitable light levels for **lettuce under screening** (green).*

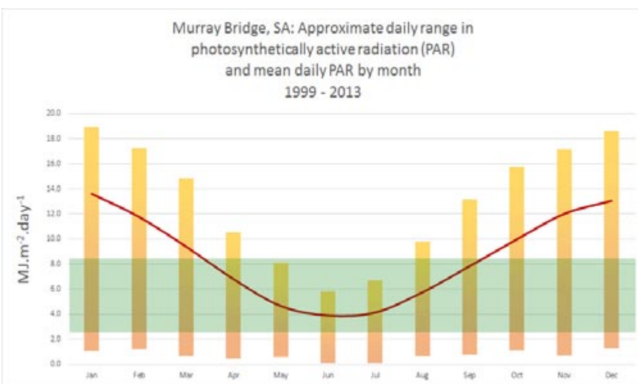

Figure 53: Approximate levels of photosynthetically active radiation (PAR) for the past 15 years at Murray Bridge, SA with overlay of suitable light levels for lettuce, extended by moveable shading (green).

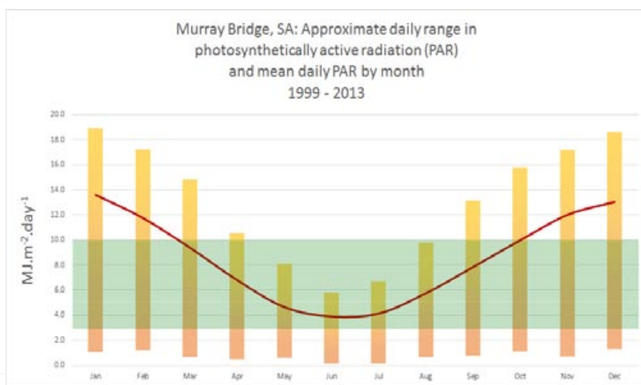

Figure 54: Approximate levels of photosynthetically active radiation (PAR) for the past 15 years at Murray Bridge, SA with overlay of suitable light levels for capsicum, extended by moveable shading (green).

5.3.6 Murray Bridge LCPC assessment

The Murray Bridge region experiences high summer temperatures, cool to cold winter temperatures with several frost days, high light levels in summer and low light levels in winter. Winds tend to be light to moderate and occasionally strong. Mid-winter rainfall can be quite variable and heavy rain events can occur.

The primary focus for protected cropping in this region should be on managing extreme high temperatures and extended heatwaves. Some frost protection may be feasible.

Shading of 30 to 50% could potentially decrease maximum temperatures by 6°C or more, containing mean maximum temperatures within crop thresholds, but more realistic expectations of maximum temperatures indicate a significant number of excess heat days would not be sufficiently moderated. The addition of fogging would have large benefit on excess heat days in this region and would effectively mitigate excess heat days.

The high summer light levels could also enable a greater shading level to be suitable and provide further reduction in maximum temperatures. Reduced crop water use through summer would be expected to be a further benefit of shading. Any reduction in light levels would be detrimental to crops in winter. Crop coverings would need to be moveable or at least installed seasonally to avoid low light conditions.

Light to moderate winds may result in increased temperatures in a screenhouse due to reduced ventilation and airflow within the crop. Local conditions will need to be assessed. Low profile greenhouses, cloches and floating crop covers are likely to result in a similar problem as the reduction in incident radiation is coupled with significantly reduced ventilation in the cropping area.

A crop canopy structure could provide a shade cooling effect without adversely affecting airflow and subsequently heat removal from the cropping area.

Floating crops covers could provide a marginal frost protection benefit in transition periods, though screening would provide a greater overall benefit in terms of temperature management. Exclusion of crop and contaminant pests could be achieved with floating covers, though adverse impacts on the growing environment in this area are likely to limit the overall benefit for much of the year.

Low profile greenhouses and plastic cloches could significantly improve frost protection and minimum temperatures but need to be moveable or used seasonally to avoid adverse high temperatures from October to May. Low light conditions in winter will need to be carefully managed and high transmission cladding would be required and be well maintained. Condensation in winter will reduce light transmission.

5.4 Devonport

5.4.1 Overview

Maximum temperatures in Devonport are expected to rise between 0.2 and 1.0°C and minimum temperatures to rise 0.2 to 0.8°C[87]. These projected changes are not likely to impact significantly on horticulture in this region. Figure 55 illustrates the mean daily maximum and minimum temperatures and the temperature range over the past 15 years. The mean temperatures demonstrate a suitable and mild growing environment with few extremes. The projected rise in mean temperature may provide some benefit.

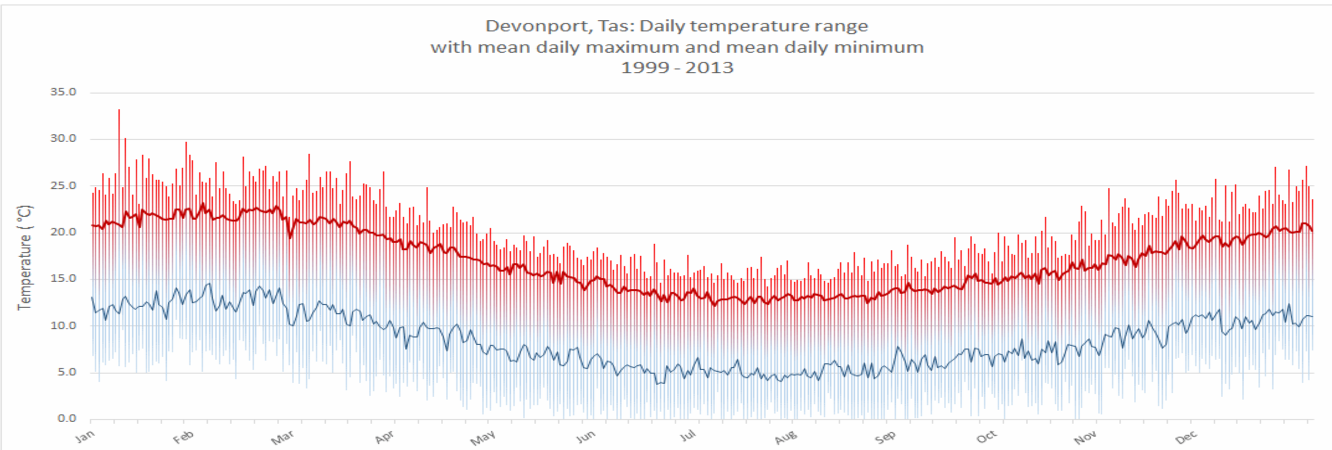

Figure 55: Mean daily temperatures and range for past 15 years at Devonport, Tas.

5.4.2 Managing high temperature

The mild climate of this region means that very few days have maximum temperatures that breach crop thresholds. This is illustrated in Figure 56 which shows the suitable temperature range for lettuce overlaid on the weather data for the past 15 years.

Over the past 15 years there has been just a couple of heat events which could have a negative impact on crops being cultivated at the time. Figure 57 presents the maximum number of days on which temperatures have exceeded 28°C and illustrates that even the worst case would only consist of a couple of hot days in mid-summer. The use of protected cropping to mitigate excess heat is not warranted in this region. Even with a projected increase in maximum temperatures of up to 1°C, managing excess heat days is not likely to be a key factor in this region.

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[87] G. Rogers (2013) Understanding and managing impacts of climate change and variability on vegetable industry productivity and profits, Final report VG12041 AHR

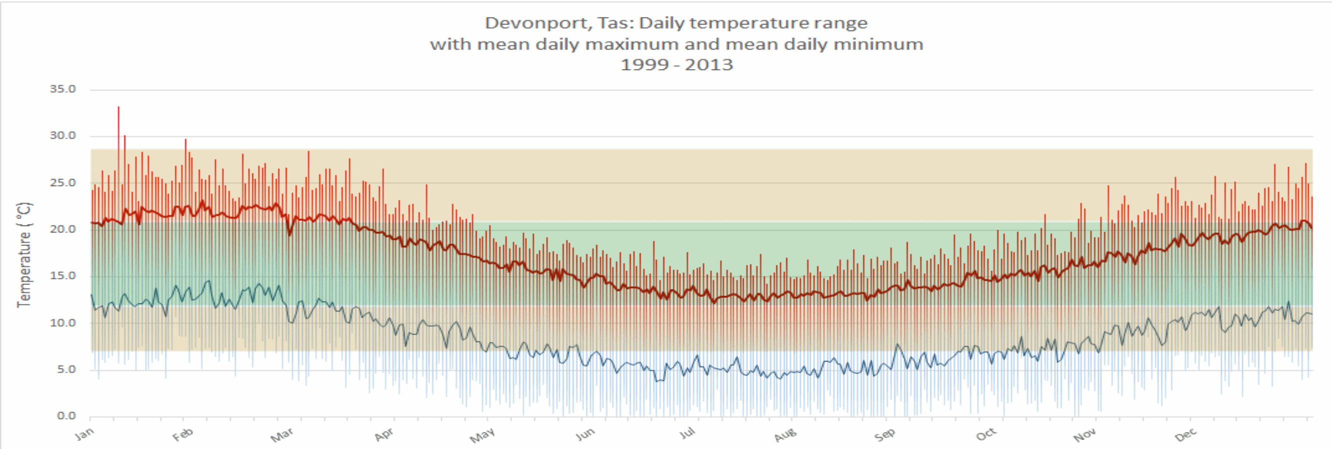

*Figure 56: Mean daily temperatures and range for past 15 years at Devonport, Tas. with overlay of suitable (green) and tolerable (tan) growing conditions for **lettuce**.*

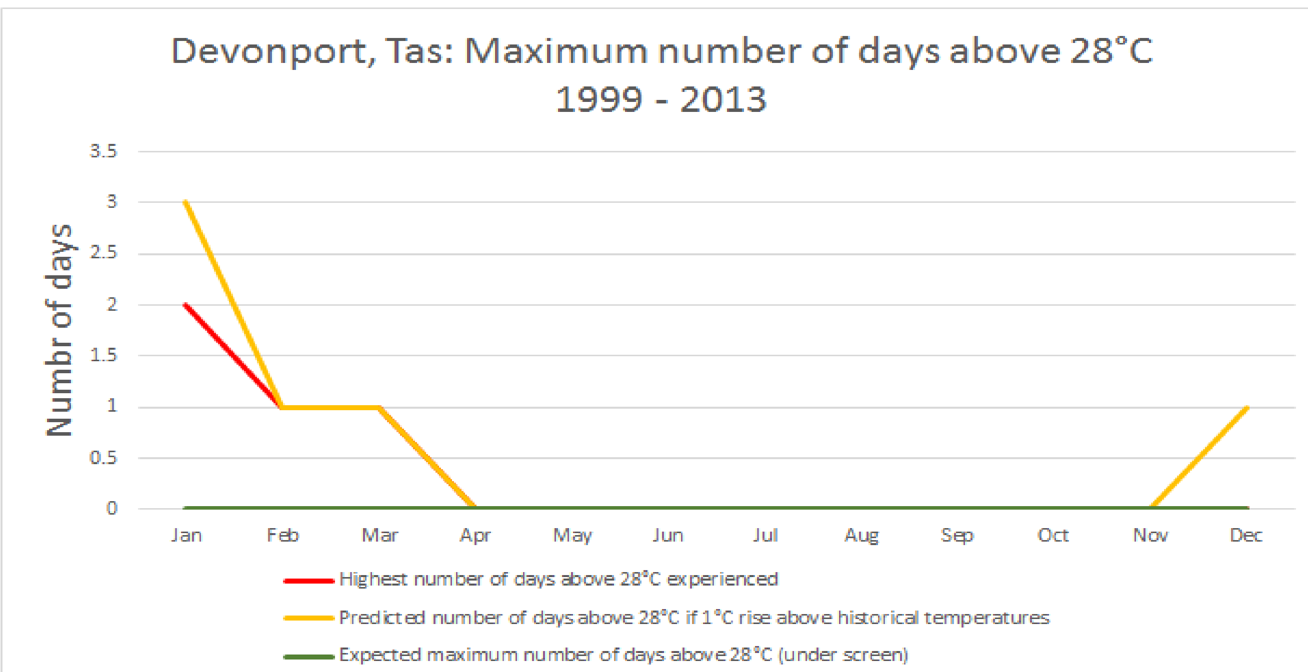

Figure 57: Maximum number of days above 28°C (red) for last 15 years at Devonport, Tasmania and with a 1°C predicted rise in temperature (yellow) and under screening (green).

5.4.3 Crop water use

Mean rainfall is fairly consistent throughout the much of the year. The mean monthly rainfall and monthly range for the past 15 years is presented in Figure 58. January and August have fairly wide range in rainfall and heavy rainfall events may pose a production risk.

The mean annual rainfall in this area is projected to potentially decline by as much as 11%, most notably in spring which would increase the requirement for irrigation[88] though crop water use is not likely to be a significant production factor, given the mild climate. The area makes use of winter river extraction and storage. Evapotranspiration rates are moderate and are presented in Figure 59.

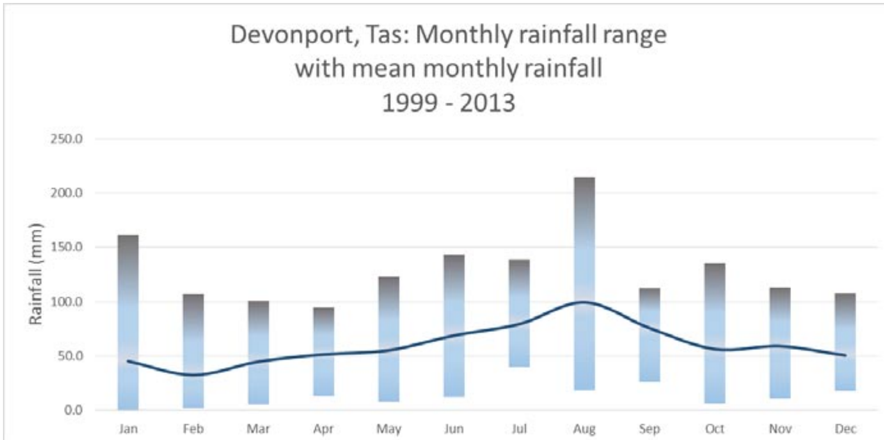

Figure 58: Mean monthly rainfall and range for past 15 years at Devonport, Tas.

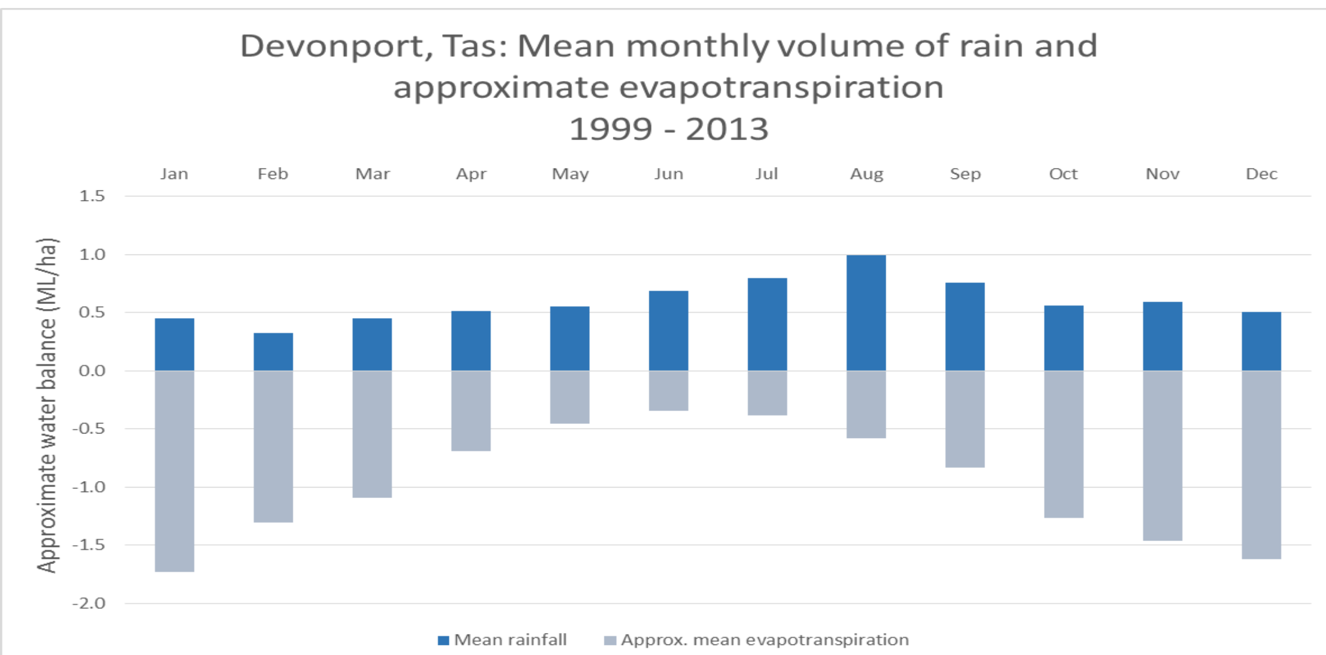

Figure 59: Approximate monthly rainfall and evapotranspiration for past 15 years at Devonport, Vic.

[88] G. Rogers (2013) Understanding and managing impacts of climate change and variability on vegetable industry productivity and profits, Final report VG12041 AHR

5.4.4 Frost and cool temperatures

The frost window is projected to increase in this area as the climate changes. Frost is a common event through winter in this region. The number of frost days over the past 15 years as approximated by the number of days that temperatures fall below 2°C is shown in Figure 60.

The current frost window extends from early April to mid-November. Later occurring frosts poses an increasing risk for establishment of summer crops while early frosts could have an impact on late finishing summer crops.

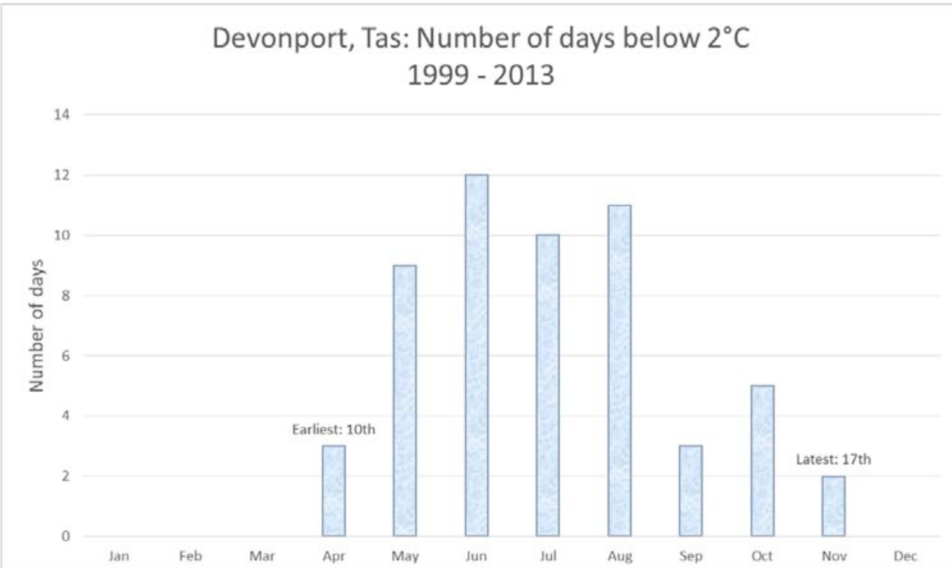

Figure 60: Highest number of days below 2°C per month (approximating the number of frosts) for the past 15 years at Devonport, Tas. Including earliest and latest occurrence.

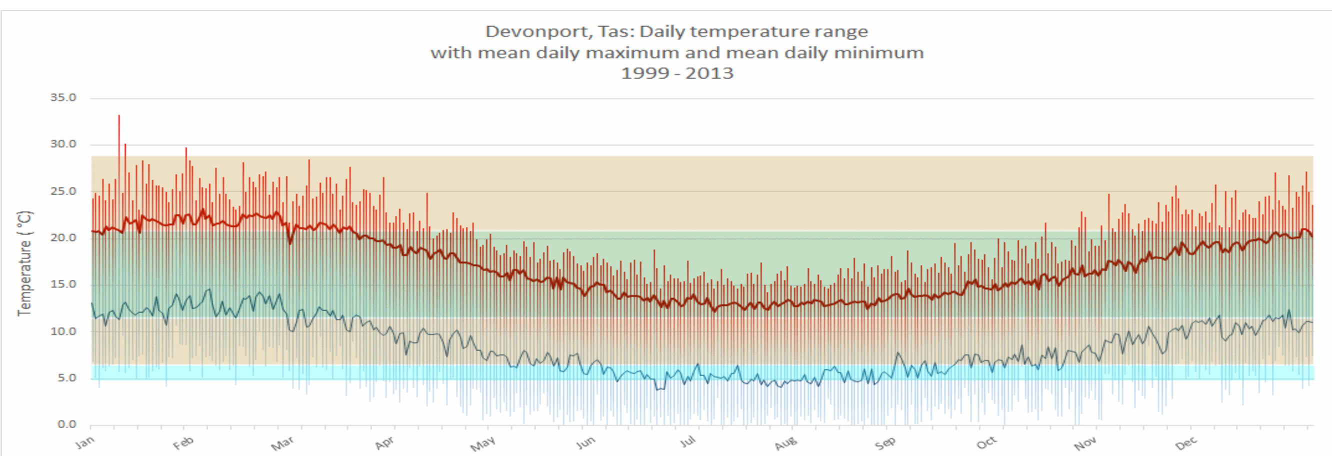

*Figure 61: Mean daily temperatures and range for past 15 years at Devonport, Tas. with suitable (green) and tolerable (tan) growing conditions for **lettuce extended with floating cover** (blue).*

Floating crop covers could be suitable to mitigate frost risk to protect warm season varieties in autumn and establishment of summer crops in spring. Figure 61 presents the potential benefit for lettuce. Mean minimum temperatures in transition periods are encompassed with a light cover that would be expected to provide 2°C warming. To address winter mean minimums a heavier cover would be needed.

Low profile greenhouses and cloches could significantly improve minimum temperatures and minimise frost risk (Figure 62) though the reduction in winter light levels will need to be considered. These options would need to be vented if used in summer to avoid adverse temperatures. The labour task in managing the ventilation of plastic cloches may render this option unsuitable but they could be used seasonally. Netted cloches could be considered over summer and even transitional periods to provide some cold protection without creating excess heat and additional labour costs.

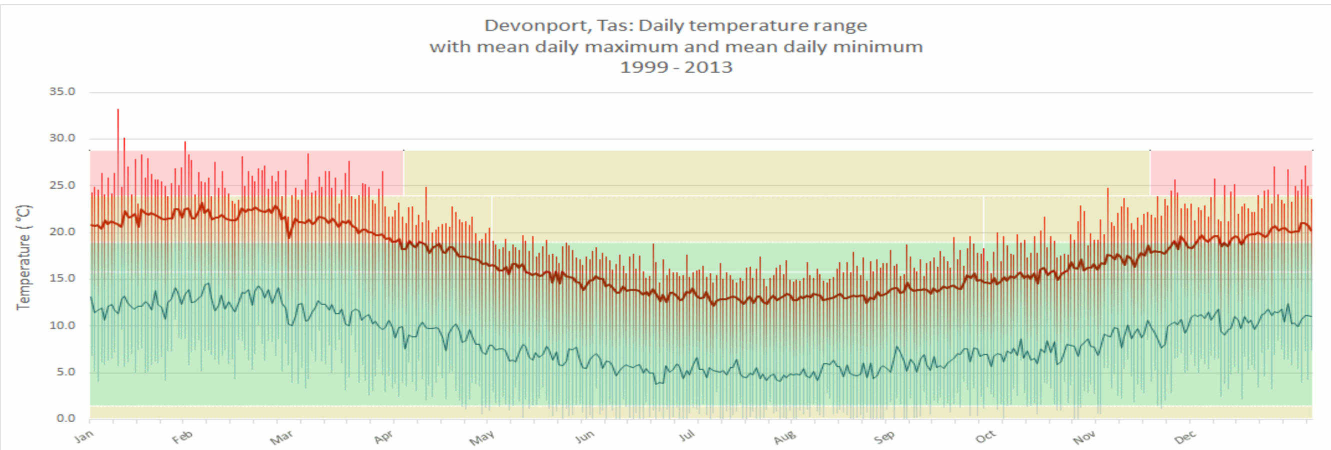

Figure 62: Mean daily temperatures and range for past 15 years at Devonport, Tas. with overlay of suitable (green) and tolerable (tan) growing conditions for ***lettuce extended with plastic tunnel house or cloche****. An adverse increase in maximum temperature over summer is indicated for a poorly vented tunnel or cloche (red).*

5.4.5 Impact on light levels

The approximate daily mean levels and range of photosynthetically active radiation (PAR) for Devonport are presented in Figure 64 with an overlay of the suitable light levels for lettuce. Any protective structure installed above a cropping area will impact on the amount and quality of light reaching the crop. Winter light levels are low in this region and the use of any covering above the cropping area will further reduce available light. If light becomes limiting, the benefit of improved temperature or wind protection is negated.

The use of a floating crop cover, low profile greenhouse or cloche in Devonport has been discussed previously in '*Frost and low temperatures*' and is potentially an LCPC option to be considered in this region. The mean daily level has been adjusted to reflect an 80% (pink) and a 50% (blue) transmission level, indicated in Figure 63. With 80% transmission, such as under a floating crop cover or tunnel house, mean PAR levels are potentially deficient. This transmission rate would be further reduced by age, dirt and condensation. Any LCPC element installed above a crop in this region would need to be opened or removed during the day between April and late August.

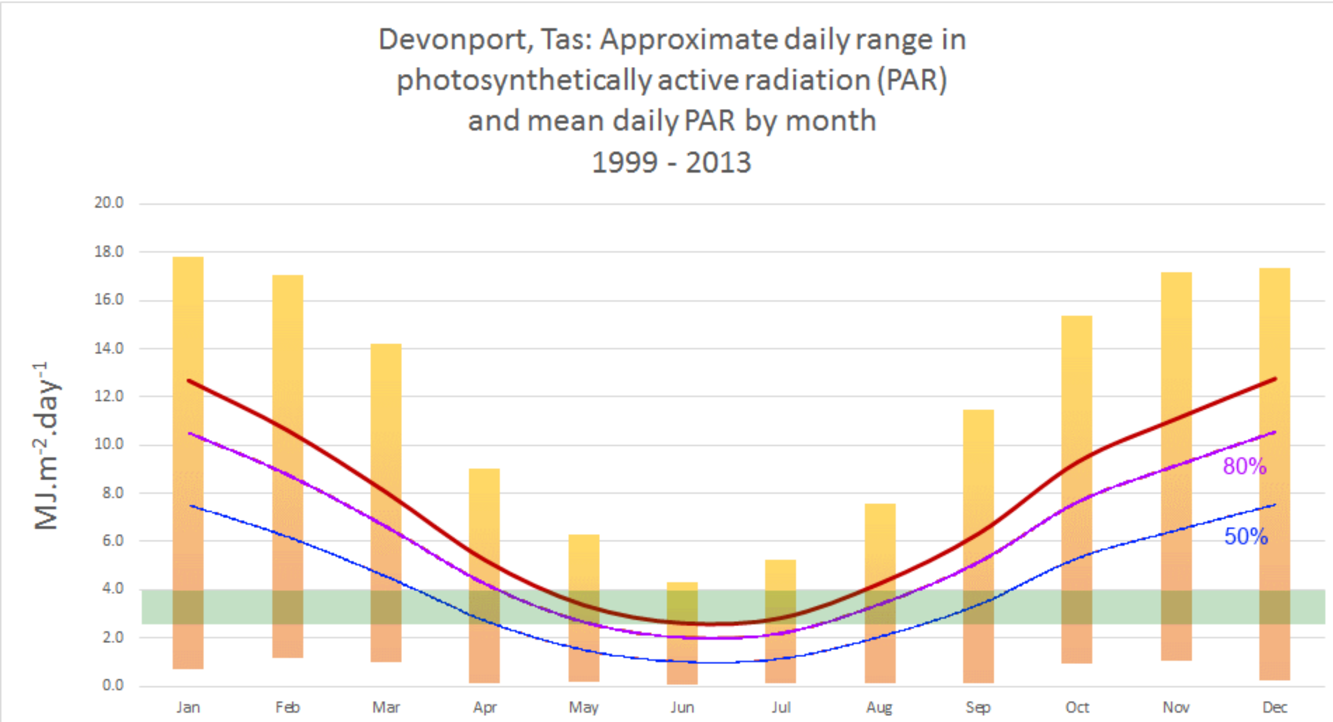

Figure 63: Approximate levels of photosynthetically active radiation (PAR) for the past 15 years at Devonport, Tas. with overlay of suitable light levels for lettuce and indication of mean daily PAR given 80% (pink) and 50% (blue) transmission rates.

5.4.6 Devonport LCPC assessment

The Devonport region represents a cool to mild climate with several frost days, fairly high light levels in summer and very low light levels in winter. Although prevailing winds are light to moderate, fresh to strong winds occur frequently. Rainfall is moderate and fairly even, though significant variation in monthly rainfall can occur in late winter and mid-summer.

The primary focus for protected cropping in this region would be wind protection and possibly management of frost and low minimum temperatures.

Floating crops covers could provide a frost protection benefit in transition periods and exclusion of crop and contaminant pests from spring to autumn. Low profile greenhouses and plastic cloches could significantly improve frost protection and minimum temperatures but need to be vented, moveable or used seasonally to avoid negative impacts of moderately high internal temperatures in summer.

Any covering installed over the cropping area between April and late August will need to be removed during the day to minimise periods of insufficient light levels.

Windbreaks, tunnel houses, cloches and floating covers could be suitable in reducing negative impacts of wind, though only windbreaks could reduce wind speeds in winter without adversely affecting light levels

5.5 Hay

5.5.1 Overview

The projected increases in annual maximum temperature in the Hay region are one of the largest with maximum temperatures likely to increase 0.7 – 1.4°C and the anticipated increase in minimum temperatures is 0.6 – 1.2°C by 2035[89]. The mean daily temperatures and daily temperature range are presented in Figure 64.

These increases will occur on top of current conditions which already exceed upper thresholds for most crops. Mean daily temperatures from mid-November to March sit slightly above the upper threshold for most crops. Potential daily maximum temperatures on any day in summer can adversely impact on plant growth and yield.

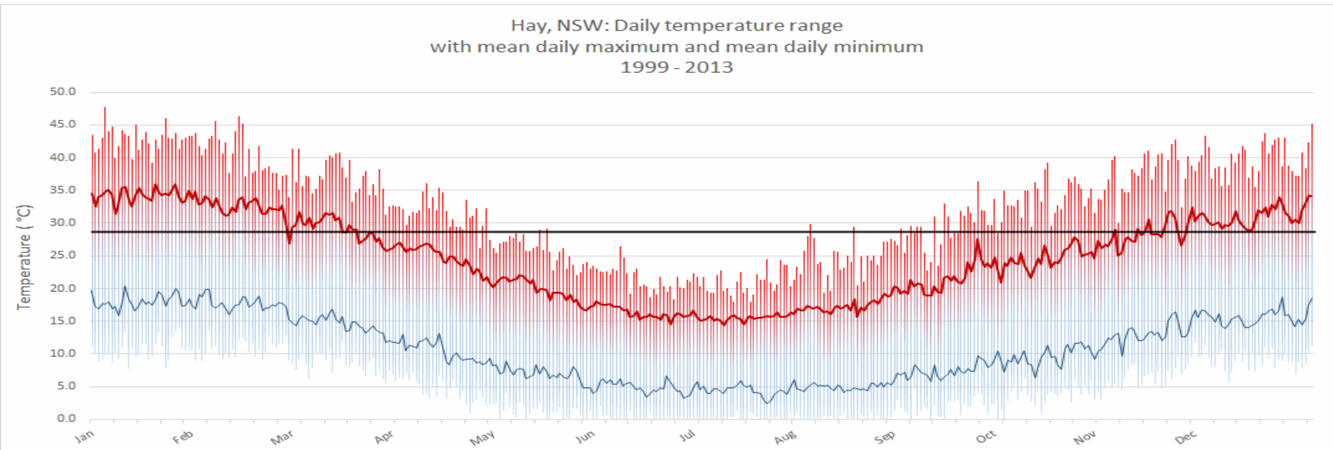

Figure 64: Mean daily temperatures and range for past 15 years at Hay, NSW with general crop upper threshold marked (black line)

5.5.2 Managing high temperature

The region represented by Hay currently experiences excess heat days from mid-September through to April and mean maximum temperatures in summer exceed the upper temperature thresholds for most vegetable crops. Daily maximum temperatures on any day in summer will adversely impact on plant growth and yield.

Excess heat days typically occur three in every five days over summer, illustrated by the median number of days over 28°C over the past 15 years in the Hay region. The maximum number of excess heat days experienced in the recent past has been up to every day in summer. The installation of 50% shading could potentially reduce the maximum number of days that exceed the upper threshold by one third. This is shown in the insert graph in Figure 65.

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[89] G. Rogers (2013) Understanding and managing impacts of climate change and variability on vegetable industry productivity and profits, Final report VG12041 AHR

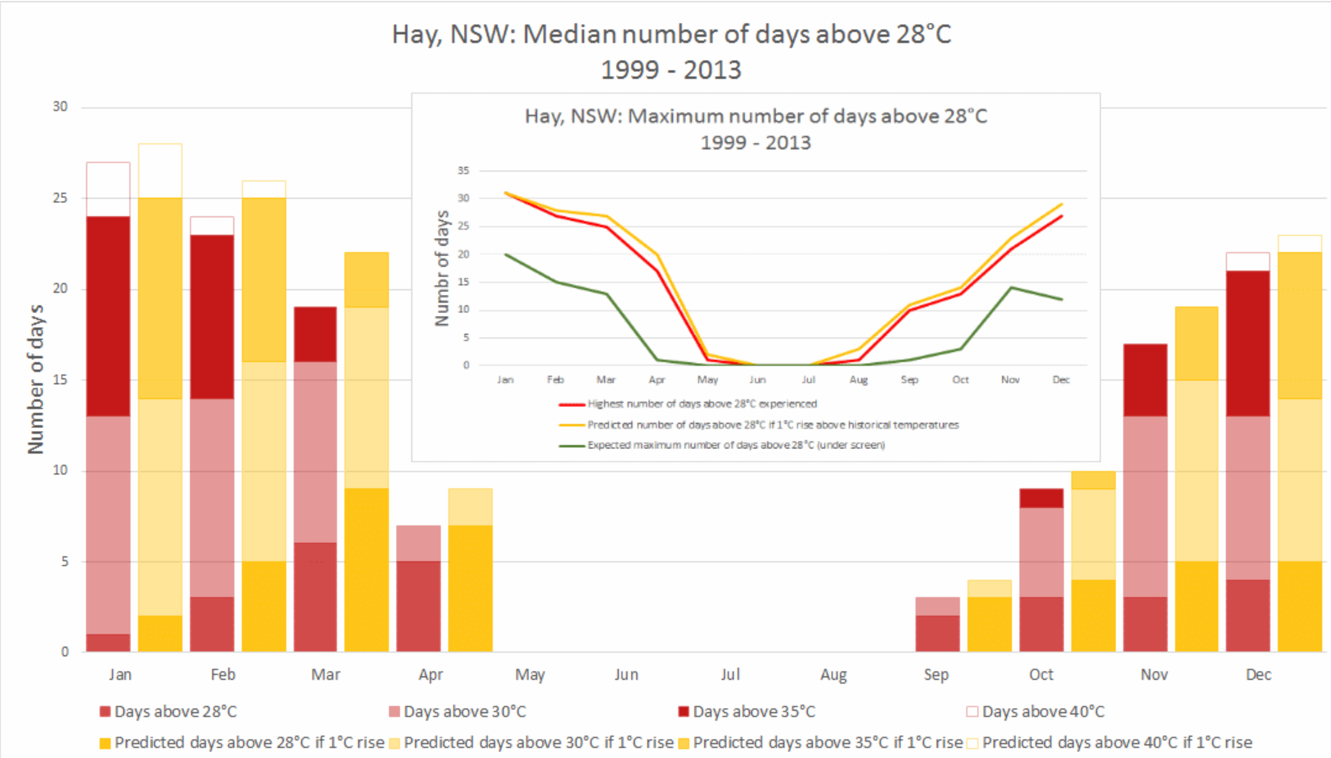

Figure 65: Median number of days above 28°C (red) for last 15 years at Hay, NSW and with a 1°C predicted rise in temperature (yellow). Insert figure shows the maximum number of days above 28°C including expected maximum under screening (green).

The traditional harvest period for crops such as lettuce or brassica is between autumn and spring. Reducing maximum temperatures is a key production opportunity for LCPC in this region. The unfavourable high temperatures are illustrated for lettuce and broccoli in Figures 66 and 67 respectively. The extreme heat over summer confines production of many crops to the cooler months.

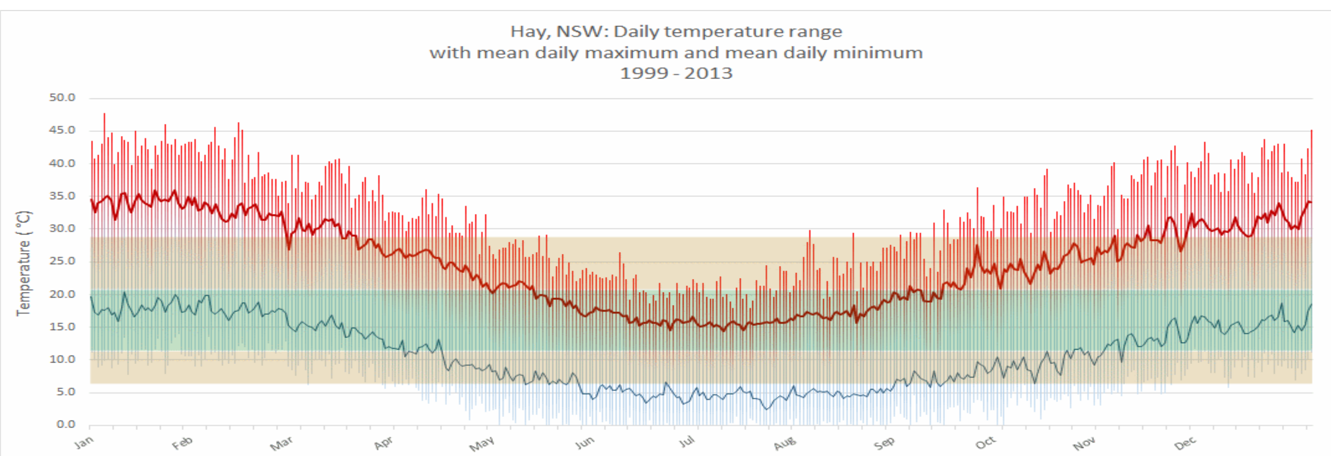

*Figure 66: Mean daily temperatures and range for past 15 years at Hay, NSW with suitable (green) and tolerable (tan) growing conditions for **lettuce**.*

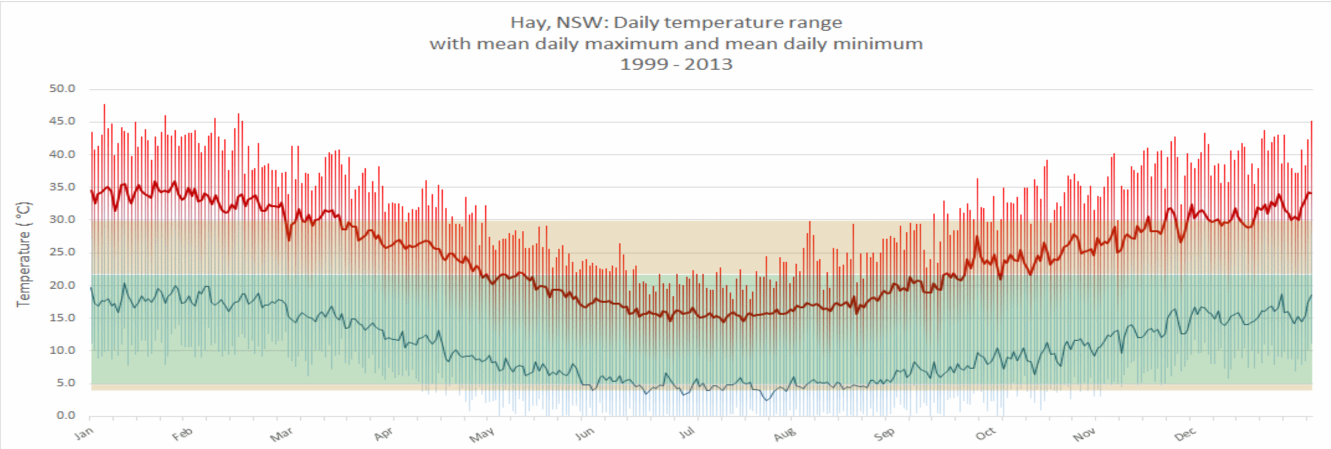

*Figure 67: Mean daily temperatures and range for past 15 years at Hay, NSW with suitable (green) and tolerable (tan) growing conditions for **broccoli**.*

Even warm season crops such as cucumbers (Figure 68) would be subject to unfavourable conditions, and a decline in yield over summer is expected. Shading can reduce the number of excess heat days by one third overall, with a dominant benefit in autumn and spring (Figure 69) producing a longer cropping window for crops such as lettuce.

Shading would reduce the impact on yield in cucumbers from extreme temperatures (Figure 70) with mean maximum temperatures encompassed within the extended crop threshold.

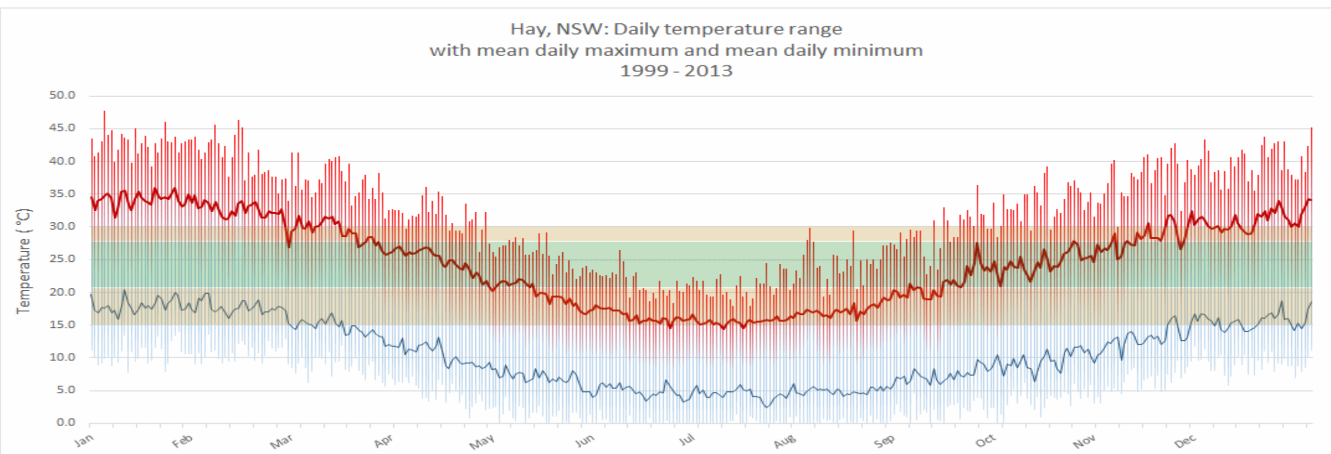

*Figure 68: Mean daily temperatures and range for past 15 years at Hay, NSW with suitable (green) and tolerable (tan) growing conditions for **cucumber**.*

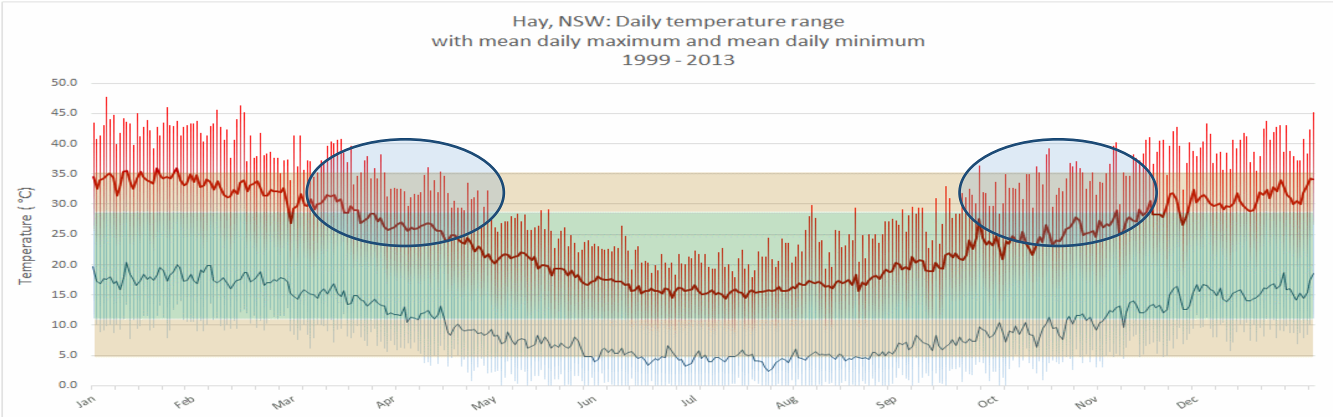

*Figure 69: Mean daily temperatures and range for past 15 years at Hay, NSW with suitable (green) and tolerable (tan) growing conditions for **lettuce extended with screening** and improved cropping window is marked (blue).*

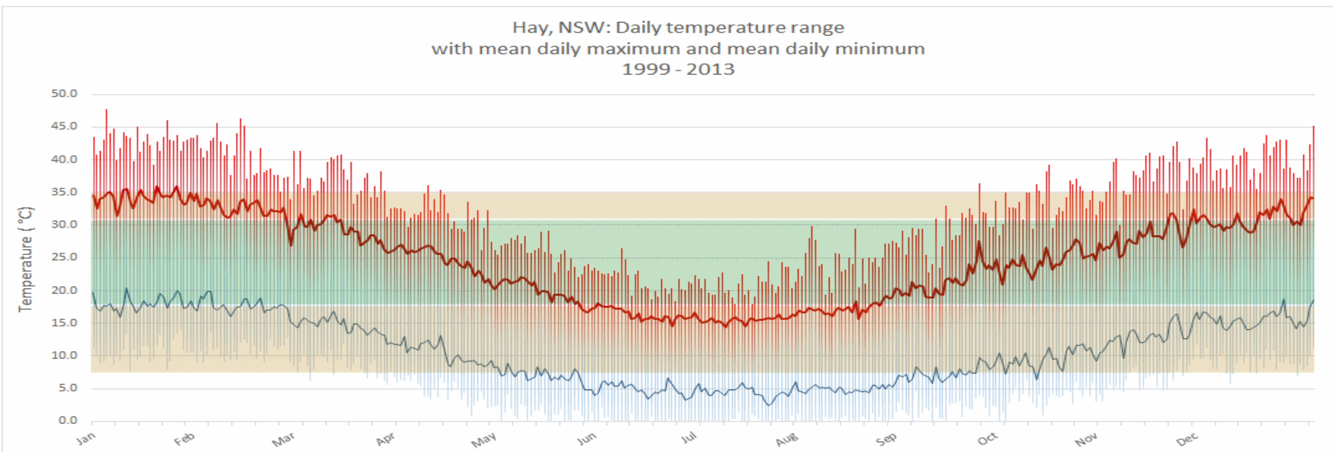

*Figure 70: Mean daily temperatures and range for past 15 years at Hay, NSW with suitable (green) and tolerable (tan) growing conditions for **cucumber extended with screening**.*

The incorporation of fogging could provide significant additional temperature reduction in summer as higher temperature conditions in this region are associated with low relative humidity. Weather data for the past year indicates that excess heat days (Figure 71) in this region are strongly associated with low relative humidity facilitating high evaporative cooling potential.

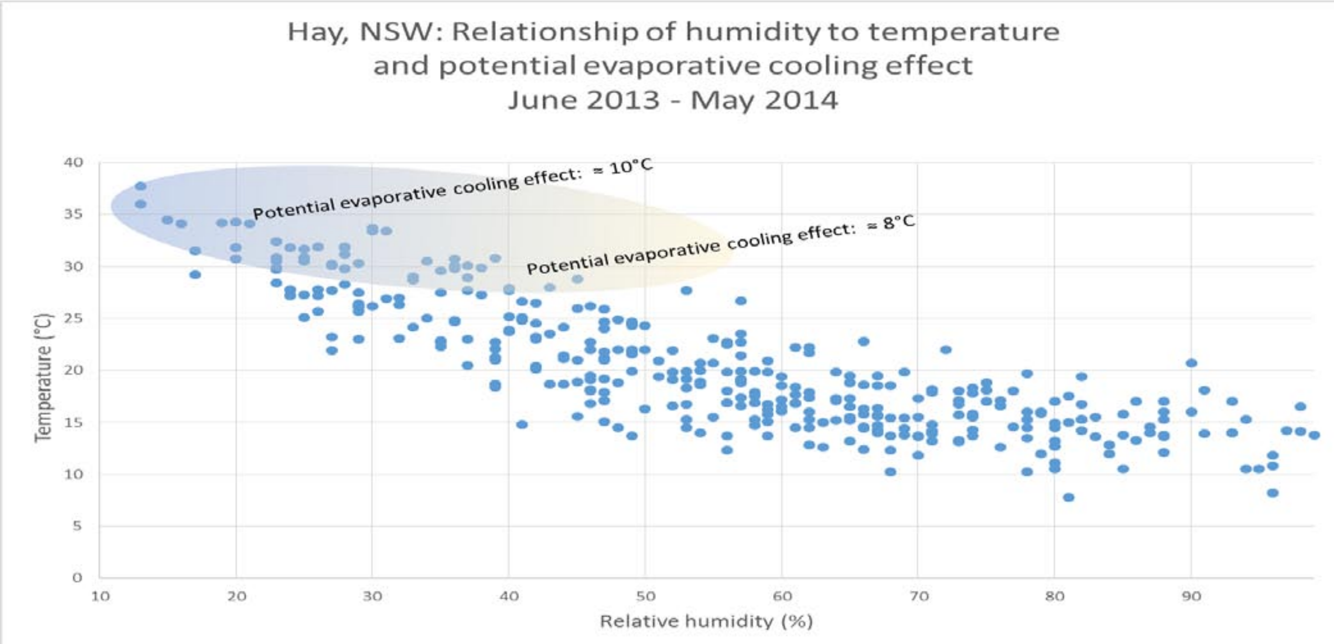

Figure 71: Warmer days are associated with a low relative humidity levels resulting in high evaporative cooling potential.

Although a detailed analysis of environmental conditions and costs would be required to properly determine whether such a protected cropping option would be suitable, Figures 72 and 73 show the potential conditions that might be attained with shade screening and fogging with reference to lettuce and cucumber, respectively. The integration of these two protected cropping options could create suitable growing conditions for most crops over summer.

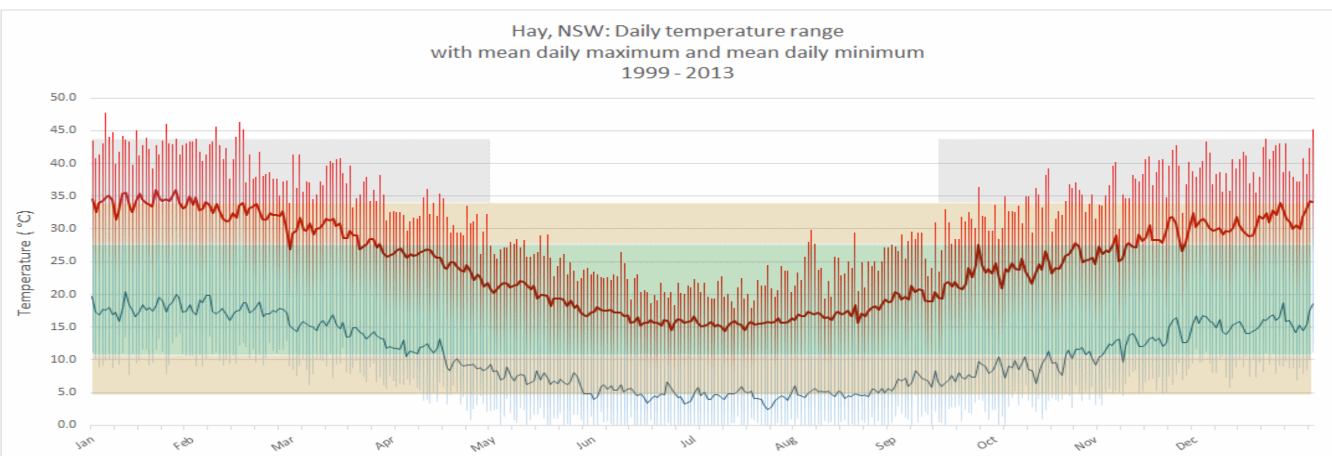

*Figure 72: Mean daily temperatures and range for past 15 years at Hay, NSW. with suitable (green) and tolerable (tan) growing conditions for **lettuce extended with screening and fogging**.*

Light to moderate winds are usual in Hay and the effect on air movement from a protected cropping element needs to be taken into account. The reduced airflow in a standard enclosed shadehouse under light wind conditions on excess heat days may impact on the crop and a shade canopy could be a more suitable option.

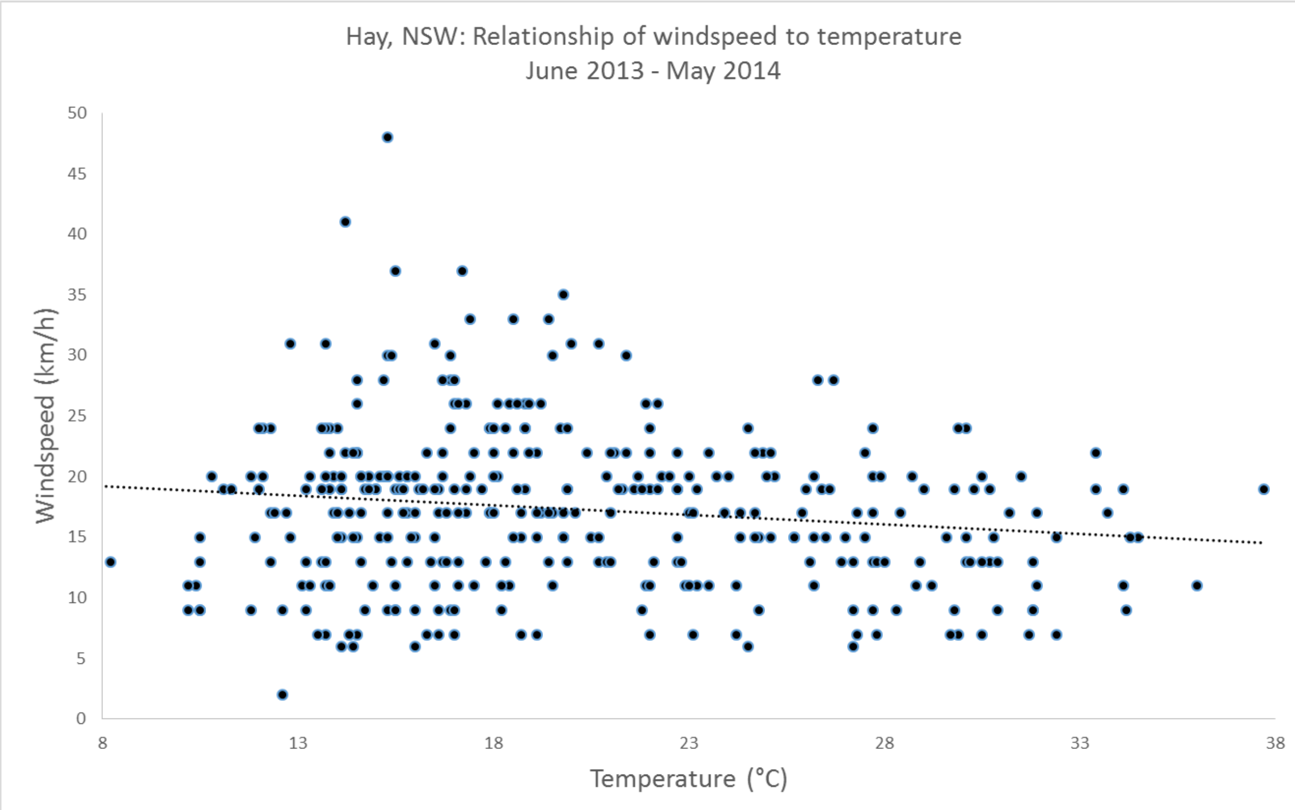

Figure 73: Light to moderate wind speeds prevail in this region, though strong winds occur during cooler periods.

However, weather data from the past year (Figure 74) show that several strong wind events occurred in this region. Windbreaks integrated with a shade canopy could offer an overall benefit. Windbreaks on their own to provide protection from strong winds are likely to exacerbate high temperatures, though also reduce evapotranspiration rates and lower crop water use.

Reduced air flow and the small air volume within a netted cloche is likely to negate any potential shade cooling benefit from this type of structure.

5.5.3 Crop water use

Increasing temperatures on top of current conditions may make crop water use a target factor in regions like Hay, even though local rainfall has little impact on water supplies.

Rainfall in this region is summer dominant, with the greatest variability and potential heavy rainfall events in late summer. The mean monthly rainfall and monthly range for the past 15 years is presented in Figure 75.

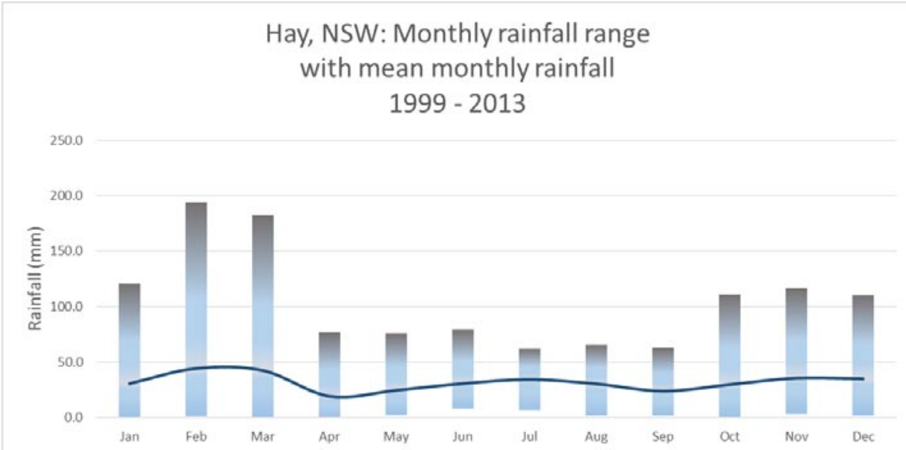

Figure 74: Mean monthly rainfall and range for past 15 years at Hay, NSW.

The mean annual rainfall is fairly consistent across the year. Climate change projections are varied with the worst case being a 12% decline in annual rainfall, with the main decrease coming in winter and spring. With horticulture dependent on river extraction, the decline in rainfall may improve general growing conditions.

Crop water use, however is a potentially important production factor given the extreme summer temperature and low relative humidity. Evapotranspiration is quite substantial, at five to six times mean monthly rainfall over summer. Crop shading could have a significant effect in reducing crop water use and/or increasing water use efficiency. Figure 76 illustrates the approximate mean volume of rain and evapotranspiration by month from the past 15 years. The shaded component of the evapotranspiration represents a 30% water saving under shade screens.

Windbreaks could also provide some reduction in crop water use by reducing air movement through the crop, but unlike shade screening, windbreaks would not have the benefit of reducing maximum temperatures and could result in higher temperatures within the cropping area by reducing the rate at which heat energy is removed.

Other protected cropping elements including tunnels, cloches and floating covers are not likely to provide any benefit in crop water use or from improved water use efficiency due to expected impacts of excessive temperatures which would occur under these options.

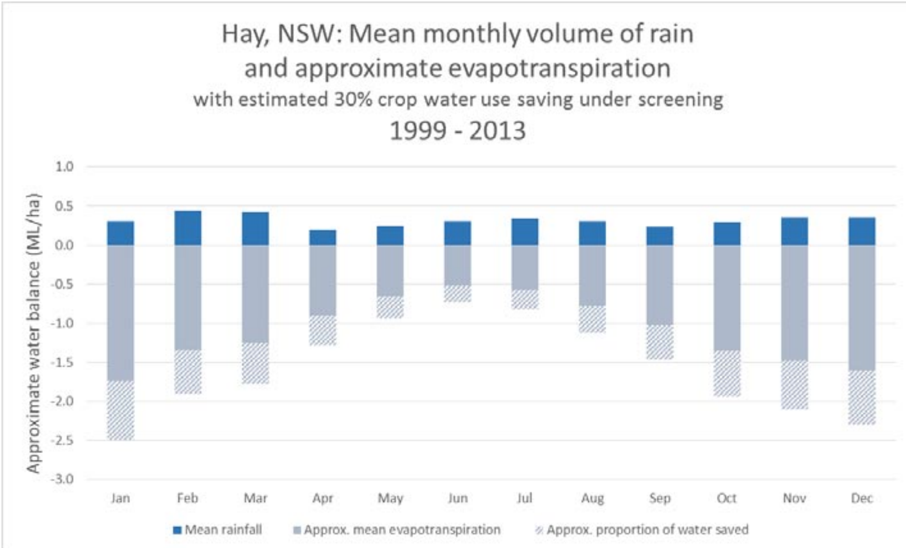

Figure 75: Approximate monthly rainfall and evapotranspiration for past 15 years at Hay, NSW.

5.5.4 Frost and low temperatures

The frost window is projected to increase in this area as the climate changes. Frost is a common event through winter in this region. The number of frost days over the past 15 years as approximated by the number of days that temperatures fall below 2°C is shown in Figure 77. The current frost window extends from mid-April to mid-October. Later occurring frosts pose a risk for establishment of warmer varieties towards the end of the main growing season. Establishing summer crops is also at risk from late frosts.

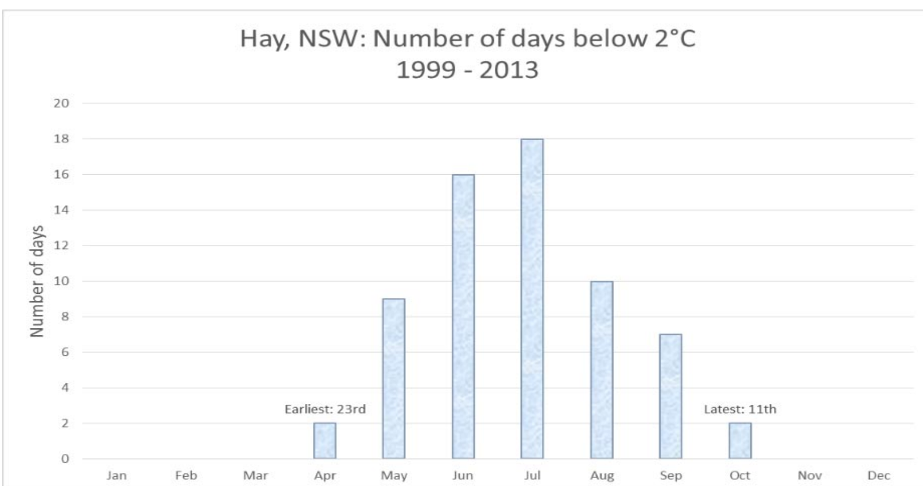

Figure 76: Highest number of days below 2°C per month (approximating the number of frosts) for the past 15 years at Hay, NSW. Including earliest and latest occurrence.

Floating crop covers are unlikely to provide a sufficient rise in minimum temperatures to protect crops against frost risk but for warm season crops like cucurbits, a floating cover could avoid minimum temperatures falling below lower temperature thresholds during spring (Figure 78).

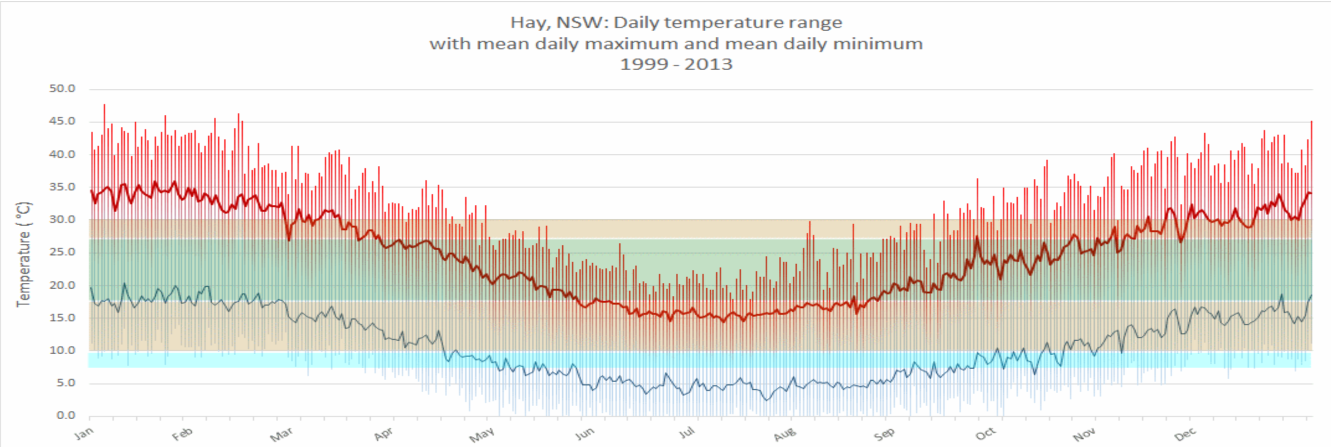

Figure 77: Mean daily temperatures and range for past 15 years at Hay, NSW. with suitable (green) and tolerable (tan) growing conditions for cucurbits extended with floating cover (blue).

Shade screening could provide a similar benefit in raising minimum temperatures slightly in the transition periods and could assist in managing excess heat during the day. The possible influence of this protective option on the suitability of growing conditions for lettuce is illustrated in Figure 79.

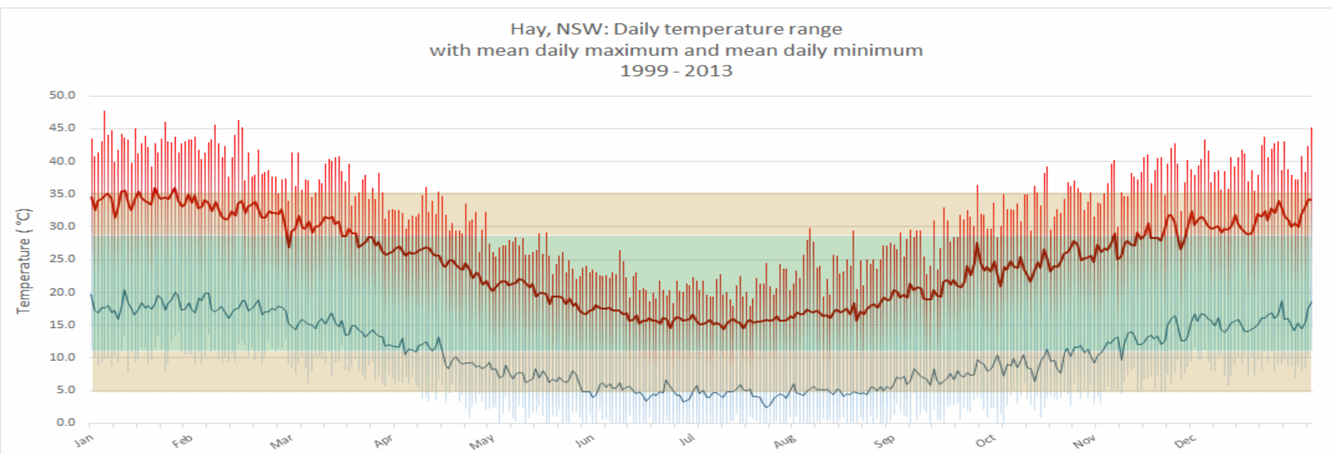

Figure 78: Mean daily temperatures and range for past 15 years at Hay, NSW. with suitable (green) and tolerable (tan) growing conditions for ***lettuce extended with screening****.*

Low profile greenhouse and cloches could significantly improve minimum temperatures and minimise frost risk, however the high maximum temperatures that can occur from early spring through to late autumn would be intensified under these structures. This is illustrated in Figure 80. To be of net benefit, these options would need to be moveable or only used seasonally. Although cloches are moveable, this task would need to be done quite regularly to avoid adverse effects of excess heat, and the likely high labour cost of this task will probably make cloches unsuitable for most enterprises.

Improved ventilation in low profile greenhouses would significantly increase the usefulness of this protected cropping option in the transitional periods and through winter, but for at least half the year the negative impacts of high temperatures would outweigh any frost protection or low temperature benefit.

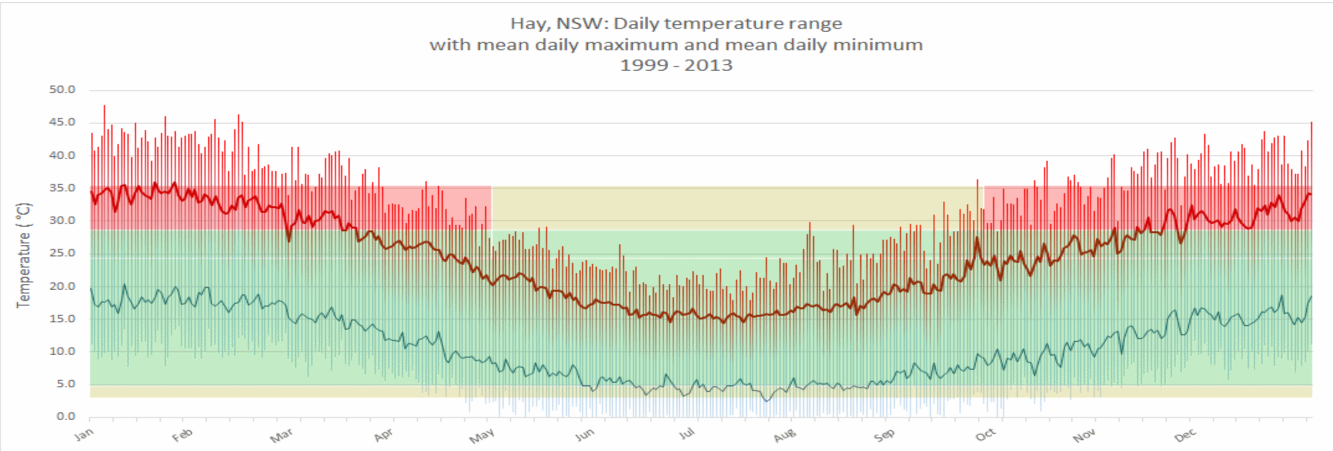

Figure 79: Mean daily temperatures and range for past 15 years at Hay, NSW with overlay of suitable (green) and tolerable (tan) growing conditions for cucurbits extended with plastic tunnel house or cloche. An adverse increase in maximum temperature over summer is indicated (red).

5.5.5 Impact on light levels

Any protective structure installed above a cropping area will impact on the amount and quality of light reaching the crop. The use of a screening material to reduce temperatures, for example, will necessarily also affect crop light levels. If light becomes limiting, the benefit of reduced temperatures is negated.

Figure 81 shows the approximate daily mean levels and range of photosynthetically active radiation (PAR) for Hay with an overlay of the suitable light levels for lettuce (green) and cucurbits (pink). The mean daily level has also been adjusted to reflect a 50% (blue) transmission level. With 50% transmission, such as under a 50% shade screen or a dirty and wet floating cover, mean PAR levels can be limiting in winter.

The use of a screening material in Hay has been discussed previously in '*Managing high temperatures*' and there is a high likelihood that shade screening could provide a beneficial cooling effect to most crops in this region. This example illustrates that any screening or covering over the crop would need to be moveable or at least installed seasonally, otherwise mid-winter light levels could be deficient even for a low light requirement crop such as lettuce.

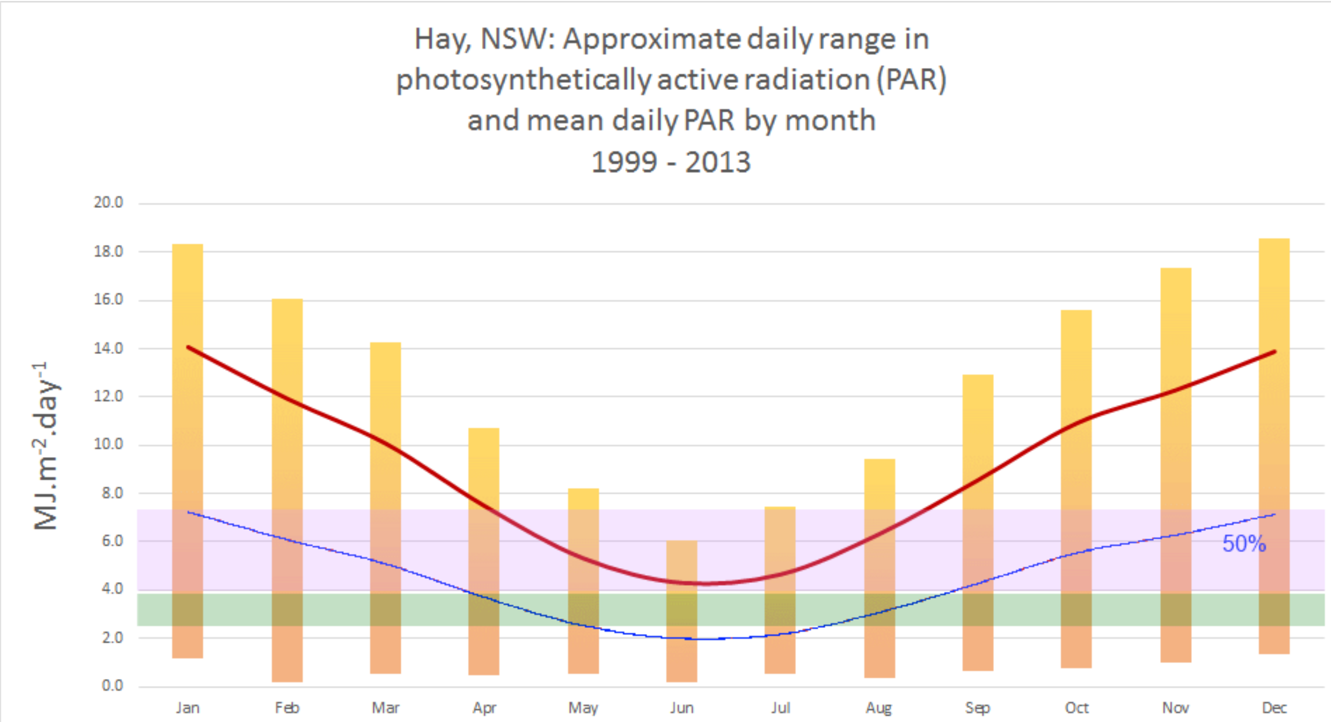

Figure 80: Approximate levels of photosynthetically active radiation (PAR) for the past 15 years at Hay, NSW with overlay of suitable light levels for lettuce (green) and cucurbit (pink) with an indication of mean daily PAR given 50% (blue) transmission rates.

5.5.6 Hay LCPC assessment

The Hay region experiences very high summer temperatures, cool to cold winter temperatures with several frost days, high light levels in summer and low light levels in winter. Winds tend to be light to moderate with occasional fresh to strong winds. Mean rainfall is fairly consistent year-round though summer falls can be quite variable and heavy rain events can occur.

The primary focus for protected cropping in this region should be on managing extreme high temperatures and extended heatwaves. Some frost protection or low temperature mitigation may be feasible.

Shading of 50% could potentially decrease maximum temperatures by 6°C or more containing mean maximum temperatures within general crop thresholds, but more a realistic expectation of maximum temperatures indicates a significant number of excess heat days would not be sufficiently moderated. The addition of fogging would have a large benefit on excess heat days in this region and would effectively mitigate excess heat days.

The high summer light levels could also enable a greater shading level to be suitable and provide further reduction in maximum temperatures. Reduced crop water use through summer would be expected to be a further benefit of shading. Any reduction in light levels would be detrimental to crops in winter. Crop coverings would need to be moveable or at least installed seasonally to avoid low light conditions.

Light to moderate winds may result in increased temperatures in a screenhouse due to reduced ventilation and airflow within the crop. Local conditions will need to be assessed. Low profile greenhouses, cloches and floating crop covers are likely to result in a similar problem as the reduction in incident radiation is coupled with significantly reduced ventilation in the cropping area. A crop canopy structure could provide a shade cooling effect without adversely affecting airflow and subsequently heat removal from the cropping area.

Floating crops covers are not likely to provide much frost protection but would improve minimum temperatures for a general benefit in transition periods. Screening could provide an equivalent benefit in raising minimum temperatures marginally and could also provide a greater overall benefit in terms of high temperature management. Exclusion of crop and contaminant pests could be achieved with floating covers, though adverse impacts on the growing environment in this area (excess heat in summer and low light levels in winter) are likely to limit the overall benefit for much of the year.

Low profile greenhouses and plastic cloches could significantly improve frost protection and minimum temperatures but need to be moveable or used seasonally to avoid adverse high temperatures from October to May. Low light conditions in winter (and potentially in shoulder periods) need to be carefully managed and covering structures will need to be moveable to avoid negative impacts.

5.6 Gatton

5.6.1 Overview

Along with Hay, this region bears one of the largest projected increases in annual maximum temperature with the maximum likely to increase 0.7 – 1.4°C, while annual minimum temperatures are expected to rise 0.8 – 1.2°C by 2035[90]. The mean daily temperatures and the daily maximum and minimum temperature range over the past 15 years are presented in Figure 82.

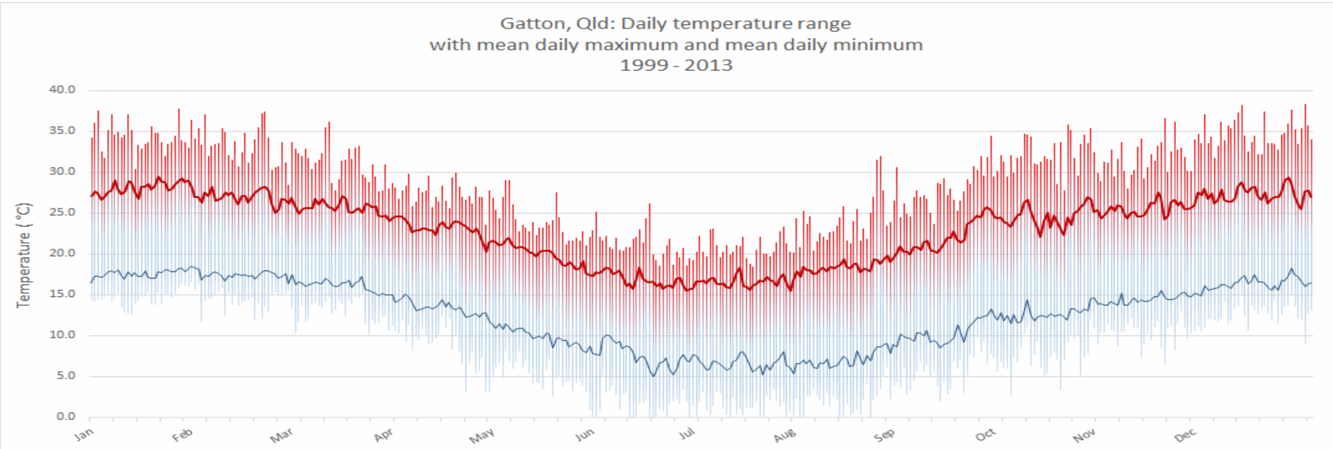

Figure 81: Mean daily temperatures and range for past 15 years at Gatton, Qld

Mean temperatures represent quite suitable growing conditions year-round, however the potential for maximum daily temperatures to exceed upper temperature thresholds for most vegetable crops is high over summer.

5.6.2 Managing high temperature

The Gatton region currently experiences significant excess heat days from October through to February. Excess heat days in December and January typically occur one in every two days, as illustrated by the median number of days over 28°C over the past 15 years experienced in the region (Figure 83). A further rise in mean temperatures will increase the likelihood for adverse maximum temperatures. Figure 84 also presents the possible median number of days with maximum temperatures above 28°C if a 1°C rise is placed on the conditions experienced over the past 15 years.

[90] G. Rogers (2013) Understanding and managing impacts of climate change and variability on vegetable industry productivity and profits, Final report VG12041 AHR

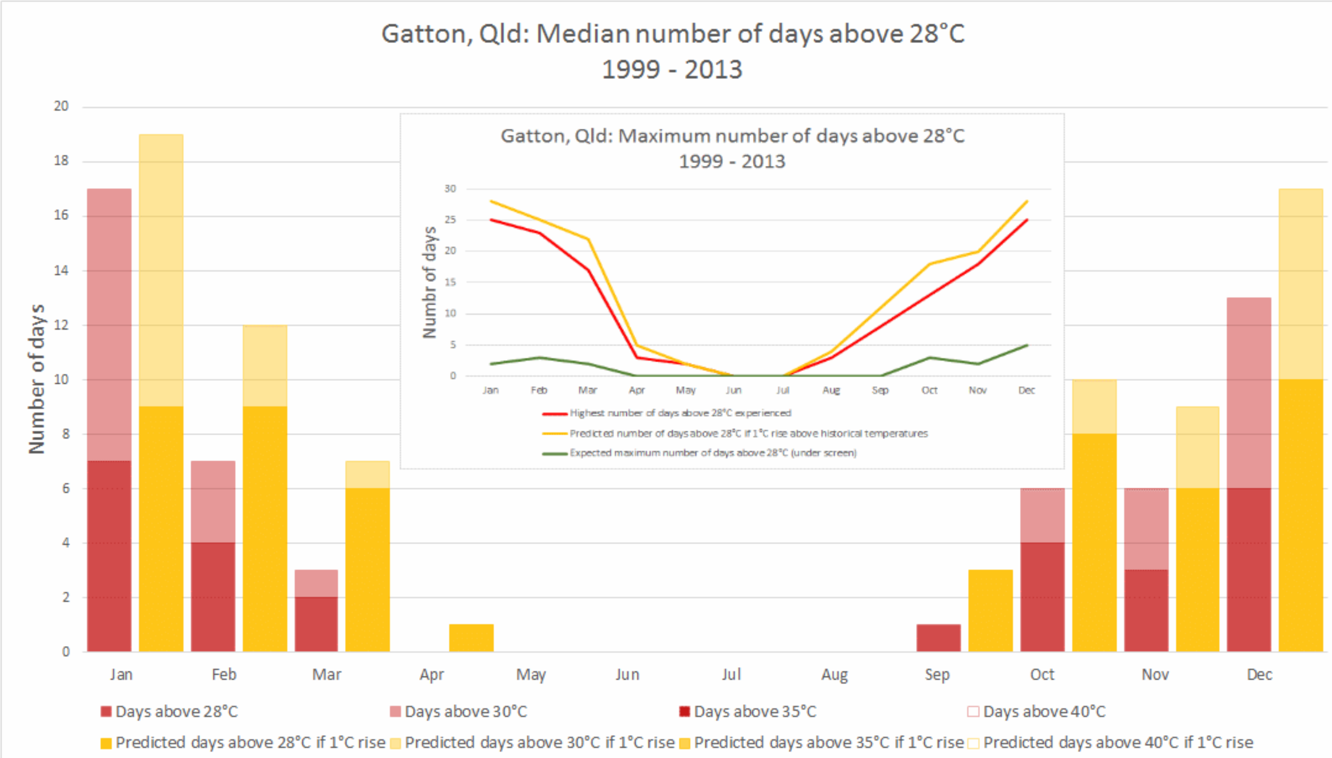

Figure 82: Median number of days above 28°C (red) for last 15 years at Gatton, Qld and with a 1°C predicted rise in temperature (yellow). Insert figure shows the maximum number of days above 28°C including expected maximum under screening (green).

Currently, over the warmest two months of December and January, this could represent a 10 to 30% increase in median number of days above 28°C, while in February and March the potential increase could be 70% and 130% respectively. The possible increase in median number of days over 28°C in spring with a 1°C rise on actual conditions over the past 15 years is 50 to 65%.

The installation of shading could substantially reduce the maximum number of days that exceed the upper threshold. This is shown in the insert graph in Figure 83.

The traditional harvest period for crops such as lettuce or baby leaf crops is between May and October. If an average rise of 1°C resulted in a doubling of days over 28°C in spring, a significant impact on yield would occur. For lettuce, temperatures exceeding the upper threshold could potentially halve yield and quality due to bolting, tipburn and bitterness[91].

[91] G. Rogers (2013) Understanding and managing impacts of climate change and variability on vegetable industry productivity and profits, Final report VG12041 AHR

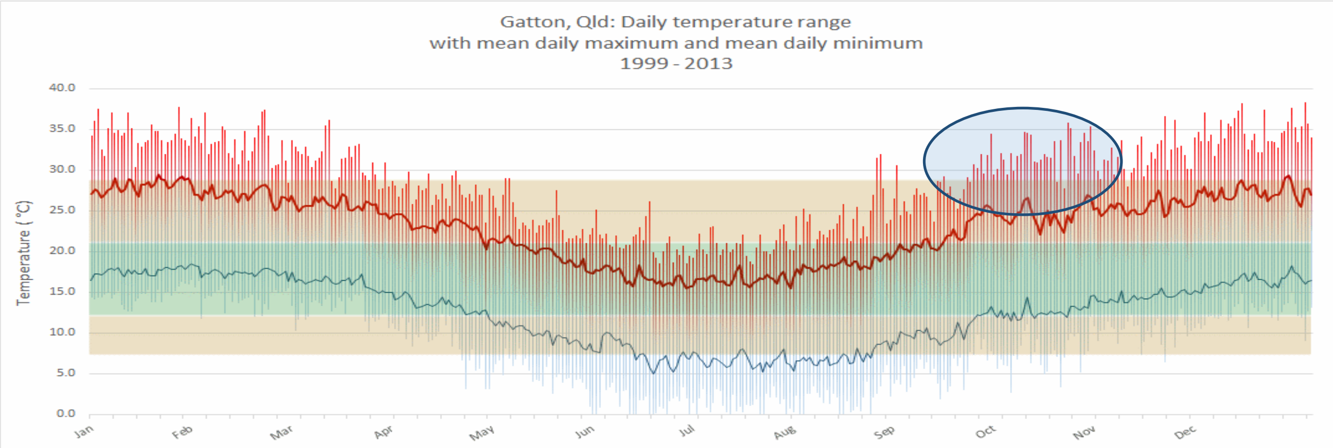

*Figure 83: Mean daily temperatures and range for past 15 years at Gatton, Qld with suitable (green) and tolerable (tan) growing conditions for **lettuce**.*

The unfavourable high temperatures are illustrated for lettuce in Figure 84. While the mean temperatures suggest suitable conditions, almost any day from October to late April may exceed thresholds and affect yield and/or quality. Reducing maximum temperatures is a key production opportunity for LCPC in this region. Figure 85 illustrates the likely benefit of reducing maximum temperatures with shading, particularly during the spring harvest period (highlighted).

Other crops in this region such as capsicum and brassica crops, traditionally harvested in spring/autumn and winter/spring respectively are also likely to be impacted with an increased number of days over the upper threshold leading up to and during the harvest periods.

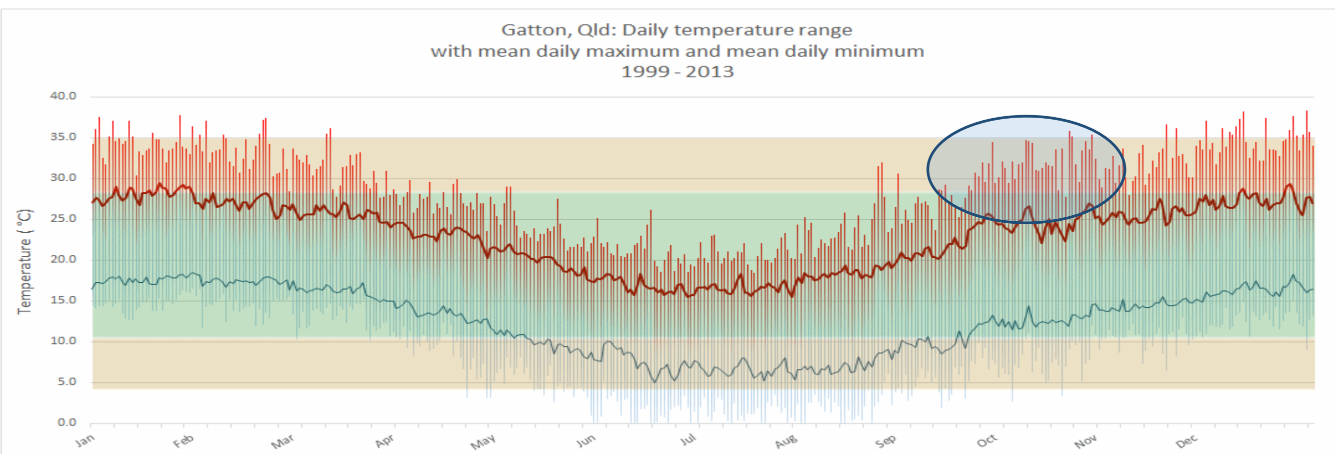

*Figure 84: Mean daily temperatures and range for past 15 years at Gatton, Qld with suitable (green) and tolerable (tan) growing conditions for **lettuce extended with screening**.*

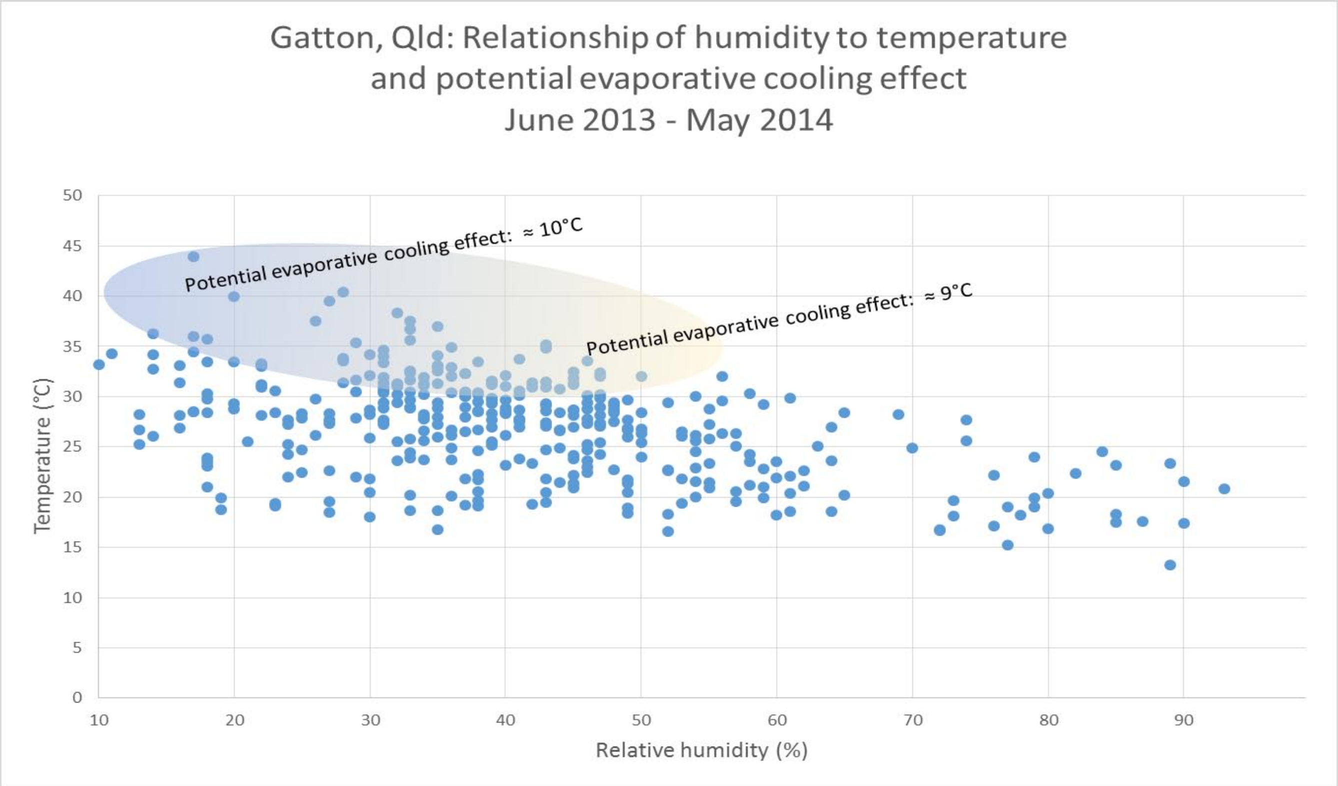

Figure 85: Warmer days are associated with a low relative humidity levels resulting in high evaporative cooling potential.

Higher temperature conditions in this region are associated with low relative humidity which indicates that the application of fogging could provide significant temperature reduction in summer (Figure 86).

Light to moderate winds are usual in Gatton and the effect on air movement from a protected cropping element needs to be taken into account. The reduced airflow in a standard enclosed shadehouse under light wind conditions on excess heat days may impact on the crop and a shade canopy could be a more suitable option. However, weather data from the past year (Figure 87) also shows that a few fresh to strong wind events occurred in this region during cooler periods. Strong winds have the potential to damage crops and structures.

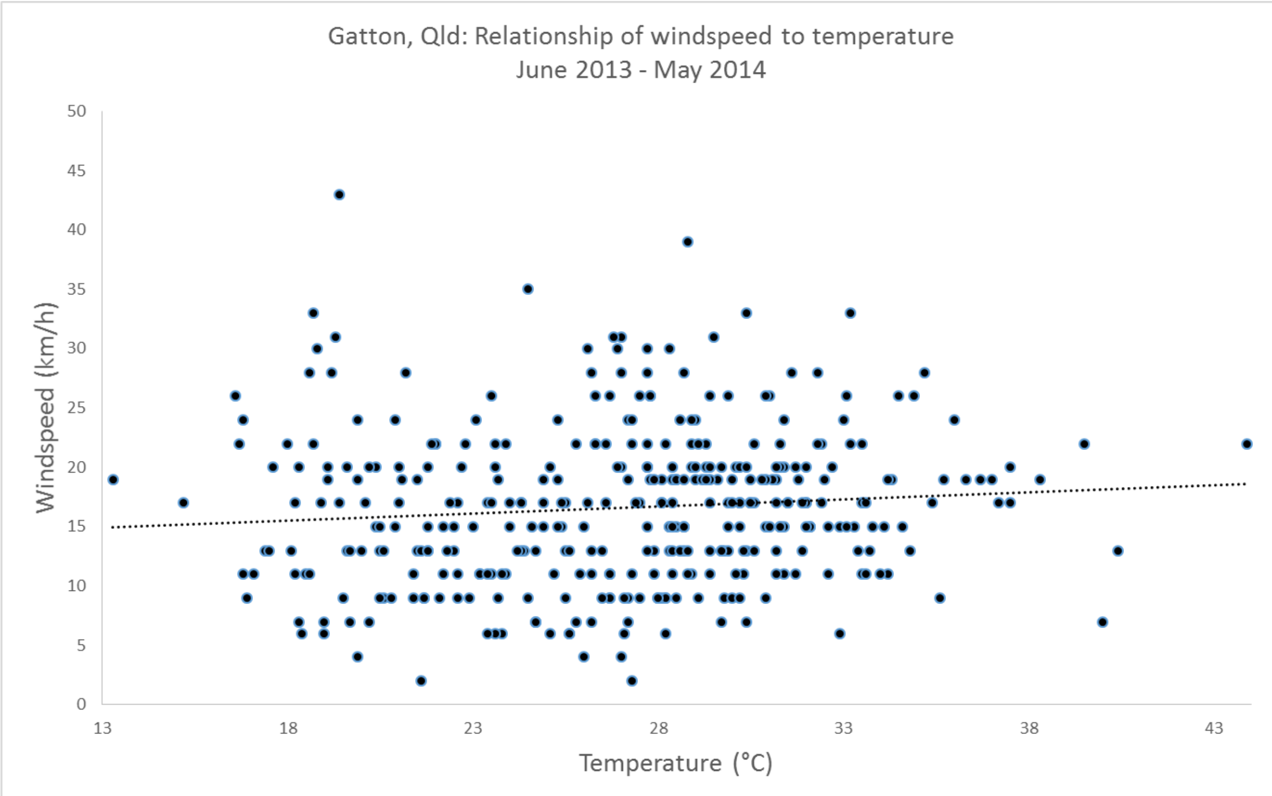

Figure 86: Light to moderate wind speeds prevail in this region, though some fresh to strong winds do occur.

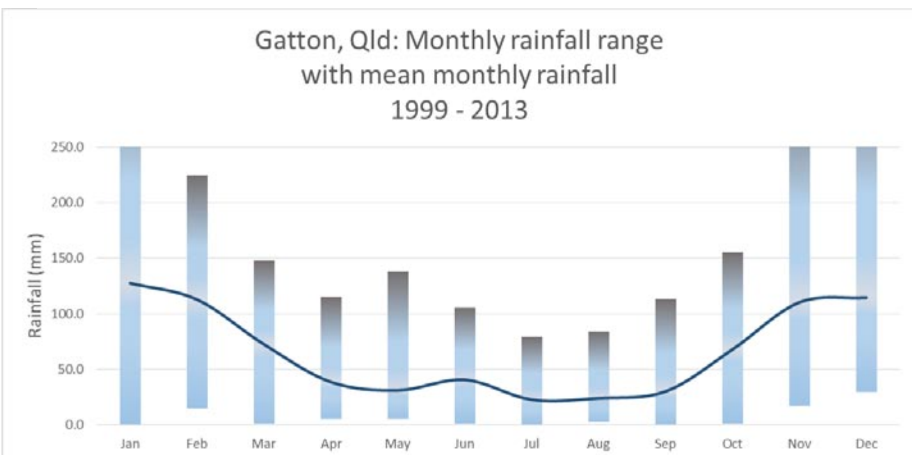

Figure 87: Mean monthly rainfall and range for past 15 years at Gatton, Qld.

5.6.3 Crop water use

Rainfall in this region is summer dominant with the greatest variability and potential for heavy rainfall events in late summer. The mean monthly rainfall and monthly range for the past 15 years is presented in Figure 88. Although annual rainfall is not expected to change significantly[92], variability will remain a factor. Increasing mean temperatures on top of current conditions may increase crop water use in regions like Gatton. The increase in variability could result in longer and more frequent dry periods and heavy rain periods including flooding, though crop water use is not expected to be a key factor on its own to warrant protected cropping.

However, given the prospect for summer maximum temperatures to exceed crop temperature thresholds and the low relative humidity during these warm conditions, improved management of crop water use may be an additional benefit of reducing maximum temperature.

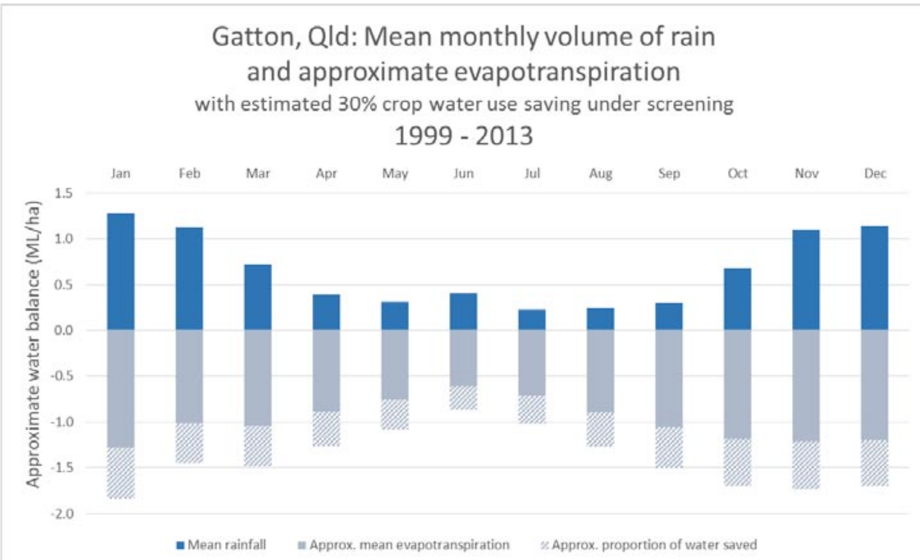

Figure 88: Approximate monthly rainfall and evapotranspiration for past 15 years at Gatton, Qld.

Evapotranspiration is quite substantial in winter, at around four times the mean monthly rainfall, though in summer the approximate mean evapotranspiration is around 30% more than the mean monthly rainfall (Figure 89).

Crop shading could have a potential benefit in reducing crop water use and/or increasing water use efficiency. The shaded component of the evapotranspiration values represents a 30% water saving under moderate shade.

Other protected cropping elements including tunnels, cloches and floating covers are not likely to provide any benefit in crop water use or from improved water use efficiency over the warmer months due to expected impacts of excessive temperatures which would occur under these options. During winter, the potential reduction in crop water use would be close to the mean monthly rainfall, however the associated reduction in temperature would not provide much benefit and could have a negative impact.

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[92] G. Rogers (2013) Understanding and managing impacts of climate change and variability on vegetable industry productivity and profits, Final report VG12041 AHR

5.6.4 Frost and low temperatures

The potential for frost is not uncommon in regions such as Gatton, however the risk of cold shock and frost is projected to decrease based on historical trends[93] and is therefore not likely to be a factor in the consideration of low cost protected cropping in this region. The number of frost days over the past 15 years as approximated by the number of days that temperatures fall below 2°C is shown in Figure 90.

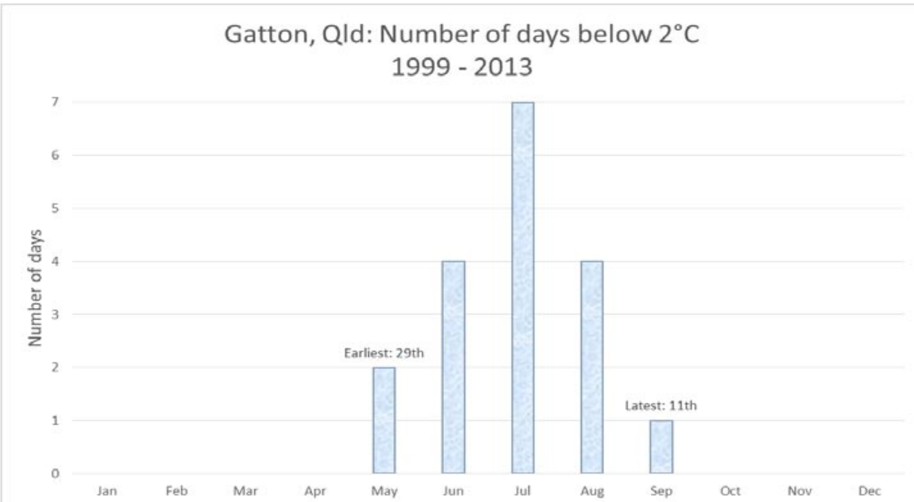

Figure 89: Highest number of days below 2°C per month (approximating the number of frosts) for the past 15 years at Gatton, Qld. Including earliest and latest occurrence.

The current frost window extends from late May to mid-September and may shorten. An extension of the frost window, particularly into spring could increase risk for summer crops.

Additionally, minimum temperatures in winter can drop below suitable crop thresholds on almost any day between May and late September which can impact on winter crops. Temperatures below 10°C can have a substantial impact on beans, affecting root development and plant growth. Yield can be reduced by up to 50%[94]. Brassica crops are unlikely to be affected due to the availability of a broad variety selection.

A light floating crop cover can provide a 2°C rise in minimum temperatures while a heavier plastic cover can increase minimum temperatures by close to 4°C. In late May and September the cover could mitigate cold days, though the benefit will be more limited across winter.

Leaving the cover on during the day may negate the benefit as daytime maximum temperatures could exceed the suitable range for this crop. This is shown in Figure 91 by

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[93] D. Singh, R. Routley, S. Argent and A. Zull (2012) Historical trends in rainfall and temperature in Queensland's mixed farming zone. Australian Society of Agronomy conference. Accessed online (2014): http://www.regional.org.au/au/asa/2012/climate-change/8146_singhdk.htm

[94] G. Rogers (2013) Understanding and managing impacts of climate change and variability on vegetable industry productivity and profits, Final report VG12041

the reduced 'suitable' maximum temperatures corresponding to the extension in 'suitable' minimum temperature as a result of a floating cover.

The labour requirement of moving the covers on a forecast warm day is expected to limit the feasibility of this type of protected cropping option, though this would need to be assessed at an individual enterprise level.

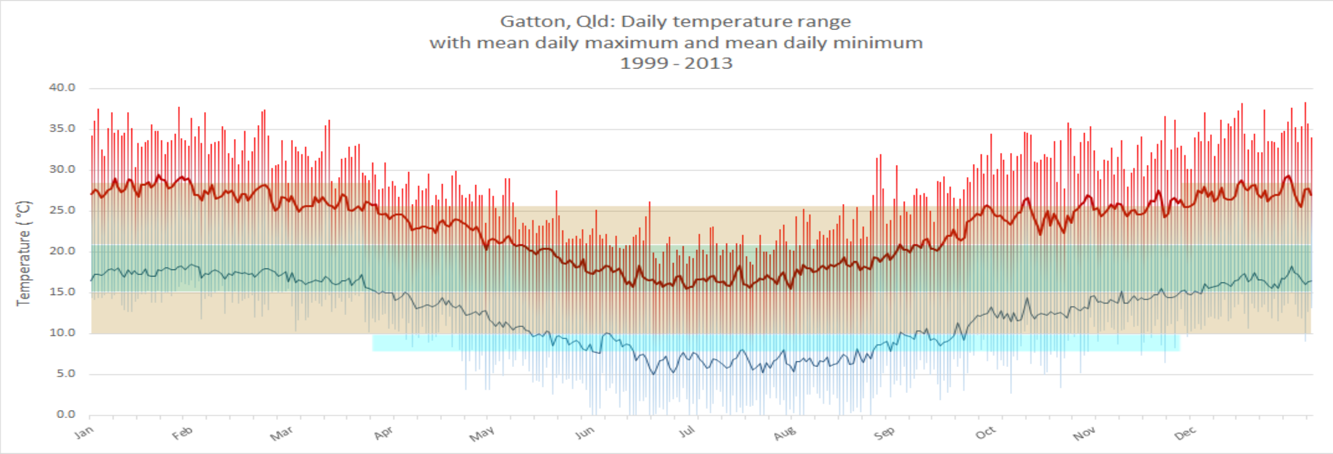


Figure 90: Mean daily temperatures and range for past 15 years at Gatton, Qld with suitable (green) and tolerable (tan) growing conditions for ***bean adjusted with a floating cover.***

5.6.5 Impact on light levels

Any protective structure installed above a cropping area will impact on the amount and quality of light reaching the crop. The use of a screening material to reduce temperatures, for example, will necessarily also affect crop light levels. If light becomes limiting, the benefit of reduced temperatures is negated.

Gatton represents a high light region. Figure 92 shows the approximate daily mean levels and range of photosynthetically active radiation (PAR) for Gatton with an overlay of the suitable light levels for lettuce (green) and bean (pink). The mean daily level has also been adjusted to reflect a 50% (blue) transmission level. With 50% transmission, such as under a 50% shade screen, the mean PAR levels would not be limiting.

The use of a screening material in Gatton has been discussed previously in '*Managing high temperatures*' and there is a high likelihood that shade screening could provide a beneficial cooling effect to most crops in this region, particularly in the autumn and spring leading up to and during traditional harvest periods. This example illustrates that there is not likely to be any significant negative impact of reduced light levels.

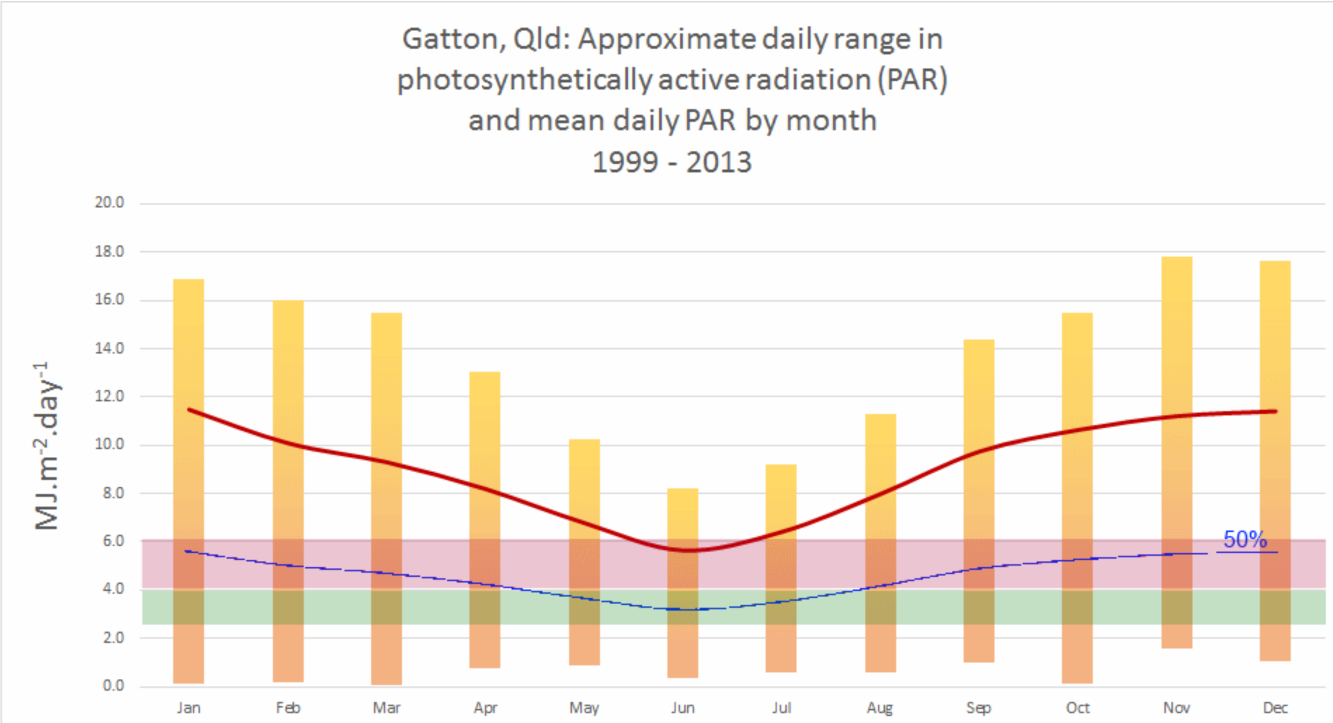


Figure 91: Approximate levels of photosynthetically active radiation (PAR) for the past 15 years at Gatton, Qld with overlay of suitable light levels for lettuce (green) and bean (pink) with an indication of mean daily PAR given 50% (blue) transmission rates.

5.6.6 Gatton LCPC assessment

The Gatton region experiences moderate to high summer temperatures with a reasonable number of excess heat days during summer, cool winter temperatures with several frost days and high light levels year-round. Winds tend to be light to moderate with occasional fresh to strong winds. Mean rainfall is summer dominatant and quite variable. Heavy rain events can occur.

The primary focus for protected cropping in this region should be on managing extreme high temperatures and extended heatwaves with a particular focus on autumn and spring to maintain yield and quality leading up to and during harvest.

Shading of 50% could potentially decrease maximum temperatures by 6°C or more and contain mean maximum temperatures within general crop thresholds. Furthermore, a realistic expectation of current and potential future maximum temperatures indicates a significant number of excess heat days can and will occur, with the greatest increase in excess heat days likely to occur in autumn and spring. Shading would dramatically improve crop temperatures under these conditions. The addition of fogging would also have a large benefit on reducing crop air temperature on excess heat days in this region.

The high light levels suggest that permanent shading is unlikely to cause deficient light levels even in winter. Alternatively, the high light levels could also enable a greater shading level to be suitable and therefore facilitate a greater reduction in maximum temperatures. Reduced crop water use through summer would be expected to be a further benefit of shading.

Light to moderate winds may result in a reduced benefit in cooling temperatures in a screenhouse during summer due to reduced ventilation and airflow within the crop. Local conditions will need to be specifically assessed. Low profile greenhouses, cloches and floating crop covers are likely to result in a similar problem with significantly reduced ventilation in the cropping area. A crop canopy structure could provide a shade cooling effect without adversely affecting airflow and subsequently heat removal from the cropping area.

Exclusion of crop and contaminant pests could be achieved with floating covers, though they may not be suitable during summer due to reduced ventilation and consequently an increase in temperature. Floating crop covers may offer a good benefit from autumn to spring.

Low profile greenhouses and plastic cloches are not likely to provide much overall improvement in growing conditions.

5.7 Bowen

5.7.1 Overview

This region bears a projected increase in mean annual maximum temperature of 0.6°C, ranging from a mean monthly increase in winter of 0.4°C to a summer increase of up to 1.0°C[95]. The mean daily temperatures and the daily maximum and minimum temperature range over the past 15 years are presented in Figure 93.

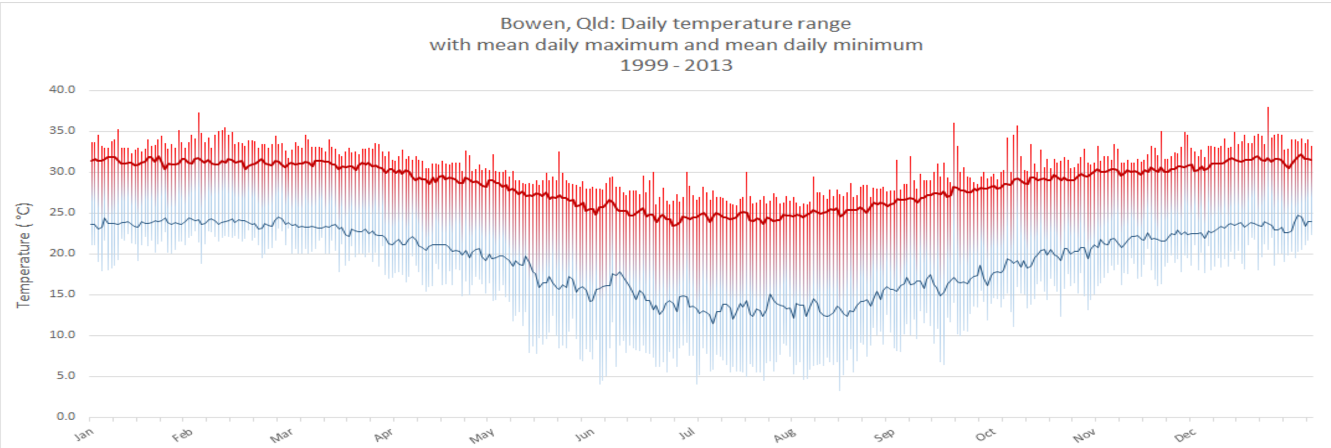


Figure 92: Mean daily temperatures and range for past 15 years at Bowen, Qld.

Mean temperatures through winter represent quite suitable growing conditions for warm season crops, however the mean maximum daily temperatures in summer sit at or marginally above the upper temperature thresholds for even warm season vegetable crops.

5.7.2 Managing high temperature

The potential maximum temperature on any day from November to April can be expected to exceed the crop threshold. Figure 94 presents the general suitable conditions for capsicum and shows that the upper temperatures are marginally high in summer. Though, the tropical climate moderates the extreme high temperatures. This is illustrated in Figure 95 which displays the median number of days above 28°C and provides an approximation of conditions that could typically be expected.

[95] P.Deuter, N. White and D. Putland (2012) Critical temperature thresholds - case study (tomato). *Agriscience Queensland*. Accessed online (2014): http://www.managingclimate.gov.au/publications/

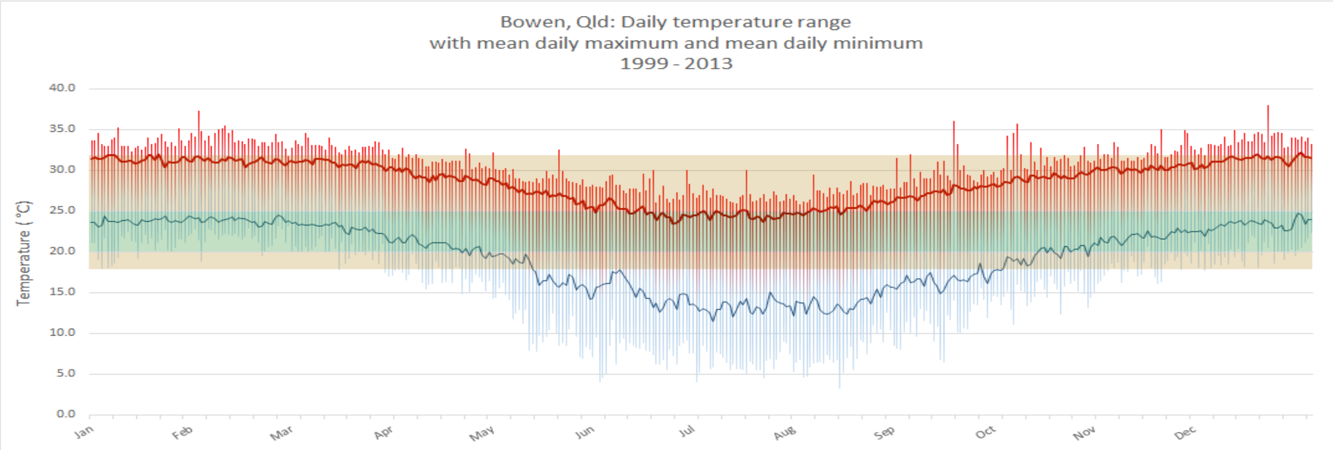


*Figure 93: Mean daily temperatures and range for past 15 years at Bowen, Qld with suitable (green) and tolerable (tan) growing conditions for **capsicum**.*

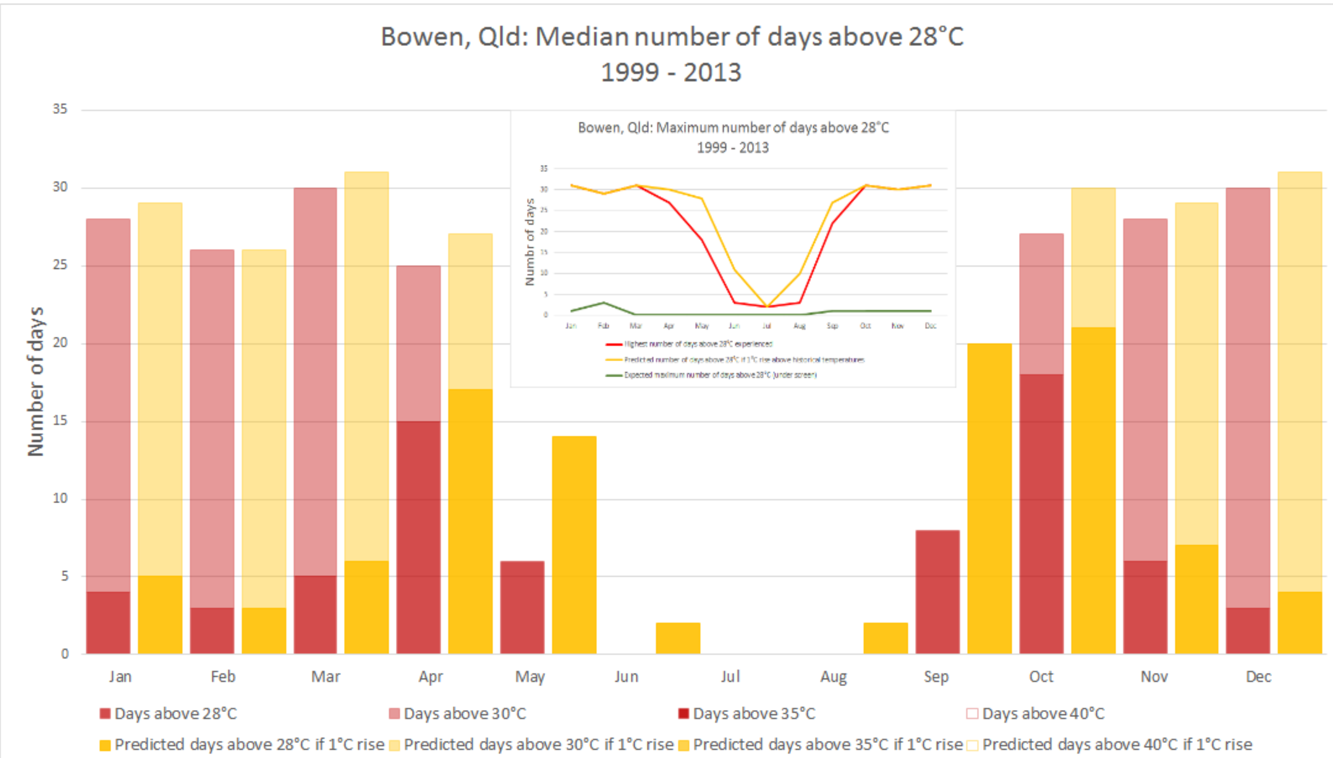


Figure 94: Median number of days above 28°C (red) for last 15 years at Bowen, Qld and with a 1°C predicted rise in temperature (yellow). Insert figure shows the maximum number of days above 28°C including expected maximum under screening (green).

While a substantial number of days through summer will exceed the upper temperature threshold, it is very uncommon for temperatures to exceed 35°C. The potential effectiveness of crop shading is high. The insert graph in Figure 95 shows the maximum number of days in the past 15 years which exceeded 28°C and indicates that a shade screen providing a 6°C cooling benefit, would largely eliminate this. This is also represented in Figure 96 which shows the shading benefit on capsicum that might be attained with the installation of a protective screen. This protected cropping option could significantly reduce the potential for maximum temperatures to breach crop thresholds. Temperatures exceeding 32°C can contribute to yield declines of up to 20% in capsicum1[1]. A similar situation exists for sweet corn, while cucurbit crops and bean would gain an even greater benefit.

The projected rise in mean temperatures will produce a minimal increase in the likelihood for extreme maximum temperatures over summer, however a quite pronounced increased in the median number of days over 28°C could be expected during the transition months of May and September (Figure 95). This could be expected to have an impact on winter production of beans. Above 28°C, bean can suffer reduced yields (as much as 35% decline[9]) and lower quality.

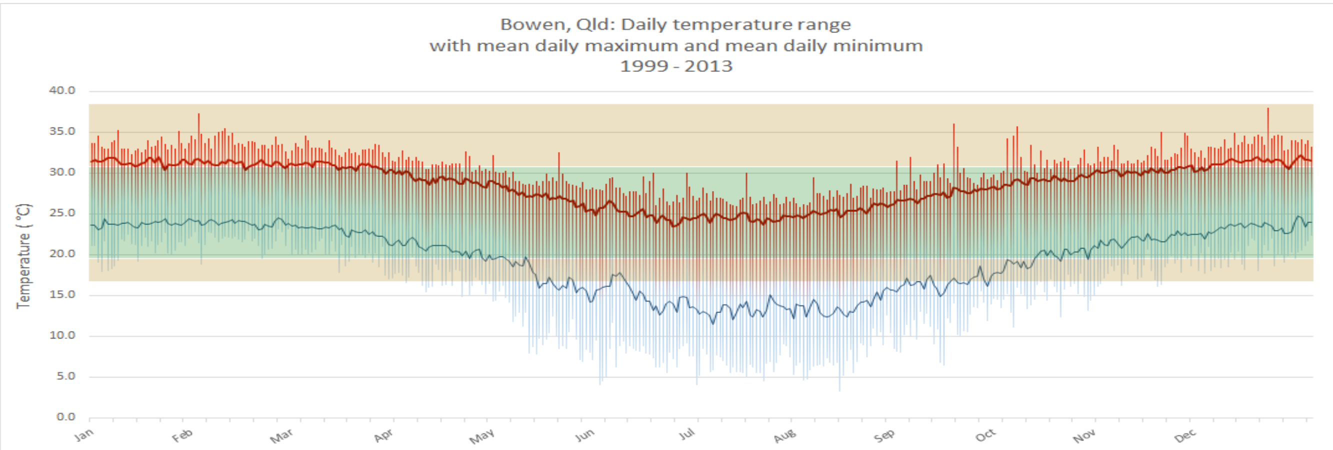


*Figure 95: Mean daily temperatures and range for past 15 years at Bowen, Qld with suitable (green) and tolerable (tan) growing conditions for **capsicum extended with screening**.*

The indicative benefit of shading for bean production is shown in Figures 97 and 98 which compare the suitable range under ambient and shaded conditions, respectively. This type of modification of the growing environment could redress the potential excess heat days in spring improving current yield and quality of the spring harvest period in this region and even significantly extend the cropping period, though the impact of high summer rainfall needs to be taken into account.

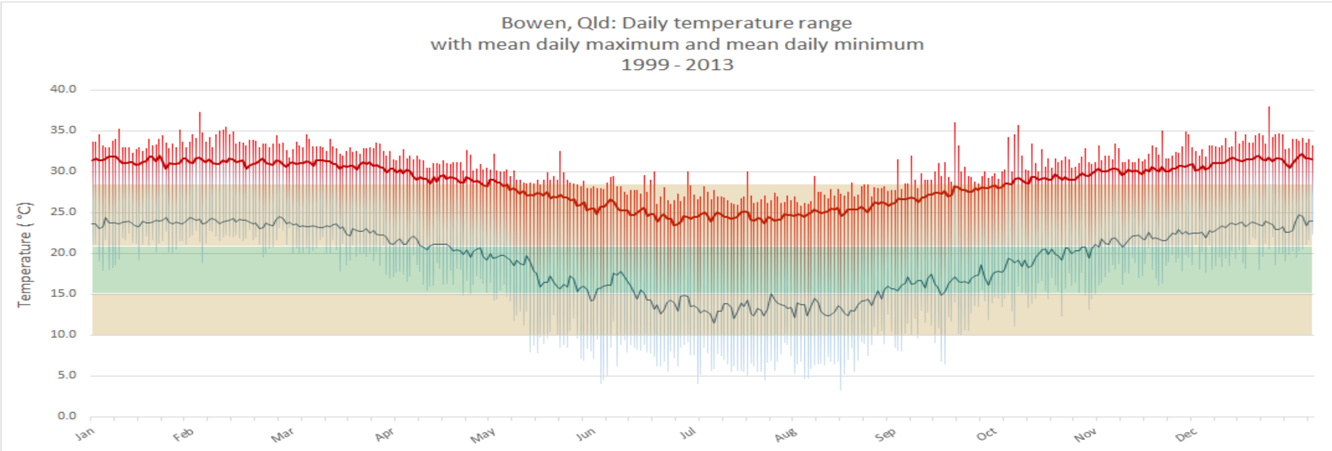


*Figure 97: Mean daily temperatures and range for past 15 years at Bowen, Qld with suitable (green) and tolerable (tan) growing conditions for **bean**.*

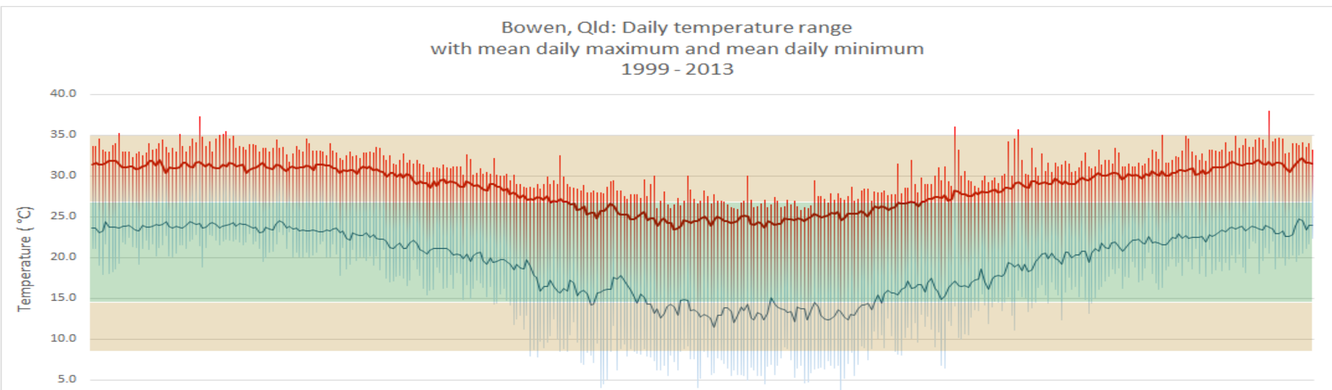


*Figure 96: Mean daily temperatures and range for past 15 years at Bowen, Qld with suitable (green) and tolerable (tan) growing conditions for **bean extended with screening**.*

The impact of reduced air exchange under structures needs to be considered. A shadehouse could provide effective crop protection from strong winds (red), however lower ventilation rates during periods of warm to hot weather (yellow) may negate the benefit of shading (Figure 99). In this sort of location, a shade canopy is likely to offer a better proposition than an enclosed shadehouse.

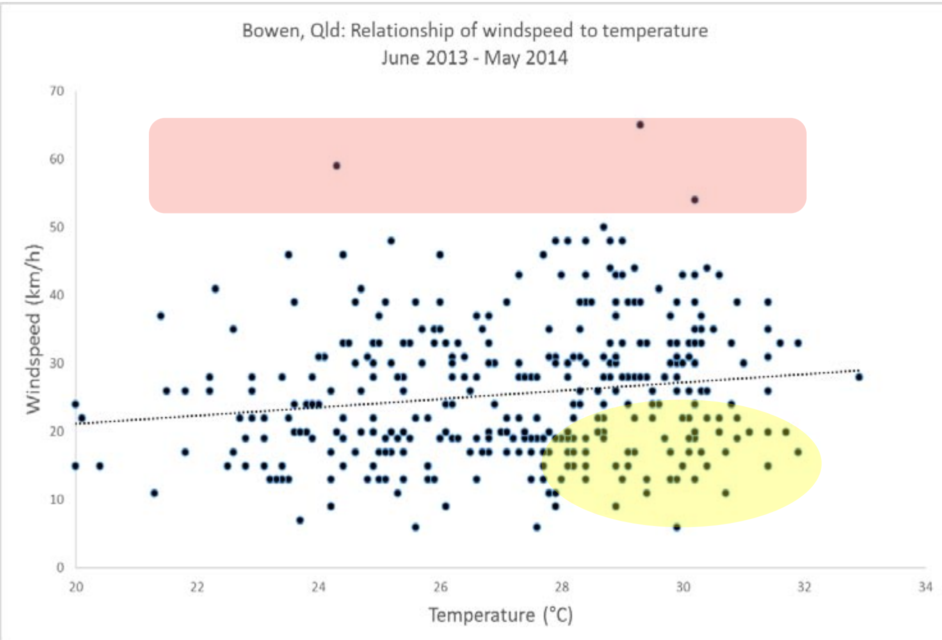


Figure 98: Light to strong wind speeds occur in this region and are not strongly associated with temperature.

The dry tropical climate of this region generates some potential for evaporative cooling (Figure 100), though it would offer little additional cooling benefit compared with shading and is unlikely to be feasible.

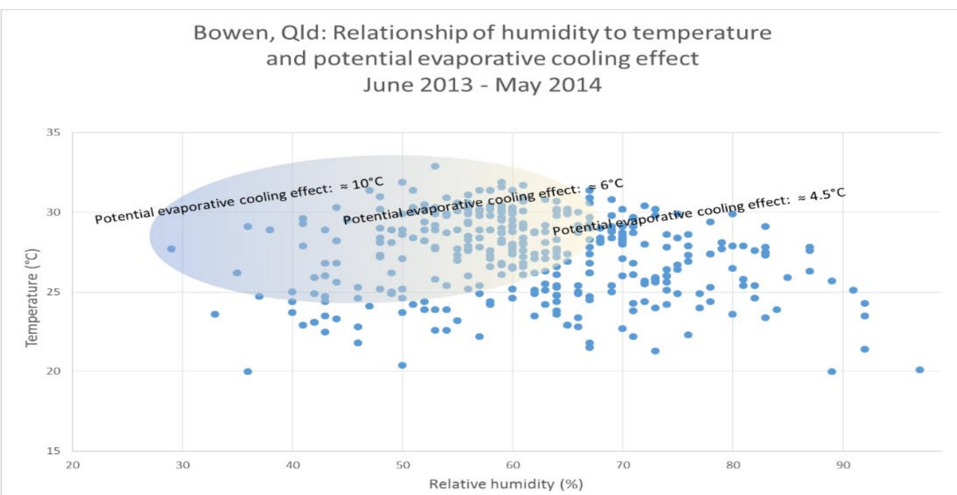


Figure 99: Warmer days are commonly associated with a medium relative humidity levels resulting in variable evaporative cooling potential.

5.7.3 Crop water use

Rainfall in this region is summer dominant with the greatest variability and potential for heavy rainfall events in late summer. The mean monthly rainfall and monthly range for the past 15 years is presented in Figure 101. Annual rainfall is projected to decrease by up to 5%[96] in this region and this is unlikely to create significant reason to specifically manage crop water use, though increasing mean temperatures on top of current conditions may increase overall crop water use.

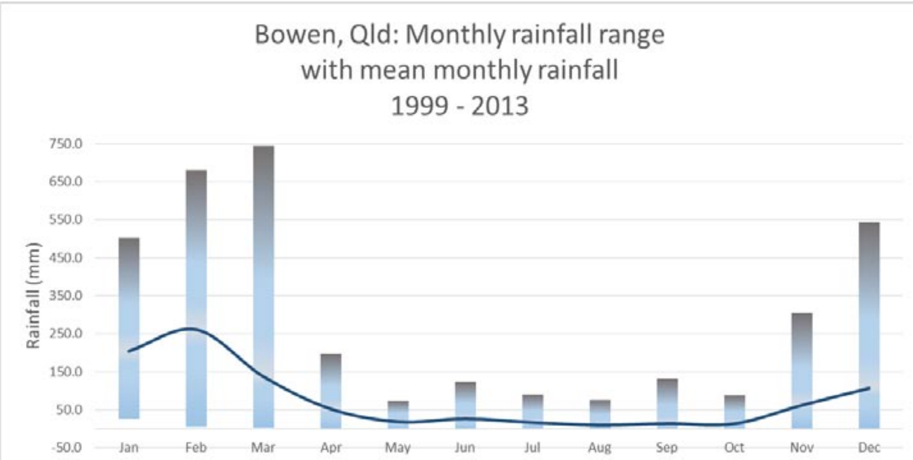


Figure 100: Mean monthly rainfall and range for past 15 years at Bowen, Qld.

Evapotranspiration is substantially greater than mean monthly precipitation year-round with the exception of January and February.

Crop shading could have a benefit in reducing crop water use and/or increasing water use efficiency. The shaded component of the evapotranspiration values (Figure 102) represents a 30% water saving under moderate shade.

[96] L. Whitfield, K. Oude-Egberink, B. Wecker, L. Cravigan, R. Pozza, V. Hernaman, J. Scott and S. Chidzambwa (2010) Climate change in Queensland: what the science is telling us. Dept. of Environment and Resource Management.

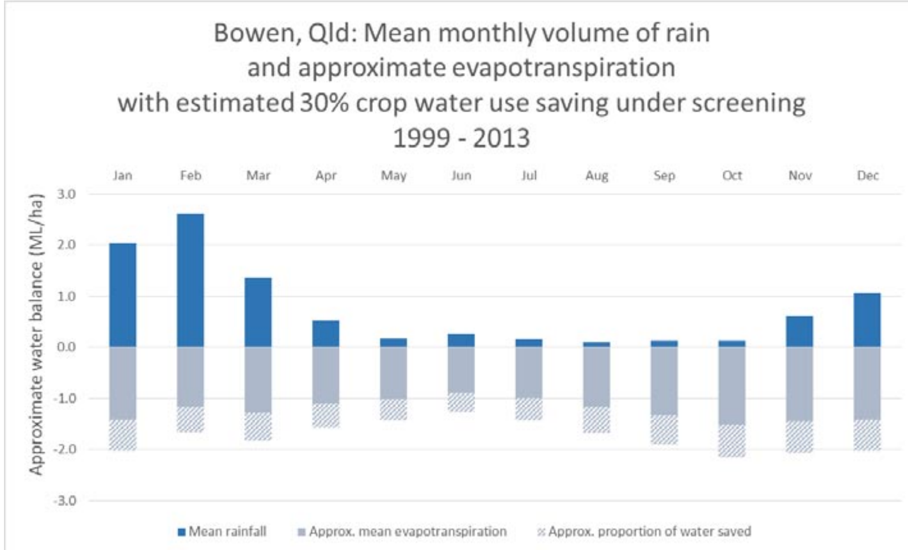


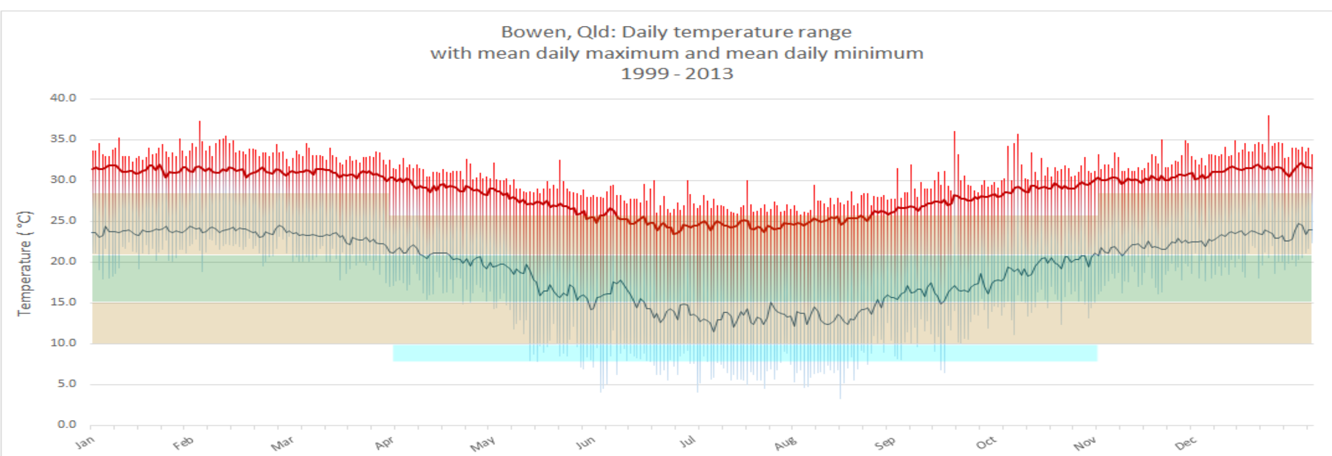
Figure 101: Approximate monthly rainfall and evapotranspiration for past 15 years at Bowen, Qld.

5.7.4 Frost and low temperatures

Frost is not a concern in this region, however minimum temperatures in winter can drop below suitable crop thresholds on almost any day between late May and late September which can impact on winter crops. Temperatures below 10°C can have a substantial impact on beans, affecting root development and plant growth. Yield can potentially be reduced by up to 50%[97].

A light floating crop cover can provide a 2°C rise in minimum temperatures while a heavier plastic cover can increase minimum temperatures by close to 4°C. In late May and September the cover could mitigate cold days, though the benefit will be more limited across winter. This is shown illustrated in Figure 103. However, leaving the cover on during the day may negate the benefit, as daytime maximum temperatures could exceed the suitable range for this crop.

The labour requirement of removing the covers on a forecast warm day is expected to limit the feasibility of this type of protected cropping option, though this would need to be assessed at an individual enterprise level.



[97] G. Rogers (2013) Understanding and managing impacts of climate change and variability on vegetable industry productivity and profits, Final report VG12041 AHR

5.7.5 Impact on light levels

Bowen represents a high light region, though there is significant daily variation in light levels, particularly in summer due to cloud cover. Any protective structure installed above a cropping area will impact on the amount and quality of light reaching the crop. The use of a screening material to reduce temperatures, for example, will necessarily also affect crop light levels. If light becomes limiting, the benefit of reduced temperatures is negated.

Figure 104 shows the approximate daily mean levels and range of photosynthetically active radiation (PAR) for Bowen with an overlay of the suitable light levels for capsicum (green) and bean (pink stripe). The mean daily level has also been adjusted to reflect a 50% (blue) transmission level. With 50% transmission, such as under a 50% shade screen, the mean PAR levels would not be limiting and would be more suitable for these

*Figure 102: Mean daily temperatures and range for past 15 years at Bowen, Qld with suitable (green) and tolerable (tan) growing conditions for **bean adjusted with a floating cover**.*

crops. Although bean has a high light tolerance, capsicum fruit is susceptible to sun damage and could benefit from lower light intensity in this region. During winter under 50% shading, there is potential for light levels to fall below the threshold for bean. A retractable or seasonal shade installation could avoid this situation, or a lower shade level such as 40% could provide a reasonable level of cooling without creating deficient mid-winter light levels.

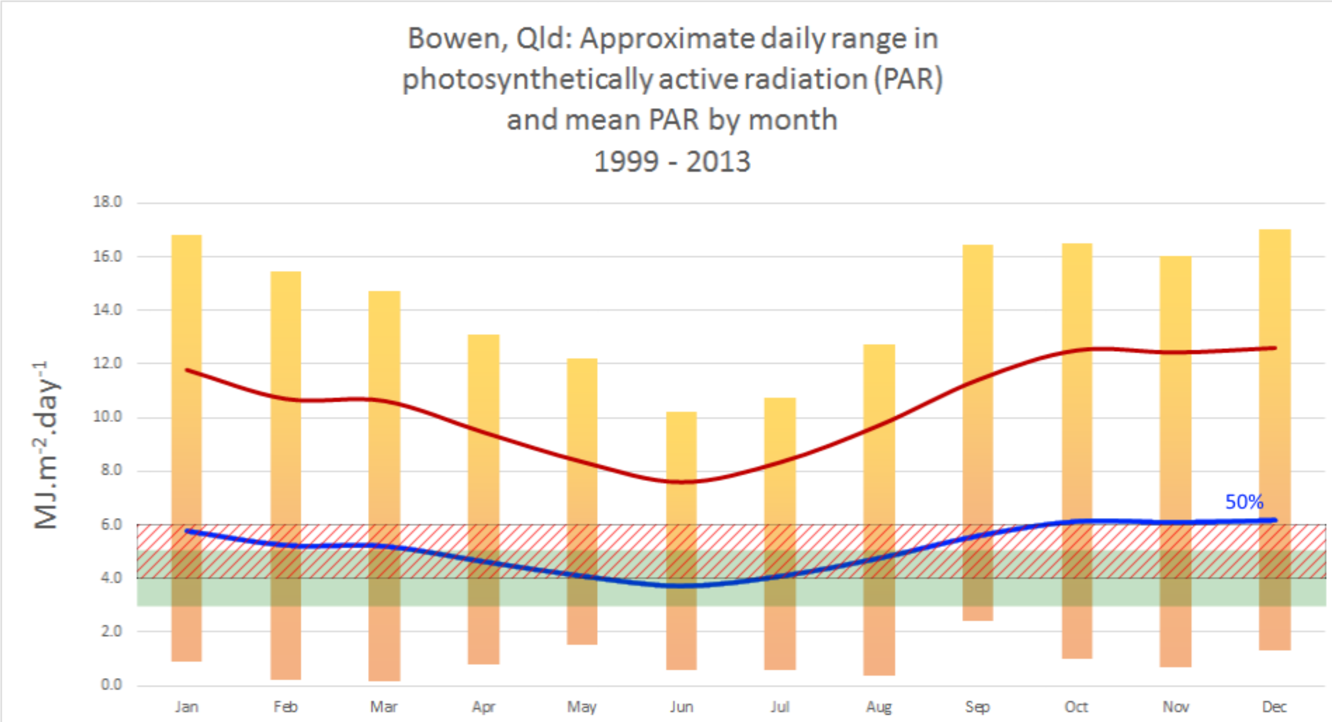


Figure 103: Approximate levels of photosynthetically active radiation (PAR) for the past 15 years at Bowen, Qld with overlay of suitable light levels for capsicum (green) and bean (pink stripe) with an indication of mean daily PAR given 50% (blue) transmission rates.

5.7.6 Bowen LCPC assessment

The Bowen region experiences moderate to high summer temperatures with only a few extreme heat days during spring and summer. Winter temperatures are mild with no frost days. Light levels are high year-round. Winds are light to strong with occasional very strong winds. Rainfall is highly summer dominant and quite variable. Heavy rain events can occur.

The primary focus for protected cropping in this region should be on alleviating excess heat days. Shading of 50% could potentially decrease maximum temperatures by 6°C or more and contain maximum temperatures within general crop thresholds. Projected increases in temperature would have minimal additional impact on example vegetable crops. Reduced crop water use could be expected to be a benefit of shading, particularly during the low rainfall period from autumn to spring, while screening could also reduce potential damage from heavy rain events in summer.

Although light levels are high, permanent medium shading may cause some light deficiency for beans during winter. A lower shading level would be suitable. Capsicum production would benefit from reduced temperatures and light levels.

Potential for light wind conditions during warm to hot weather increases the risk that an enclosed structure would exacerbate excess heat days. A shade canopy would be a more suitable option. The potential of very strong wind events needs to be considered with respect to structures and crop protection.

Exclusion of crop and contaminant pests could be achieved with floating covers, though they are unlikely to be suitable during summer due to reduced ventilation and consequently an increase in temperature. Floating crop covers may offer a good benefit for leafy crops from autumn to spring.

Low profile greenhouses and plastic cloches are not likely to provide much overall improvement in growing conditions.

5.8 Carnarvon

5.8.1 Overview

Several vegetable crops including capsicum, eggplant, sweetcorn, cucumbers and beans are grown in the Carnarvon region.

Mean maximum temperature in this region could increase by up to 1.9°C, ranging from a mean monthly increase in winter of 1.2°C to a summer increase of up to 3.1°C[98]. The mean daily temperatures and the daily maximum and minimum temperature range over the past 15 years are presented in Figure 105. Mean maximum temperatures through winter represent quite suitable growing conditions for warm season crops, however the mean maximum daily temperatures in summer sit at or a little above the upper temperature thresholds.

Over the last 15 years, maximum temperatures have exceeded upper thresholds for most vegetable crops on almost any day from mid-October to mid-May. During winter, mean minimum temperatures fall below the lower crop temperature threshold for cucurbits, sweet corn, capsicum and bean.

5.8.2 Managing high temperature

The maximum temperature on any day from spring to autumn can be expected to exceed the threshold for warm season crops such as cucurbits and capsicum. This is presented in Figures 106 and 108, respectively. Under these conditions, production of capsicum would be reduced by up to 20%[99], while yield of cucumber would decline by 25% or more[100].

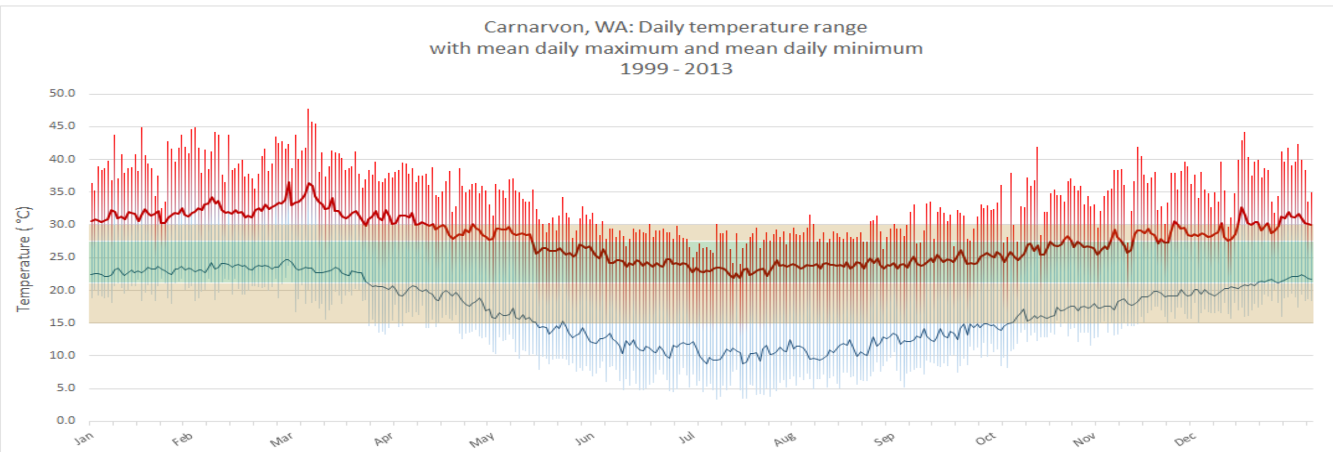


*Figure 104: Mean daily temperatures and range for past 15 years at Carnarvon, WA with suitable (green) and tolerable (tan) growing conditions for **cucumber**.*

[98] P.Deuter, N. White and D. Putland (2012) Critical temperature thresholds - case study (banana). Agriscience Queensland. Accessed online (2014): http://www.managingclimate.gov.au/publications/

[99] G. Rogers (2013) Understanding and managing impacts of climate change and variability on vegetable industry productivity and profits, Final report VG12041 AHR

[100] J Badgery-Parker (2011) *Cost effective improvements to tunnel houses* [workshop presentation] Extension activity within 'Development of a cost effective protected vegetable cropping system in the Philippines', HORT/2007/066-2, ACIAR.

Sunburn damage of extended season capsicum is 70%, resulting in just 22% of harvest fruit being marketable[101]. Assessment of the median number of days above 28°C (Figure 107) further illustrates the typical occurrence of excess and extreme heat days in this region.

A substantial number of days from late spring through to autumn will exceed the upper temperature thresholds. The potential effectiveness of crop shading is high. The insert graph in Figure 107 shows the maximum number of days in the past 15 years which exceeded 28°C and indicates that a shade screen providing a 6°C cooling benefit, would halve this number. In terms of the typical season, approximately four days in every five could be expected to exceed the upper temperature threshold and have an adverse impact on yield. A projected increase in mean temperature over the next twenty years would have a minor impact over summer as temperatures are already high.

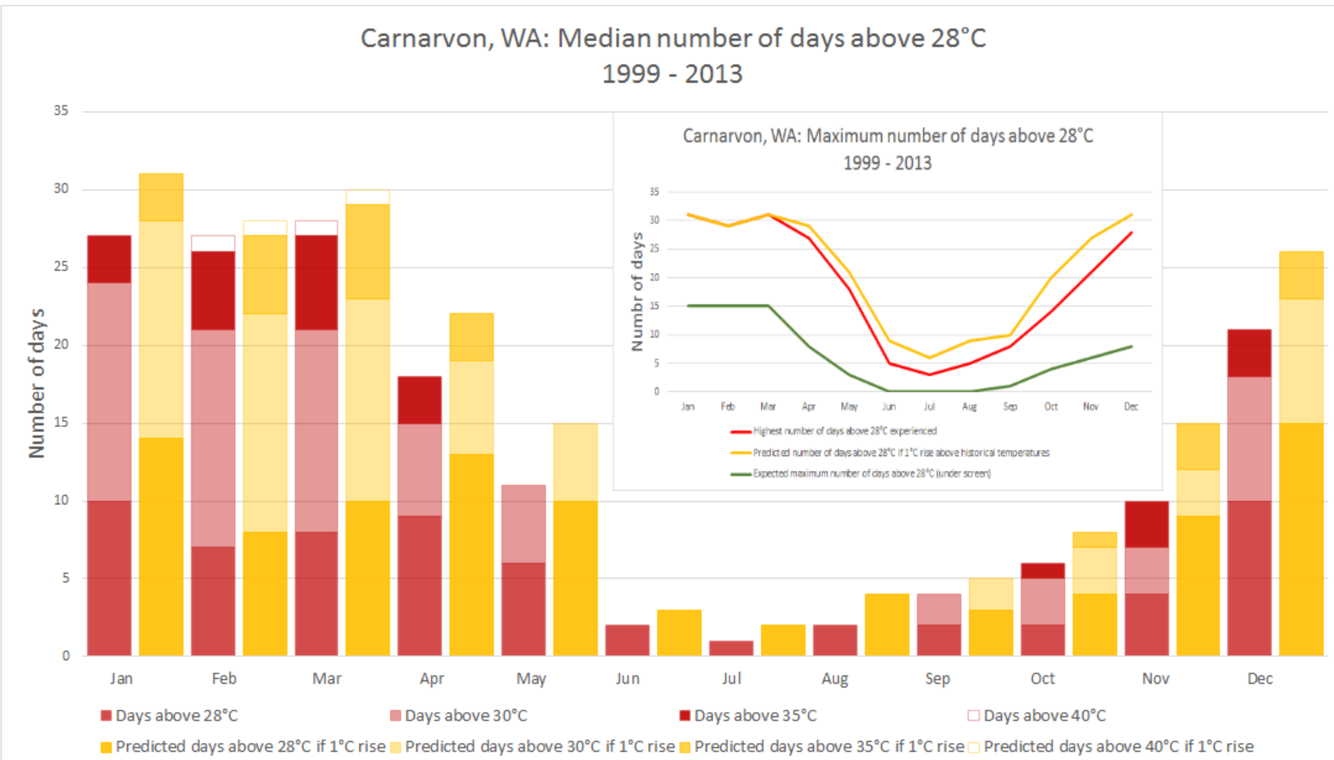


Figure 105: Median number of days above 28°C (red) for last 15 years at Carnarvon, WA and with a 1°C predicted rise in temperature (yellow). Insert figure shows the maximum number of days above 28°C including expected maximum under screening (green).

[101] V. Kesavan (2002) Sustainable production of quality capsicums in Carnarvon. Project VG99013 Final report Horticulture Australia.

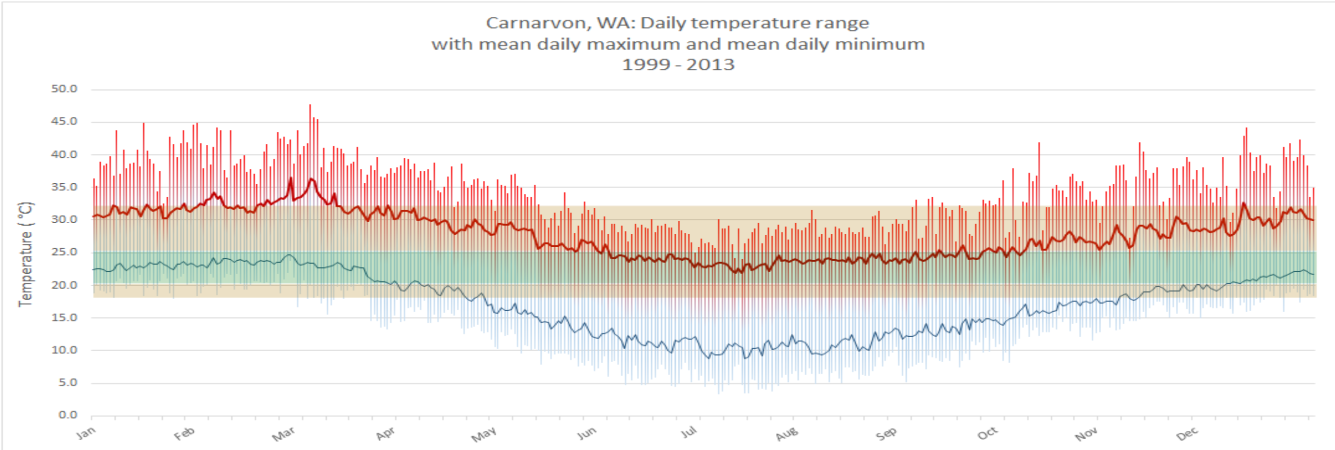


Figure 106: Mean daily temperatures and range for past 15 years at Carnarvon, WA with suitable (green) and tolerable (tan) growing conditions for ***capsicum****.*

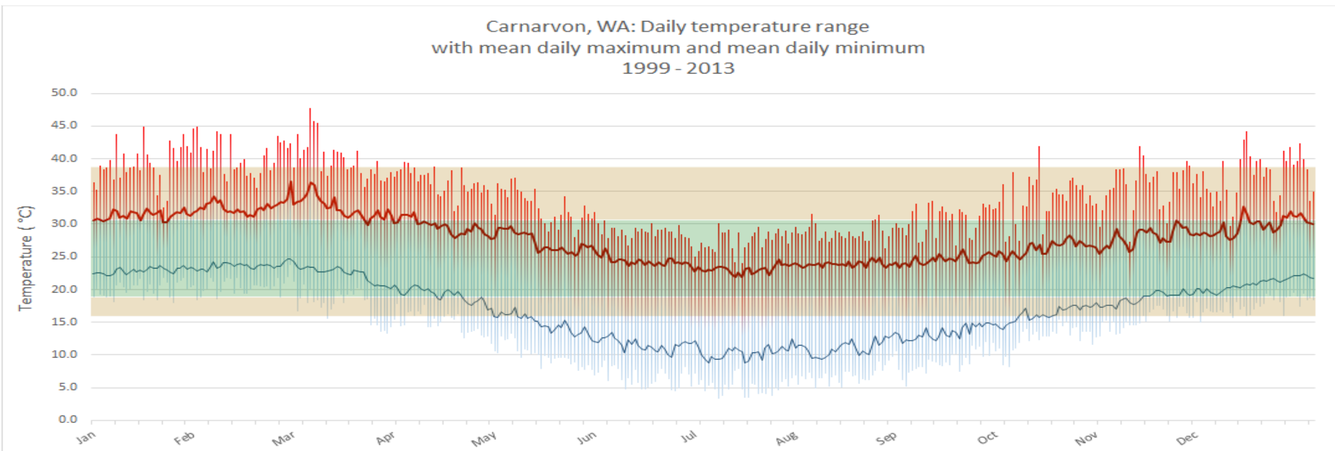


Figure 107: Mean daily temperatures and range for past 15 years at Carnarvon, WA with suitable (green) and tolerable (tan) growing conditions for ***capsicum extended with screening****.*

The potential impact of the installation of shade screen is shown for capsicum in Figure 109. A cooling benefit of just 6°C would contain mean maximum temperatures to within crop thresholds. Additionally, in this region moderate wind speeds (Figure 111) will generally offset the restriction of air flow through screening materials. Subsequently, enclosed shadehouses and shade canopies could be practical options for managing high temperatures.

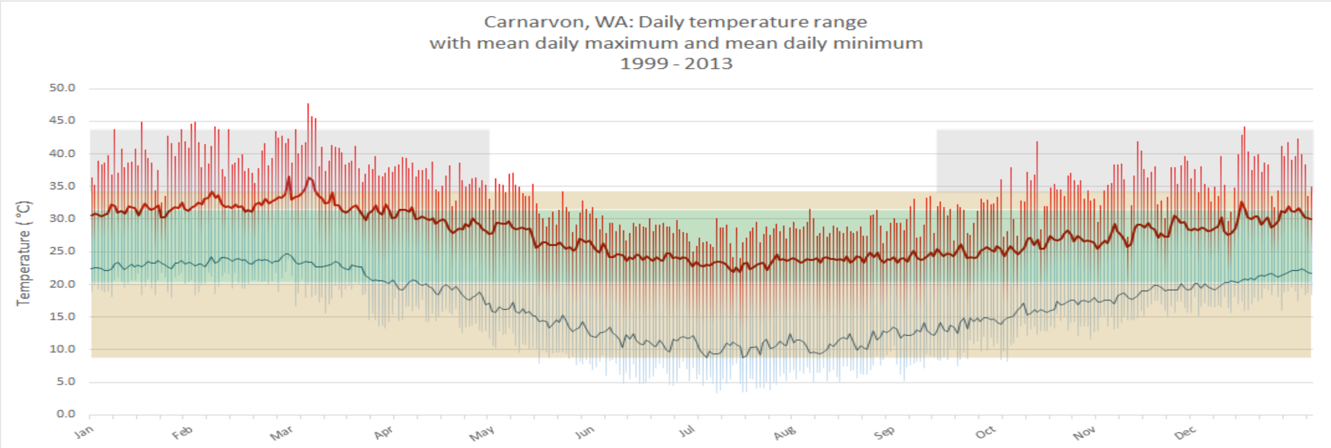


Figure 108: Mean daily temperatures and range for past 15 years at Carnarvon, WA with suitable (green) and tolerable (tan) growing conditions for ***capsicum extended with screening and fogging.***

The climate of this region generates some potential for evaporative cooling (Figure 112) particularly during periods of high temperature. The installation of fogging with shading could almost fully mitigate the extreme heat days and further protect crops. This is illustrated for capsicum in Figure 110, and could be a viable option, though it needs to be assessed at an enterprise level.

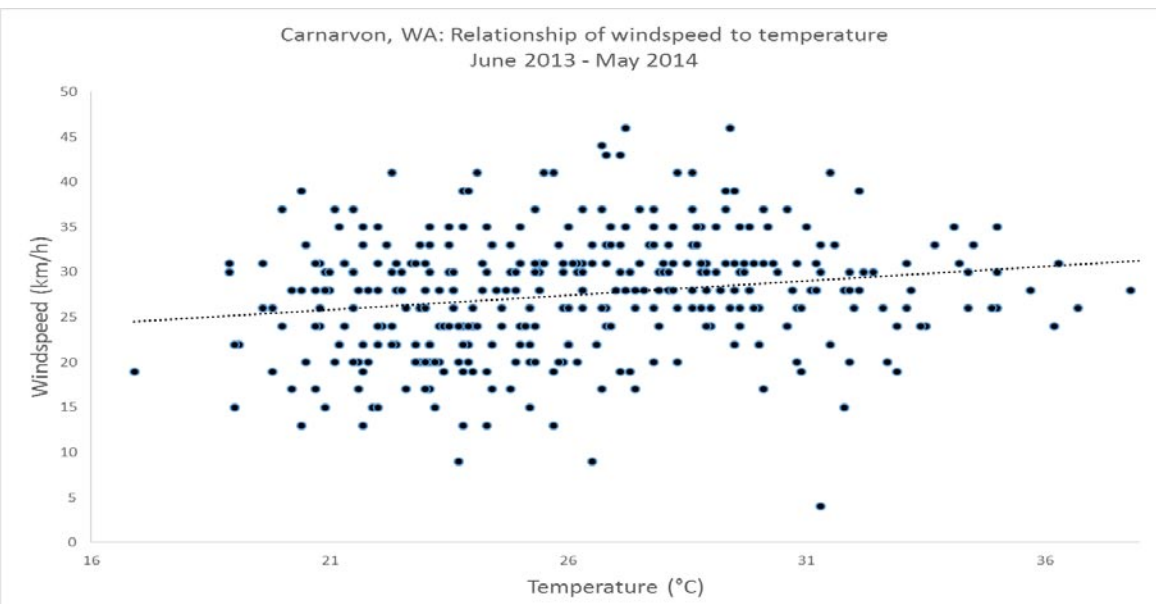


Figure 109: Moderate to strong winds are common in this region and are not strongly associated with temperature.

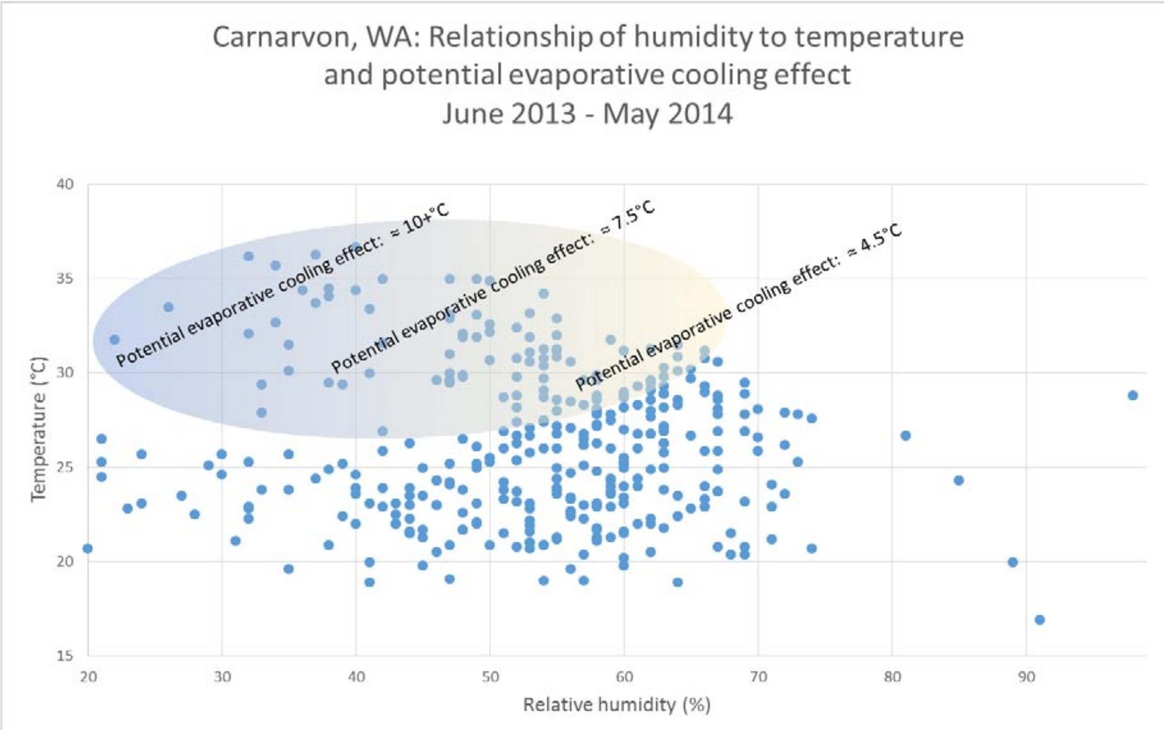


Figure 110: Warmer days are commonly associated with a medium relative humidity levels in Carnarvon resulting in variable evaporative cooling potential.

5.8.3 Crop water use

This region tends to have a dry spring, with mean monthly rainfall fairly consistent over the remainder of the year, however significant variability in rainfall occurs in December as well as through autumn and into winter, and heavy rainfall events can occur. The mean monthly rainfall and monthly range for the past 15 years is presented in Figure 113. Annual rainfall projections are uncertain in this area though it is generally expected that seasons will become drier. A decrease of up to 9% is considered likely in winter but less of a decline is expected in the already drier spring period[102].

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[102] I. Foster (2010) Climate trends and change for the Southern Rangeland, Dept of Agriculture and Food, WA. Presentation at Climate Change Forum, 2010.

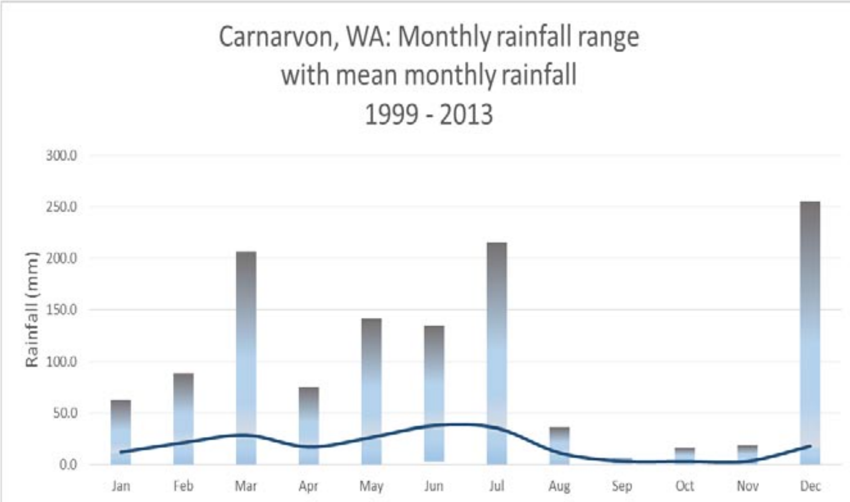

Figure 111: Mean monthly rainfall and range for past 15 years at Carnarvon. WA.

The dry climate and high temperatures indicate that a reduction of crop water use may be a potential target for protected cropping in this region.

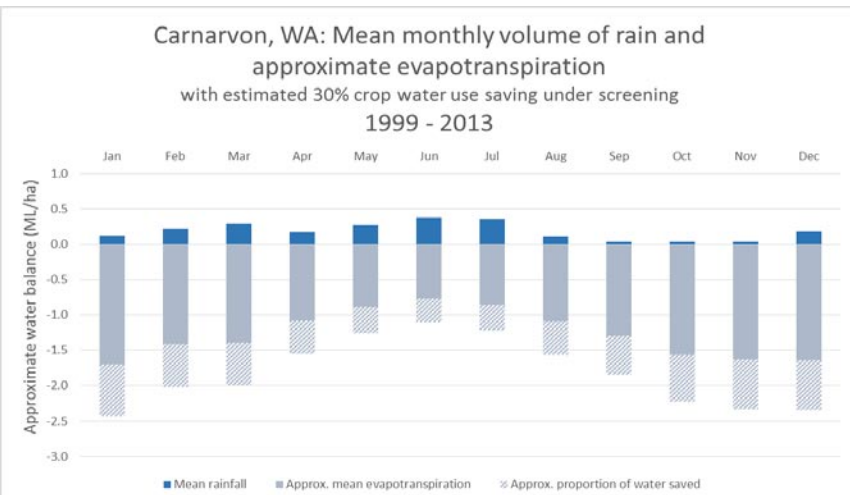

Figure 112: Approximate monthly rainfall and evapotranspiration for past 15 years at Carnarvon, WA.

Evapotranspiration is substantially greater than mean monthly precipitation year round. Crop shading could have a potential benefit in reducing crop water use and/or increasing water use efficiency.

The shaded component of the evapotranspiration values (Figure 114) represents a 30% water saving under moderate shade. Reductions in water use could also be achieved with floating crop covers.

5.8.4 Frost and low temperatures

Frost is not a concern in this region, however minimum temperatures can drop below suitable crop thresholds on almost any day between late May and late September which can impact on winter crops. Mean winter temperatures limit production of warm season crops during this season. Temperatures below 10°C can have a substantial impact on beans, affecting root development and plant growth. Capsicum can become stunted with misshapen fruit and often do not fully recover from a cold spell. Yield can potentially be reduced by up to 35% for capsicum and as much as 50% for bean[103].

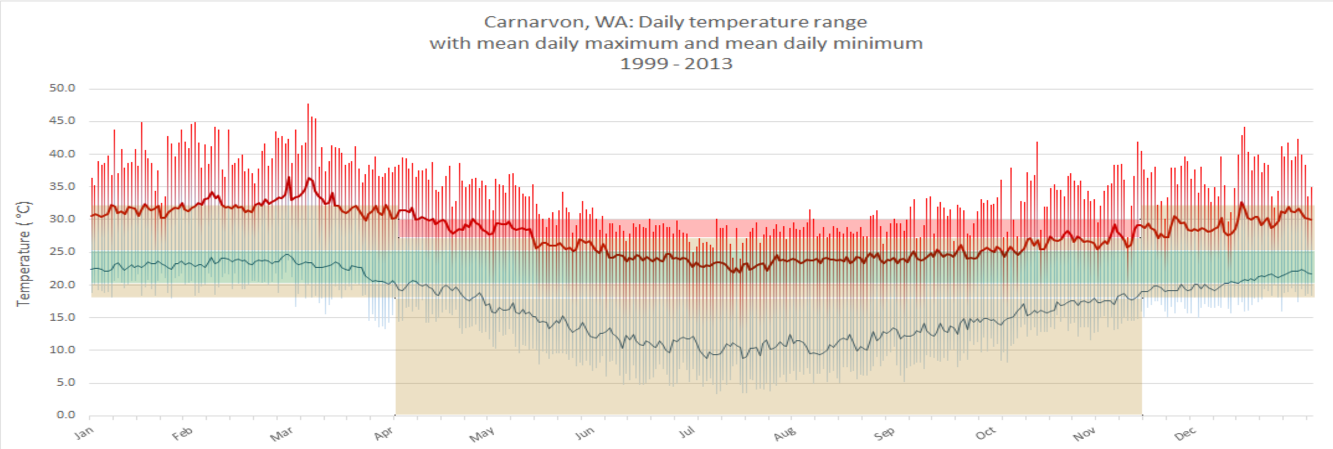

Figure 113: Mean daily temperatures and range for past 15 years at Carnarvon, WA with overlay of suitable (green) and tolerable (tan) growing conditions for capsicum extended with plastic tunnel house or cloche. An adverse increase in maximum temperature if structure is poorly ventilated is indicated (red).

Low profile greenhouse and plastic cloches could provide a low cost means of raising minimum temperatures over the winter period. Any such structure would be unsuitable over summer due to excess heat. During the cooler season, these structures would need to be moveable or well vented to avoid excess daytime temperatures (Figure 115).

A light floating crop cover can provide a 2°C rise in minimum temperatures while a heavier plastic cover can increase minimum temperatures by close to 4°C. In late May and September a cover could mitigate cold days and contain mean minimum temperatures within crop thresholds, though would not be adequate to fully mitigate potential lows. This is shown illustrated in Figure 116. Leaving the cover on during the day may negate the benefit, particularly over the transition periods of autumn and spring. Although modified mean maximum temperatures over winter would not be expected to affect yield of this crop, a floating crop cover could raise maximum temperatures sufficiently that any day during winter may be expected to exceed the upper temperature threshold. To minimise this risk, covers would need to be removed on forecast warm days which would increase the labour requirement.

[103] G. Rogers (2013) Understanding and managing impacts of climate change and variability on vegetable industry productivity and profits, Final report VG12041 AHR

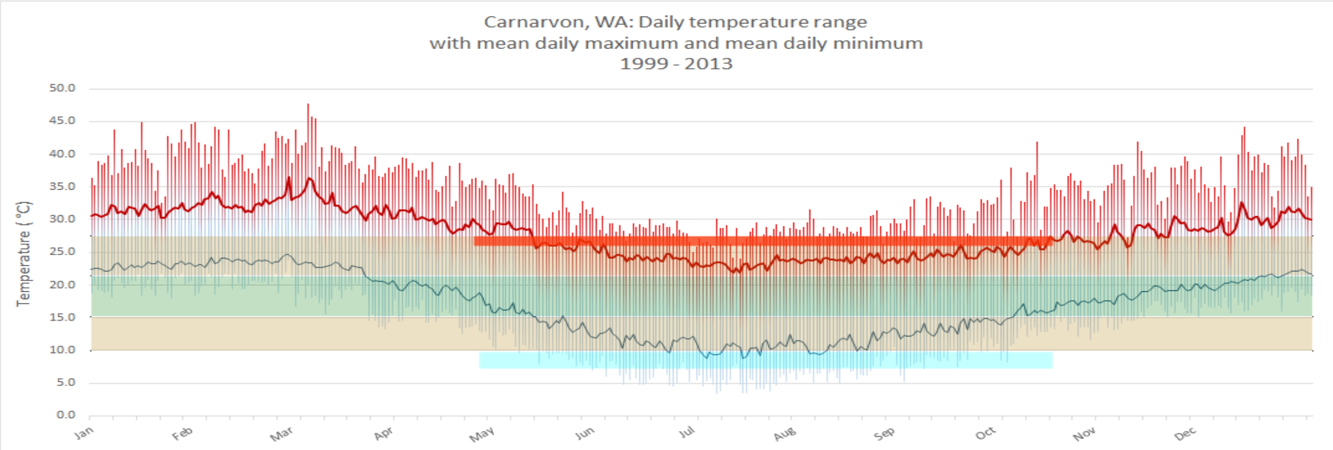

Figure 114: Mean daily temperatures and range for past 15 years at Carnarvon, WA with suitable (green) and tolerable (tan) growing conditions for ***bean adjusted with a floating cover****. Excess heat threshold indicated (red).*

5.8.5 Impact on light levels

Carnarvon represents a moderately high light region, though there is significant daily variation in light levels due to cloud cover and quite low light levels can occur through autumn and winter. However mean light levels are suitable for example crops. Any protective structure installed above a cropping area will impact on the amount and quality of light reaching the crop. The use of a screening material to reduce temperatures, for example, will necessarily also affect crop light levels. If light becomes limiting, the benefit of reduced temperatures is negated.

The approximate daily mean levels and range of photosynthetically active radiation (PAR) for Carnarvon are shown in Figure 117 with an overlay of suitable light levels for capsicum (green) and cucumber (pink stripe). The mean daily level has also been adjusted to reflect a 50% (blue) transmission level. With 50% transmission, such as under a 50% shade screen, the mean PAR levels would not be limiting and would be more suitable for these crops.

Although capsicum has a moderate light tolerance, capsicum fruit is susceptible to sun damage and could benefit from lower light intensity in this region. During winter under 50% shading, there is potential for light levels to fall below the nominal threshold for cucurbits, though this is not likely to impact greatly unless low light periods are prolonged.

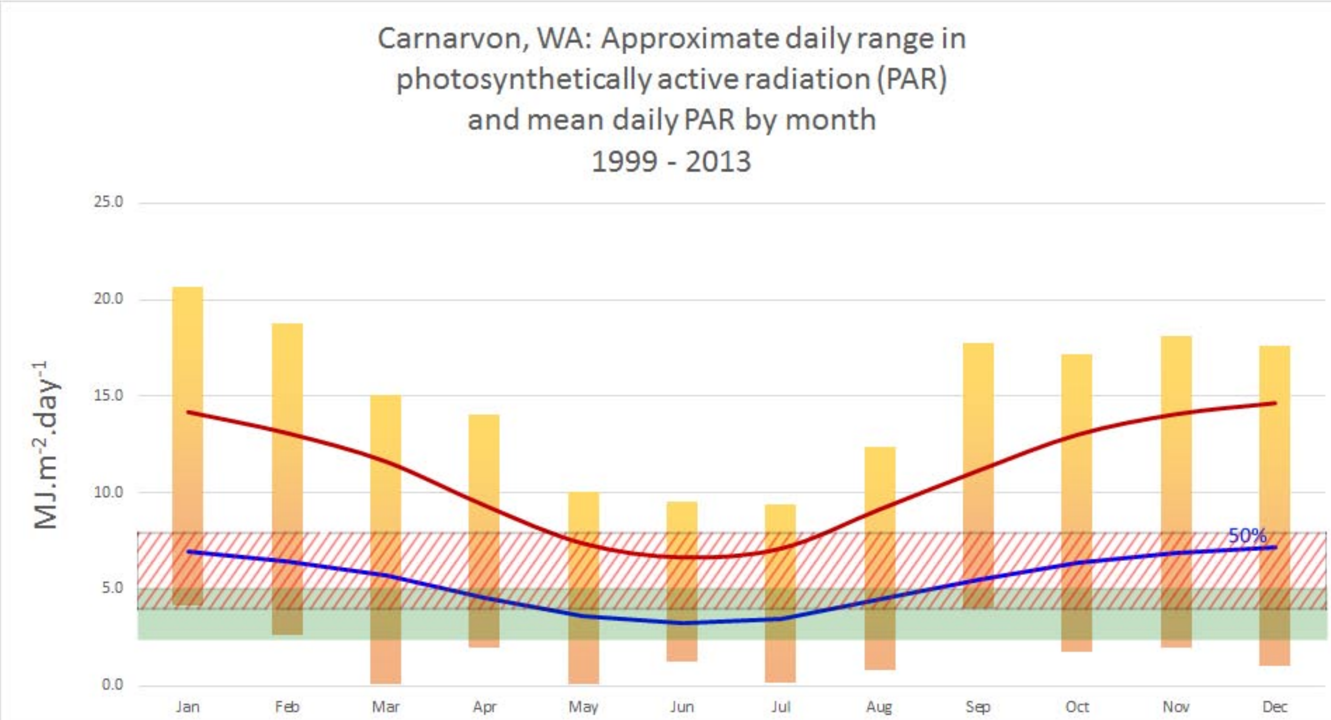

Figure 115: Approximate levels of photosynthetically active radiation (PAR) for the past 15 years at Carnarvon, WA with overlay of suitable light levels for capsicum (green) and cucumber (pink stripe) with an indication of mean daily PAR given 50% (blue) transmission rate.

5.8.6 Carnarvon LCPC assessment

The Carnarvon region experiences high summer temperatures with frequent extreme heat days from spring through to the end of autumn. Mean winter daytime maximum temperatures are close to approximate optimal conditions for many crops. Minimum winter temperatures are marginal for warm season crops. Light levels are generally high year round, though very low light conditions can occur. Winds tend to be moderate with occasional strong winds. Rainfall is generally autumn and winter dominant and quite variable. Heavy rain events can occur. Spring is dry.

The primary focus for protected cropping in this region should be on alleviating excess heat days. Shading of 50% could potentially decrease maximum temperatures by 6°C or more and contain maximum temperatures within general crop thresholds. Projected increases in temperature would have minimal additional impact on example vegetable crops. Reduced crop water use could be expected to be a benefit of shading, while screening could also reduce potential damage from heavy rain events in summer. Low light days may result in occasional deficient light levels under shading but would not be expected to pose a problem unless conditions are prolonged.

Potential for moderate wind conditions during warm to hot weather increases air movement and removal of heat from the cropping area, offsetting the impact of reduced ventilation in an enclosed shade structure. A shade canopy could also be a suitable option. The potential of very strong wind events needs to be considered with respect to structures and crop protection. Wind protection for crops should also be a consideration in its own right.

Exclusion of crop and contaminant pests could be achieved with floating covers, though they are unlikely to be suitable during summer due to reduced ventilation and consequently an increase in temperature. Floating crop covers may offer a good benefit from autumn to spring, however the potential for high daytime temperatures needs to be considered and these covers may need to be removed on forecast warm days.

Low profile greenhouses and plastic cloches could provide effective protection from low temperatures over winter but need to be well vented. For cloches, this may considerably increase labour requirements.

For winter production of beans, several protected cropping options, including a floating cover, well vented tunnel and cloche, could prevent a substantial reduction in yield resulting from low temperatures. The impact of excess heat on summer production of crops, for example capsicum, could be halved with shading.

6 Key risk areas for LCPC

Across crops and regions, the opportunity to improve yield is a common objective. In the preparation of this report, growers and industry allied trade spoken with identified frost risk and heat waves as being important production issues. Prices and energy were also raised but are out of context in the investigation of LCPC. The over-riding comment with regards to protected cropping was reserved for the challenge of 'cost'.

The general sentiment is that protected cropping elements would be considered provided the financial merit could be demonstrated. This is not surprising and supports the foundation of this review, that is, that the suitability of protected cropping for broad acre vegetable production needs to be low cost and hence the financial criteria of an investment that satisfies a short payback period. A five year simple payback is used as the financial limit to define LCPC. Interestingly, industry comments indicated a seven to eight year breakeven point would be acceptable.

Key risk areas that can be managed using protected cropping[104]:

High temperatures

"Heatwaves"	(three or more very hot days in a row)
"Hot days"	(temperatures cause plant stress/wilting/blossom drop)
"Early break"	(persistent warm conditions suggesting spring followed by cold snap)

Frost

"Late frosts"	(frost comes well after last expectation)

Crop water use

"Reduce irrigation"	(improve water use efficiency and/or irrigation efficiency)

Extreme weather

"Damage"	(storm damage to infrastructure)

Pest exclusion

"Pests"	(pest management is a consistent and ongoing need in industry in all contexts)

[104] Compiled from discussions with and comments from some growers and allied traders. Not from a constructed survey.

7 Economic feasibility of LCPC

Detailed financial analyses have not been undertaken as part of this review. Significant variations in operating costs and infrastructure investment exist across the vegetable industry reflecting regional differences, crop choices and planting schedules.

A detailed financial study of each case study site will be undertaken as part of demonstration site activities in the second phase of the project.

Conservative values for potential LCPC investments are used, and isolated production possibilities have been selected to establish a reasonable basis for follow-up. These assessments do not encompass a full cropping schedule or whole enterprise. Subsequently, the estimated benefits are conservative and except for the inclusion of an annual additional cost for basic maintenance of the protective element, production costs are assumed to remain the same. With an increased crop yield, costs of product sold (including harvest, packing and marketing) will increase and this has been approximated to 30% of the value of the additional yield. In some examples where an additional crop is assumed, the total cost has been approximated to be 50% of the value of the nominal yield. These approximations are anticipated to be conservative and to over-estimate the actual cost. All examples assume cropping occurs in the year of installation and each subsequent year.

The financial considerations presented in this section have been developed as *feasibility indicator points* to determine whether field testing and full economic analysis are warranted. These calculations cannot be relied upon as financial advice.

7.1 Typical costs of LCPC structures

There is a range of potential protected cropping options which could be used as LCPC. Costs vary widely. Retractable shade screening is increasingly being used in the greenhouse industry to optimise crop growing conditions. Installation of these thermal screens as an outdoor protected system is estimated to cost around $70/m^2 [105] with a life expectancy of over ten years. These systems are highly versatile and effective and offer a feasible investment over a longer term. They could be considered as a farm development strategy, but the high capital cost excludes this type of system from the concept of low cost protected cropping. It would be unlikely that a broad acre vegetable enterprise could achieve payback of such an investment within five years.

Netting systems, particularly using hail and bird net have been used in the orchard industry for many years. Typical costs range from $2 to 10/m^2 installed, with some up to $20/m^2. The variation in costs can reflect the height of the structure and the type of covering material. Specific site considerations will impact installation costs. The typical cost of shade netting installations in Victorian orchards was $4/m^2 ($40,000/hectare) in 2011[106], while the standard cost for crop canopies is currently expected to be $4.50 – 5/m^2 [107] for a minimum installation of three hectares.

[105] R. Clough (2014) Living Shade. Pers comm.

[106] S. Loicato (ed) (2011) Sun protection for fruit. A practical manual for preventing sunburn on fruit – 2011. Dept of Primary Industries, Victoria.

[107] Net Pro Canopies price quotation, 2014.

For the purposes of this review, a conservative upper cost estimate of $10/m^2 and a likely more typical estimate of $5/m^2 were used for shade canopies in preliminary feasibility as a LCPC option for vegetables.

Fogging systems are commonly used in greenhouses to improve growing conditions and present an additional strategy in cooling conditions under a screen system. Misting and sprinkler systems have been used as both heat and frost management strategies. A field based fogging system could provide better cooling and less water use than overhead sprinkler type systems, though would be most suitable installed in conjunction with a shading structure. Installation costs for fogging systems range from $10 to 30/m^2 and have a life expectancy of at least ten years. An installation cost of $15/m^2 is assumed for this review.

Floating crop covers cost from $0.19 to 0.31/m^2 [106] for light materials which may be single use, or at most have useful life expectancy of one to two years. Some more durable covers are available at a higher cost of around $0.5 to 0.75/m^2. With potential additional costs of labour and risk of tearing involved in applying and removing these materials, as well as the risk of poor light transmission resulting from dirt and condensation, floating covers are conservatively assumed to be single use and cost at the upper end $1/m^2 and more typically, $0.3/m^2. To establish an approximate feasibility indicator point, values of $3/m^2 and $10/m^2 over ten years are used.

Plastic cover systems (low profile greenhouses and cloches) have been costed at $20/m^2. The covers are assumed to have a life expectancy of five years. Although cloches are generally lower cost than tunnels, there is a significant potential for high labour cost in managing excess heat in cloches, and for simplicity, these have been grouped with simple tunnel. The more limited scale of these structures tends to direct a greater level of intensification than other LCPC options and may not readily fit with larger scale vegetable production, however these elements could be suitable as options for risk management and farm diversification strategies.

Windbreaks can vary significantly in cost depending on type. An artificial windbreak constructed from shadecloth and consisting of several 'walls' to provide wind protection over a hectare is assumed to cost $20,000/hectare ($2/m^2).

7.2 Economic feasibility scenarios

The potential benefit was estimated from the difference between the assumed current production and the expected yield, which is then adjusted by an estimated offset factor. This offset is based on the weather data and the extended suitable crop conditions that could be attained with the relevant protected cropping element. For example, if 30% of potential conditions still exceed the crop threshold, the offset would be 70%. Production costs are assumed to be the same and the additional cost of product sold is approximated at 30% of the nominal value of the increase in yield. The total costs where an additional crop is included are approximated at 50% of the nominal value of the crop. A discount (interest) rate of 3.5%pa was used.

The following scenarios have been evaluated:

- Heat management in Manjimup

- Shading in Werribee
- Excess heat in Murray Bridge
- Cool minimums in Murray Bridge
- Shade screens in Hay
- Minimum temperatures in Devonport
- Keep cool in Gatton
- Improving temperatures in Bowen
- Screening in Carnarvon
- Frost protection

7.2.1 Heat management in Manjimup

Lettuce is traditionally harvested from December to May, however, excess heat days occur frequently during summer. Yield loss resulting from high temperatures can be up to 50%. Shading could offset an estimated 85% of excess heat days and mitigate this loss by extending the suitable growing conditions.

A shade cloth canopy is assumed to cost (a) $100,000/ha or (b) $50,000/ha installed. An additional annual operating cost of $1000 assumed for maintenance and other production costs remains the same. Additional costs of product sold are approximated at 30% of the increased value of yield. Using 20t/ha as a benchmark yield for the region, an expected yield of lettuce of 30t/ha is assumed. With a static value of $1400/tonne, the net value gain per hectare is possibly $8,330 per year.

(a) Costing $10/m^2, the potential benefit to cost[108] is 0.44 over 5 years. The calculated simple payback period is over 11 years.

(b) Costing $5/m^2, the potential benefit to cost is 0.83 over 5 years. The calculated simple payback period is just outside the LCPC target at 5.6 years.

Although at an installation cost of $5/m^2, shading in this scenario would not meet the LCPC criteria of a maximum five year payback, over ten years the return on investment would be around 30%, making it a very reasonable longer term investment. To attain a five year breakeven point in this basic single crop scenario, an installation cost of no more than $4.05/m^2 would be required.

The inclusion of a fogging system with shade screening at an additional cost of $15/m^2 would fully offset the excess heat days though it would take more than 18 years to recover the investment cost.

Extending production and gaining an additional cropping cycle producing the base yield with the same temperature offset over the extended period:

[108] The benefit to cost represents the potential return per unit investment. A benefit to cost of '2' indicates that for every dollar invested, a $2 return is made. This is calculated over 5 years on the basis of the LCPC target, though the expected life of these structures is at least 10 years. A benefit : cost ratio of greater than 1 is a positive investment over the given period.

(a) Costing $10/m^2$, the potential benefit to cost is 1.06 over 5 years. The calculated simple payback period is over 4.5 years and within the LCPC target.

(b) Costing $5/m^2$, the potential benefit to cost is 2.01 over 5 years. The calculated simple payback period is just 2.3 years.

For broccoli in this scenario, at a static value of $1500/t a potential improvement of 4t/ha might be attained by fully offsetting the impact of high temperatures. A five year simple payback would require the shading system to be no more $1.76/m^2$.

7.2.2 Shading in Werribee

The use of shading in a region such as Werribee could be expected to offset up to 70% of the excess heat days for a crop such as lettuce and the cooling benefit could be attained for two to three crop cycles. A shade cloth canopy is assumed to cost (a) $100,000/ha or (b) $50,000/ha installed. An additional annual operating cost of $1000 is assumed for maintenance and other production costs remain the same. Additional costs of product sold are approximated at 30% of the increased value of yield. Using 15t/ha as a base yield for a single crop cycle, and an expected yield of 20t/ha is assumed, with a static value of $1400/tonne, the net value gain per hectare is possibly $3,430 per crop.

(a) Costing $10/m^2$, the potential benefit to cost is 5.54 over 5 years if the temperature offset benefit is attained for 3 cropping cycles per year. The calculated simple payback period is 8.9 years.

(b) Costing $5/m^2$, the potential benefit to cost is 1.02 over 5 years if the temperature offset benefit is attained for 3 cropping cycles per year. The calculated simple payback period is within the LCPC target at 4.5 years.

Installation cost	1 crop cycle benefited	2 crop cycles benefited	3 crop cycles benefited
(a) $10/m^2$			
Benefit:Cost (5yr) / Payback	0.18 / 26.8yr	0.36 / 13.4yr	0.54 / 8.9yr
(b) $5/m^2$			
Benefit:Cost (5yr) / Payback	0.34 / 13.5yr	0.68 / 6.8yr	1.02 / 4.5yr

Under milder conditions (more closely reflecting mean maximums) in which the shading could fully offset high temperatures, the same scenario with a benefit over three cropping cycles would have the following outcomes:

(a) Costing $10/m^2$, the potential benefit to cost is 0.77 over 5 years. The calculated simple payback period is 6.25 years. For a 10 year investment horizon, a shading system at this high installation cost would be a positive investment generating a 25% return on investment.

(b) Costing $5/m^2$, the potential benefit to cost is 1.46 over 5 years. The calculated simple payback period is well within the LCPC target at 3.15 years.

7.2.3 Excess heat in Murray Bridge

Production of lettuce in a region such as Murray Bridge is traditionally harvested from November to May, however, excess heat days occur frequently during this period. Using 30t/ha as a benchmark yield for the region over six months, the potential loss in yield could be up 10t/ha. Shading could offset an estimated 70% of excess heat days in this region by extending the suitable growing conditions, delivering an added value of $6,860.

(a) Costing $10/m^2, the potential benefit to cost is 0.36 over 5 years. The calculated simple payback period is 13.4 years.

(b) Costing $5/m^2, the potential benefit to cost is 0.68 over 5 years. The calculated simple payback period is just outside the LCPC target at 6.76 years. For a 10 year investment horizon, a shading system at this installation cost would be a positive investment generating just under 8% return on investment.

In a situation of an additional cropping cycle with 80% of the excess heat days offset, a shading system at the conservative high cost would potentially provide a very good five-year investment.

(a) Costing $10/m^2, the potential benefit to cost is 1.24 over 5 years. The calculated simple payback period is just 3.9 years.

(b) Costing $5/m^2, the potential benefit to cost is 2.35 over 5 years. The calculated simple payback period is well within the LCPC target at under 2 years.

In this scenario, a five-year simple payback could be achieved up to a shading system installation cost of $12.44/m^2. The addition of fogging with $5/m^2 shading in an area such as this could fully offset the excess heat days and break even at five years if the fogging could be installed for less than $11.40/m^2.

For capsicum production in the same region, using a base yield of 25t/ha as a benchmark, the difference between this level of production and an expected yield of 35t/ha represents the possible yield impact of high temperatures and high light intensity (sunburn). Shade screening over summer could potentially offset 60% of excess heat days and extend suitable conditions to encompass mean maximum temperatures. Assuming a value of $2600/tonne and an installation cost of $5/m^2, this protected cropping option would have a payback period of 4.25 years and a benefit to cost of 1.08 over five years.

(b) Costing $5/m^2, the potential benefit to cost is 1.08 over 5 years. The calculated simple payback period is within the LCPC target at 4.25 years.

In a milder year, in which maximum temperatures mirror the 15 year mean, 50% shading would offset 98% of excess heat days, reducing losses and delivering a simple payback at 2.6 years. The return on investment in this situation could be 70%.

(b) Costing $5/m^2, the potential benefit to cost under mild conditions is 1.77 over 5 years. The calculated simple payback period is well within the LCPC target at 2.6 years.

7.2.4 Cool minimums in Murray Bridge

Low profile greenhouses and plastic cloches could be used to mitigate yield loss from minimum temperatures during cool season production. For a lettuce crop over winter, unheated plastic tunnel houses costing $200,000/ha could generate a net benefit of $18,200 and have a payback period of just over ten years, but the five-year benefit to cost would be only 0.49. Furthermore, these structures would need to be removed for the remainder of the year due to excess heat making this unviable as a low cost protected cropping option.

A floating crop cover could be used in a region such as Murray Bridge to reduce yield decline due to cool conditions and to obtain an additional cropping cycle. The floating cover is expected to offset 50% of the yield decline for an existing cropping cycle and could enable an extended cropping period in which 40% of the suboptimal conditions for the additional crop might be offset[109]. This includes an estimated allowance for lower light and potential excess heat on some days. A pest exclusion benefit is also likely but this is not included in this scenario. A base yield of 25t/ha and an expected yield of 35t/ha are assumed.

A floating crop cover is assumed to cost (a) $10,000/ha or (b) $3,000/ha annually[110]. An additional annual operating cost of $1000 is assumed for installation, maintenance and removal while other production costs remain the same. With a static value of $1400/tonne, the net value gain per hectare is potentially $19,600 per year. With a one-year useful life, the covers need to have a payback period of less than a year to be viable.

(a) Costing $1/m^2, the potential benefit to cost[111] is 1.78 over 5 years. The calculated simple payback period is 0.5 years.

(b) Costing $0.30/m^2, the potential benefit to cost is 4.9 over 5 years. The calculated simple payback period is just 2.5 months.

7.2.5 Shade screens in Hay

In a region with very hot sunny summer like Hay, a crop such as cucumber — although a warm season crop — can suffer yield declines of 25% due to high temperatures. For a cucumber crop grown in this type of area, using an average yield of 70t/ha as a base, the likely loss due to excess heat could equate to 15t/ha. Shade screening could offset 70% of excess heat days and extend suitable conditions to encompass mean maximum temperatures.

[109] Note: the additional cost of product sold for the existing crop is approximated at 30% of added value and the additional costs of an extra crop have been approximated to 50% of return.
[110] Assumes covers are purchased each year and the price of the floating covers is static.
[111] The benefit to cost represents the potential return per unit investment. A benefit to cost of '2' indicates that for every dollar invested, a $2 return is made. This is calculated over 5 years on the basis of the LCPC target, though the expected life of these structures is at least 10 years. A benefit : cost ratio of greater than 1 is a positive investment over the given period.

A shade cloth canopy is assumed to cost (a) $100,000/ha or (b) $50,000/ha installed. An additional annual operating cost of $1000 is assumed for maintenance, and other production costs remain the same. Additional costs of product sold are approximated at 30% of the increased value of yield. The net value gain per hectare is possibly $18,375 per year.

(a) Costing $10/m^2, the investment is just within the LCPC target and would break even at 5 years.

(b) Costing $5/m^2, the potential benefit to cost is 1.83 over 5 years. The calculated simple payback period is well within the LCPC target at 2.5 years.

For lettuce, using 23t/ha as a base yield for the region over six months, the potential loss in yield could be up to 8 t/ha. At a nominal value of $1400/t, this represents an approximate value of $6272. Shading could offset an estimated 80% of this loss in this region by extending the suitable growing conditions.

(a) Costing $10/m^2, the investment would be unviable with a benefit to cost of 0.33 over 5 years.

(b) Costing $5/m^2, the potential benefit to cost still falls short at 0.62 at 5 years, though a there would be positive return in less than 9 years.

Similarly to Murray Bridge, the benefit of shading would be insufficient to warrant the investment at this cost. A shading system costing less than $2.95/m^2 could break even at five years in this scenario.

With an additional cropping cycle during the year with 80% of the excess heat days offset, for a shading system costing $5/m^2, a payback period of 2.4 years and a benefit to cost of 2.29 could be possible.

With shading at $5/m^2, the addition of fogging at a cost of (a) $15/m^2 and (b) $10/m^2) in an area such as this could fully offset the excess heat and could be feasible, though may fall just short of the LCPC criteria.

(a) Total cost $20/m^2, the potential benefit to cost is 0.77 over 5 years. The calculated simple payback period is outside the LCPC target at 6.6 years. A shading and fogging system at this installation cost would be a positive investment over a 10 years horizon generating a benefit to cost 1.28 this period.

(b) Total cost $15/m^2, with a lower cost fogging scenario, the potential benefit to cost could be 1.02 at 5 years.

7.2.6 Minimum temperatures in Devonport

In a cool region such as Devonport, there is minimal risk of excess heat, however suboptimal minimum temperatures can decrease yields. A low profile greenhouse or a plastic cloche could be used to offset cold temperatures during winter. An unheated a plastic cloche or tunnel is assumed to cost $20/m^2. The addition of the equivalent of another lettuce cropping cycle, assuming a yield of 20t/ha and a nominal value of $1400/t, would not have a payback until almost 10 years and replacement of the plastic covering in year five would push out the payback period more than 12.5 years. The benefit to cost over five years would be unviable at 0.42.

A floating crop cover used in the same situation to produce a crop of lettuce could provide an estimated 70% temperature which would equate to return on investment of around 25% for a high cost floating cover ($1/m^2$) and for a floating cover costing $0.3/m^2$, the benefit to cost over five years would be 3.4. For beans with a value of $1760/tonne, using a crop cover to extend the cropping period by a month is unlikely to be viable on its own, but if a cover costing $0.3/m^2$ can be used to produce an extra crop, the benefit to cost could increase to 1.5. Incorporating benefits from pest and contaminant exclusion could elevate the value of this type of LCPC.

7.2.7 Keep cool in Gatton

In a region such as Gatton, high summer temperatures can adversely affect yields of the many crops grown. Shading could reasonably offset an estimated 80% of this loss. In this scenario for lettuce, using a production benchmark of 25t/ha:

(a) Costing $10/m^2$, the investment would effectively break even at 5 years with a return on investment of 2%.

(b) Costing $5/m^2$, the potential benefit to cost is 1.95 over 5 years. The calculated simple payback period is less than 3 years.

For beans with a value of $1760/tonne, using a shading system to offset high temperature impacts would be beneficial over ten years, but is not likely to be a viable LCPC option on its own. Offsetting cool conditions in spring with a floating cover for a single crop of beans would be uneconomical, however enabling an additional crop by extending the suitable conditions and offsetting negative impacts of low temperatures could create a positive benefit to cost ratio of 1.29 for a floating cover costing $0.3/m^2$.

7.2.8 Improving temperatures in Bowen

For capsicum production using a base yield of 20t/ha as a benchmark, the difference between this level of production and an expected yield of 30t/ha represents the possible yield impact of high temperatures and high light intensity (sunburn). Shade screening over summer could potentially fully offset excess heat days and extend suitable conditions.

A shade cloth canopy is assumed to cost (a) $100,000/ha or (b) $50,000/ha installed. An additional annual operating cost of $1000 is assumed for maintenance, and other production costs remain the same. Additional costs of product sold are approximated at 30% of the increased value of yield. Assuming a value of $2600/tonne, the net value gain per hectare is possibly $18,200 per year.

(a) Total cost $10/m^2$, the potential benefit to cost is 0.95 over 5 years. The calculated simple payback period is just outside the LCPC target. Over 10 years, this scenario could achieve a return on investment of over 50%.

(b) Total cost $5/m^2$, the potential benefit to cost is 1.81 over 5 years and would fit well within the LCPC criteria.

Cold conditions can cause up to a 50% reduction in bean yields. A floating cover in this region could be used to offset the impact of minimum temperatures during transition periods. At a cost of $0.3/m^2$, the financial benefit would be marginal and a small variation in yield could make floating covers during this period a viable investment. Extending the cover over a winter crop could potentially offset 70% of the suboptimal temperatures, and combined with an improved yield over spring, the benefit to cost would be 1.69.

7.2.9 Screening in Carnarvon

Shade screening in a region like Carnarvon could offset 60% of excess heat days and extend suitable conditions, improving yields of capsicum. Assuming a value of $2600/tonne, base yield of 17t/hectare and an expected yield of 30t/ha, a shading canopy is assumed to cost (a) $100,000/ha or (b) $50,000/ha installed. An additional annual operating cost of $1000 is assumed for maintenance, and other production costs remain the same. Additional costs of product sold are approximated at 30% of the increased value of yield. The net present value of the shading investment would be over $14,000pa.

(a) Costing $10/m^2, the net present value of the shading, from -$27000 at 5 years would increase to almost $23,000 after 10 years and have a return on investment of 20%. This would be a good investment but would not meet the criteria for LCPC.

(b) Costing $5/m^2, the net present value of the shading would be over $22,000 and the potential benefit to cost ration is 1.41 over 5 years.

Cucumber production in this region could also benefit from shading. High temperatures can cause a 25% decline in yield. Approximately half of the excess heat days in Carnarvon could be offset with 50% shade. Assuming a standard yield of 70t/ha and a value of $2500/t, the investment in shading could potentially be viable at a cost up to $7.90/m^2.

(a) Costing $10/m^2, the potential benefit to cost is 0.80 and the payback period is around 6.6 years. The benefit to cost over 10 years is 1.3 making this a viable investment, though it would not meet the criteria for LCPC.

(b) Costing $5/m^2, the net present value of the shading would be almost $29,000 at 5 years, with a potential benefit to cost 1.52. The payback period could be less than 4 years making this a viable LCPC option.

7.2.10 Frost protection

Frost damage can be severe for some crops. Late frosts, in particular, pose a risk to spring crops and establishing summer crops. In some situations, a protected cropping element may be considered solely to prevent a loss due to frost. The relative value of avoiding crop damage or complete crop loss can also be added to other potential benefits of protective structures. For example, a shade screen installed to mitigate excess heat will also have a small impact on minimum temperatures and could prevent or reduce frost damage. In such a situation, the potential value of frost protection can be added to the value of heat mitigation to evaluate the overall benefit of an investment in screening for an enterprise.

The following tables provide a means of viewing the potential value of LCPC in terms of frost impact. Given a crop situation, the breakeven at five years is the nominal cost per square metre that could be invested in expectation of a five-year simple payback period. The dollar values in the ‘Effective yield loss’ columns are an estimate of how much more could be spent to avoid frost impact and still break even at five years.

Example: For a nominal capsicum crop yielding 30t/ha, up to \$29.45/m^2 could be invested in protected cropping and have a payback period of five years. If the LCPC was to avoid 50% loss of a crop, once in the five-year period, an extra \$2.65/m^2 could be added to the original investment (table 9). If the frost risk is 50% loss in three years in every five (Table 10), an additional \$7.60/m^2 on top of the original \$29.45/m^2 could potentially be feasible.

The higher the frost risk (potential severity and frequency), the greater the potential cost and therefore a larger investment may be feasible.

Table 9: Relative investment (\$/m^2) in LCPC to achieve break even at 5 years with impact of frost, 1 in 5 years.

Frost event 1 in 5 years	**Nominal value & yield (\$/t and t/ha)**	**Effective yield loss**			
		Break even At 5 years	25%	50%	100 %
Cucumber	2500/70	\$66.70	+\$2.90	+\$5.90	\$11.80
Bean	1760/6	\$3.54	+\$0.19	+\$0.36	+\$0.74
Capsicum	2600/30	\$29.45	+\$1.35	+\$2.65	+\$5.25
Lettuce	1400/30	\$15.60	+\$0.60	+\$1.30	+\$2.80

Table 10: Relative investment (\$/m²) in LCPC to achieve break even at 5 years with impact of frost, 3 in 5 years.

Frost event 3 in 5 years	Nominal value & yield (\$/t and t/ha)	Effective yield loss			
		Break even At 5 years	25%	50%	100 %
Cucumber	2500/70	\$66.70	+\$8.40	+\$17.10	+\$34.10
Bean	1760/6	\$3.54	+\$0.55	+\$1.06	+\$2.09
Capsicum	2600/30	\$29.45	+\$3.75	+\$7.60	+\$15.25
Lettuce	1400/30	\$15.60	+\$2.05	+\$4.10	+\$8.20

7.2.11 Wind protection

Specific impacts on yield attributed to wind damage is scarce, though anecdotally it is known to have an impact. A consideration to be made in determining the value of wind protection is that, although wind speeds above 14 to 15 $km.h^{-1}$ have an impact on plants, and strong winds (above 40 $km.h^{-1}$) can physically damage vegetable crops, low wind speeds also affect temperature, evapotranspiration and heat loss from the plant which can all impact growth and development.

The use of wind protection in a region such as Carnarvon could be expected to offset the impact of wind on a range of crops. This region commonly has moderate to strong winds. Screening and floating covers can reduce the impact of wind on sensitive crops so this benefit can be added to an investment in screening.

A windbreak in isolation can improve yields. Assuming the same situation used in producing the feasibility indicator for reducing excess heat, a field capsicum crop has an average yield of 17t/ha and a typical expected yield of 30t/ha; a proportion of this difference could be attributed to wind. A constructed windbreak is estimated to cost \$20,000/ha installed. If a windbreak contributed to only 25% of the difference, the payback period would be less than five years, with a 28% return on investment over five years.

7.2.12 Pest and contaminant exclusion

Pest exclusion, and subsequently the prevention of yield decline, with row covers and netting is mostly a direct and can be a fully effective response and is dependent on the target pest and the pore size of the covering and the period of time that the crop can be covered. Various results have demonstrated pest exclusion of floating covers delivering benefits from 50 to 100% reduction in losses from pests[112]. Damage to screens and the presence of overwintering pests within the covered area will diminish the benefit. Poor farm management (biosecurity) practices may also lessen the benefit. A screen house that covers a crop for the duration of production will exclude all pests of a size related to the porosity of the material. The effective value of an investment is proportional to the yield and value of the crop, less any environmental impact of excess temperature, humidity, light and/or reduced transpiration. Similarly for floating covers, the benefit can be considered to be 100% until the cover is removed.

Production of lettuce and baby leaf crops under a floating cover can benefit from reduced pest damage (as well as less insect and foreign matter contamination). Using benchmark yield of 20t/ha and a crop value of $1400/t, a floating crop cover costing $10,000/ha per year could deliver a benefit to cost of 2.99 in offsetting a 25% loss in value due to insect damage. Offsetting 50% loss would represent a benefit to cost of 3.76 over five years.

The potential value of reduced insect damage due to screening is additional to any value achieved through an improved growing environment.

[112] Floating row covers reduced insect damage in tatsoi babyleaf by more than 55% (R. Munton (2009) The production of baby-leaf lettuce under floating crop covers. Project VG09188 Final report. Horticulture Australia)
Carrot weevil damage in carrot by 70% (D. Rekika, K. Stewart, G. Boivin and S. Jenni (2008) Floating row covers improve germination and reduce carrot weevil infestations in carrot. HortScience 43(5):1619-1622)
Completely excluded several pests from melons (M. Orozco-Santos, O. Perez-Zamora and O. Lopez-Arriaga (1995) Floating row cover and transparent mulch to reduce insect populations, virus diseases and increase yield in cantaloupe. Florida Entomologist, September: 493-501)
Yields of zucchini increased 20 fold by excluding whiteflies and virus (E. Natwick and A. Durazo (1985) Polyester covers protect vegetables from whiteflies and virus disease. California Agriculture, July-August; 21-22)

8 Current examples of low cost protected cropping

Protected cropping has been expanding rapidly in Australia over the past 30 years. The investment cost has, however, limited the use of modified and controlled growing environments to relatively high value vegetable crops including tomato, cucumber and capsicum, as well as floriculture. In recent years production of fresh herbs and leafy greens has moved into the protected cropping sphere. The development of this industry in Australia has seen a distinct divergence between field vegetable production and greenhouse vegetable production.

Financial considerations are the primary obstacle to broader investment in protected cropping options in Australia, though awareness and attitude are likely to also be significant factors. However, with a combination of an increasing need for market risk management and addressing the direct impacts of current and near future climate, the benefit to cost balance in using protective elements in broad acre vegetable production is being reviewed.

8.1 Low cost protected cropping in Australia

Low cost protected cropping represents a potential opportunity for field vegetable production to benefit from some of the environmental improvement and subsequent productivity gains enjoyed in the greenhouse industry, without the full level of investment. Despite the frequent occurrence of adverse growing conditions in most major vegetable production regions, the adoption of protected cropping elements has been largely absent in Australia.

A major component of low cost protected cropping in Australia has been the low profile, low technology greenhouse. Historically, however, this protected cropping option has generally been taken as the entry point to protected cropping, though a significant proportion of the Australian industry has remained using these ‘low cost’ systems rather than invest in improved protected cropping systems.

Field hydroponic production, primarily of lettuce and leafy crops, has a mixed response to screening with many larger growers having used light shade or hail canopies for more than a decade. It represents a third significant application of relatively low cost protection in Australia. Hail and bird netting is commonly used in orchards and there has been an increased interest in, and installation of, shading in orchards in recent years. In field vegetables, there has been the rare investment in hail protection in southern areas while vegetable growers in locations such as Carnarvon, WA, have become the effective centre for vegetable production under shade in Australia and offer a good base for demonstration and research.

Windbreaks are another type of protection which are used in some regions and cropping situations, though not universally.

Most recently, interest in floating crop covers has expanded but remains in very limited use in Australia compared with overseas.

These are the low cost protected cropping installations used for vegetable production that we know about:

1. ***Shade Canopy structure at Woodglen, Vic. - Riviera Farms***. Located near Bairnsdale, Vic. the structure is about 1.6 Ha under cover. It is used for the production of baby leaf spinach rocket and lettuce. It was installed as part of a government funded project. The structure was supplied by Net Pro canopies, Stanthorpe[113]. The project team will undertake monitoring at this site.

2. ***Shade Canopy structure at Bairnsdale, Vic. – Trevor Curtin***. The structure is about 1.6 Ha under cover. It is used for the production of baby leaf spinach rocket and lettuce. It was installed as part of a government funded project. The structure was supplied by Net Pro canopies, Stanthorpe.

3. ***Haygrove 4-Series poly tunnel at Woodglen, Vic. - Riviera Farms.*** Supplied by Haygrove Australia[114]. The structure is built alongside the shade canopy at Riviera farms, Wooglen and is used for the production of baby leaf spinach rocket and lettuce. The project team will undertake monitoring at this site.

4. ***Shade Canopy structure at Stanthorpe, Qld – Colin Britton, Britton Produce.*** The structure is about 4 Ha under cover. It is used for the production of baby leaf spinach rocket and lettuce. The structure was supplied by Net Pro canopies, Stanthorpe. The project team will undertake monitoring at this site.

5. ***Floating row covers, Stanthorpe***. Colin Britton, Britton Produce also used floating row covers for the protection of baby leaf spinach, rocket and lettuce as well as head lettuce. For more information see http://www.netprocanopies.com/documents-pdf/productsheets/Groshield30.pdf

6. ***Shade Canopy structure at Carnarvon, WA***. Details sketchy but there is a significant shade structure which has been built at Carnarvon, WA. The project team are hoping to undertake monitoring at this site, if the growers is agreeable.

7. ***Shade Canopy structure at Griffith***. Griffith vegetable growers, Tony and Frank Catazariti and John and Anthony Vitucci, using a shadecloth structure that covers one hectare to protect what are essentially field-grown vegetable crops[115].

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[113] Net Pro Canopies http://www.netprocanopies.com/ accessed 27/7/2014.
[114] Haygrove Australia http://www.haygrove.com.au/polytunnels/farm-polytunnels/4-series/ accessed 27/7/2014
[115] http://www.dpi.nsw.gov.au/research/updates/previous-stories-by-topic/water-management/sun-shield-vegetables accessed 27/7/2014

8. ***Shade for hydroponic lettuce***. This is widely practiced around Sydney and other production areas close to urban centres. The project team will monitor a lettuce grower in Mareeba who is using this system successfully.

9. ***Nurseries***: The nursery industry makes significant use of partial protective systems such as shadehouses and crop canopies, commonly alongside greenhouses. Management of light levels and moderating temperature are key production requirements for the majority of nursery crops during part or all of the production cycle. The nursery industry is the most significant user of shading in Australian horticulture.

8.2 Low cost protected cropping internationally

Vegetable production in the Mediterranean region has become a phenomenon in low cost protected cropping in the last 30 to 40 years. In the same way the Australian industry has used low profile, low technology greenhouses as an entry to protected horticulture and then had limited progress, growers in southern Europe have invested cheaply and remained fixed in a low cost, low efficiency protected production cycle.

In colder regions, the adoption of floating covers has been relatively fast. This protected cropping option facilitates multiple benefits including earlier crop establishment, frost protection, faster and earlier crop maturity and pest exclusion.

In the Middle East, extremes of temperature and radiation have supported the expansion of shading for the production of vegetables, delivering significant benefits. Shadehouses have tended to be used as a direct substitute to greenhouses in response to the climate.

The most significant growth in low cost protected cropping in recent years has been in developing countries in the tropics. Heavy rainfall severely impacts vegetable production and the limited financial resources necessitate low cost options. Rainshelters and screenhouses are strong contenders in the development of productive and viable vegetable production in these regions.

9 Conclusion

In all regions, current and projected near future summer daytime temperatures exceed upper thresholds for the example vegetable crops. This reflects an existing yield loss of all crops grown from autumn through to spring. Reducing light transmission to the crop will produce a cooling effect. A 50% shade is expected to deliver at least 6°C reduction in critical temperatures. Shade cloth, insect netting and plastic cladding can all be used to reduce light transmission.

The installation of a protective structure around a cropping area will impact air flow. An enclosed structure will cause the greatest reduction in air flow and heat exchange. A windbreak will have a moderate and variable impact on temperature, and a horizontal canopy will have the least restriction on air flow through the crop. A floating crop cover, low profile greenhouse and a cloche will all reduce airflow and increase temperatures.

Shade canopies are a significant low cost protected cropping (LCPC) option for broad acre vegetable production in many regions of Australia. In all except one region (Devonport), excess heat days for six to eight months of the year are expected to have an adverse impact on growth and yield of vegetable crops. The difference between average yield and expected yields of many crops can represent 30 to 50% of production. Expected yield impacts from high temperatures for several of the target crops have been reported to be between 20% and 50%[116]. These values do not even consider the *potential* yield of a crop which can be even greater. For example, the difference between the average yield of capsicum in Australia and the potential yield could be as high as 65%.

Feasibility indicator points suggest that shading could have a benefit-to-cost ratio of up to 3:1. In most location and crop situations, a shade canopy would be more suitable than an enclosed structure which would omit the potential additional benefits of wind protection and pest exclusion. Wind breaks would be a suitable complementary option with a shade canopy. Under high light conditions, a floating cover could be used under a shade canopy to exclude pests and provide earlier crop establishment. A shadehouse would be a suitable option in high light, high temperature locations with moderate to strong winds to offset reduced air movement through the screen.

The greater suitability of a shade canopy over an enclosed structure due to the impact of reduced air exchange also renders nethouses generally not suitable. There is potential to improve shade and net houses with engineered ventilation, however this is not considered within the LCPC context of this review.

Floating covers are likely to be a suitable LCPC option for crop establishment and transition seasons in most locations and for most crops. Build-up of heat under the covers will limit the period that they can be used in most regions before they cause a negative impact. Light could be limiting, particularly in winter, but floating covers could be appropriate for the dual benefits of increasing minimum temperatures and excluding pests for lower light tolerant crops in transition seasons. Floating covers can be unsuitable for windy conditions, although a windbreak could be used to manage this limitation.

[116] G. Rogers (2013) Understanding and managing impacts of climate change and variability on vegetable industry productivity and profits, Final report VG12041

Feasibility indicator points suggest that a floating crop cover could have a benefit-to-cost ratio of 2:1 for growing conditions and 3:1 for pest exclusion.

Windbreaks could provide local benefits to all regions where they are not already being used, and a complementary and protective aspect for other LCPC options. Feasibility indicator points suggest that wind protection could have a benefit-to-cost ratio of 12:1 in sites with prevailing moderate to strong wind.

In hot, dry locations, fogging to provide an evaporative cooling benefit can be added to a shading option to ensure efficacy in the cropping environment.

Plastic clad structures (rainshelters, tunnels and cloches) are unlikely to be suitable investment options. Rainshelters are highly suitable in wet tropics but present limited benefit for the example vegetable crops and the drier climate of Australia. (They may have merit in far northern parts of Australia, but these locations were not part of this review.) Low profile greenhouses and cloches are unlikely to be suitable LCPC options. The benefits attained are diminished by adverse impacts, particularly from excess heat. Investment at a higher level into appropriate medium to high technology protected cropping systems would deliver greater dividends.

An overview of the suitability of the various protected cropping elements as low cost protected cropping options for Australian vegetable growers is presented in Table 11. The technical suitability of these options in addressing the five target factors is shown in Table 12.

Table 11: Suitability of the various protected cropping elements as low cost protected cropping options for Australian vegetable growers

	Shade canopy	Shadehouse	Fogging	Rainshelter	Low profile greenhouse and/or cloche	Floating crop cover	Windbreak
Manjimup	✓	☑				✓	✓
Murray Bridge	✓	☑	✓				
Werribee	✓	☑	✓			✓	
Hay	✓	☑	✓				
Devonport						✓	✓
Gatton	✓	☑				✓	
Bowen	✓	✓				✓	
Carnarvon	✓	✓				✓	✓

Boxed tick indicates that option may be suitable in some local condition/crop situations

Table 12: Technical suitability of LCPC options in addressing the 5 target factors.

	Shade canopy	Shadehouse	Fogging	Rainshelter	Low profile greenhouse and/or cloche	Floating crop cover	Windbreak
High temperatures	✓	☑	✓	✓			☑
Frost and low temperatures	✓	☑	✓	✓	✓	✓	☑
Extreme weather	✓	✓		✓	✓	✓	✓
Impact of light	☑	☑		☑	☑	☑	
Pest exclusion		✓			✓	✓	✓

Boxed tick indicates that option may have contradictory effects depending on situation and ambient conditions

Recommendations

The review makes the following recommendations:

1. ***Shade canopies*** should be field tested and performance monitored with a full economic evaluation conducted at locations such as Carnarvon (WA), Murray Bridge/Virginia (SA), Mildura/Dareton – Hay (Vic/NSW), Werribee/Gippsland (Vic) and Bowen (Qld).

   A shade level of 50% (30% and 70% as extra options) should be considered. Retractable versus fixed shade. Addition of fogging could also be considered under shade canopy.

   Target benefits: Increasing reliability of supply by minimising the effects of temperature extremes, improved water use, longer production season and improved quality.

2. ***Floating crop covers*** be field tested and performance monitored and have a full economic evaluation conducted for locations such as Manjimup (WA), Murray Bridge/Virginia (SA), Mildura/Dareton – Hay (Vic/NSW), Werribee/Gippsland (Vic) and Gatton (Qld).

   Target benefits: Increasing reliability of supply by minimising the effects of temperature extremes, earlier and longer production season, insect control and improved quality.

3. ***Windbreaks*** be field tested and performance monitored and have a full economic evaluation conducted for locations such as Manjimup (WA), Murray Bridge/Virginia (SA), Mildura/Dareton – Hay (Vic/NSW), Werribee/Gippsland (Vic) and Gatton (Qld).

   Target benefits: Reducing wind damage, reducing water stress during hot, dry windy conditions, pest and disease management.

4. Develop ***economic feasibility indicators*** for a number of the protected cropping options. This could include longer payback period options, and would help growers to make informed decision about whether or not to invest in LCPC for a given location and crop.

An investigation of low cost protected cropping options for vegetable growers

Contents

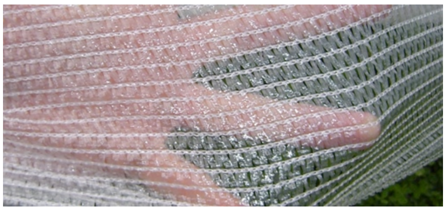
1. Netting materials and trial summary

1.1. Netting materials

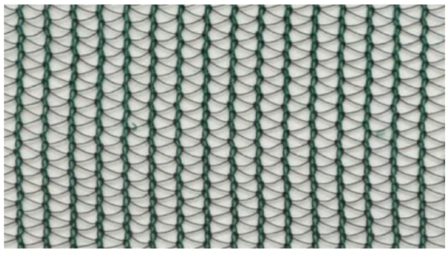
The trials reported in this document have all tested one or more netting materials and / or spunbonded polypropylene (fleece) on temperatures, RH, yield and quality of different crops.

Materials included;

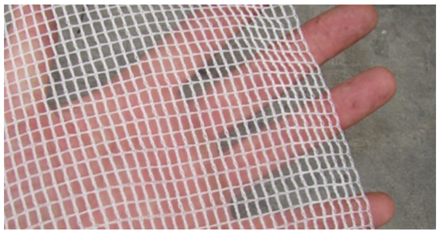
Insulnet Semi-transparent, knitted material designed to exclude larger pests and provide some protection from rain, hail and light frosts. Supplied by Redpath Australia. Mesh size approx. 4 x 2mm, 105g/m^2, low cost option.



Shade cloth Long lasting, knitted HDPE filament shade material, rated for a minimum 10 year life. Used as a 'crop top' cover on a frame. Available in colours including black, green, red and white and beige and shade density from 30 to 80%. Many suppliers, including NetPro.

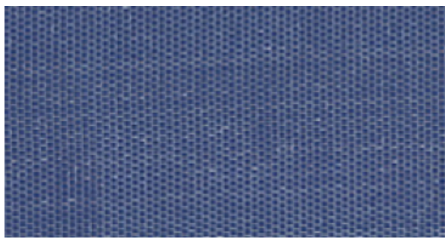


Vent Net White, open strand knitted fabric used for screening the sides of greenhouses and other structures. Prevents entry of birds and large insects, reduces impact of wind or strong rain. Supplied by Redpath Australia. Mesh size approx. 6 x 4mm



VegeNet Knitted white high density polyethylene net designed to exclude larger pests and provide some protection from wind and rain. Mesh size approx. 1 x 3mm, shading 10%, weight 45g/m^2. Supplied by NetPro Pty Ltd.

Insect Net Translucent woven material made from high density polyethylene. Long lasting material used to construct insect-proof net houses. Mesh size approx. 0.5 x 0.9mm, shading 27%, weight 125g/m^2. Supplied by NetPro Pty Ltd.



Aphid Net Translucent woven material made from high

density polyethylene. Designed to exclude most insects and last 8-10 years. Mesh size 0.6 x 0.6mm, shading 14%, weight 45g/m^2. Supplied by Crop Solutions UK.

GroShield Spunbonded polypropylene 'fleece' used primarily for frost protection but also insect exclusion and reduction of evaporation. Inexpensive but single use only as tears easily. Cohesive barrier (no holes), shading approximately 10-15%, range of thickness/weights from 18-50g/m^2. Supplied by NetPro Pty Ltd.

Agryl Spunbonded polypropylene 'fleece' similar to Groshield but with (claimed) stronger tear strength. Cohesive barrier, shading approximately 19-25%, range of thickness/weights from 17-30g/m^2. Manufacturer Fiberweb, Germany, supplied by Crop Solutions UK.

1.2. Summary of trials conducted and results

	Netting / structure	Location	Season	Crop	Result compared to uncovered control
PERMANENT STRUCTURES	Hail net	Tolga, Qld	Summer	Lettuce	Lower maximum temperatures under hail net.
	Hail net, Insect net	Stanthorpe, Qld	Summer	Babyleaf spinach	Higher temperatures under Insect net, hail net similar. Yield and shelf life unaffected.
	Red, white shade netting	Bairnsdale, Vic	Summer	Babyleaf spinach	Slight (~1°C) increase in maximum temperature under red net. Yield unaffected. Darker leaves under red netting, shelf life extended under both nettings.
	White shade netting	Carnarvon, WA	Summer	Capsicum	Temperature similar, wind speed halved, structure destroyed by cyclone.
	Green shade netting	Adelaide Hills, SA	Summer	N/A	Temperature significantly reduced under 70% shade.
	Cravo® house	Bundaberg, Qld	Spring	Capsicum	Temperatures elevated in Cravo® below 35°C, decreased in Cravo® above 35°C. Plant growth, vigour and health increased, yield and quality improved. Rain and hail damage was prevented by structure.
FLOATING ROW COVERS ON LEAFY VEGETABLES	Insulnet	Camden, NSW	Summer	Direct seeded spinach	Temperatures similar, RH higher, yield similar.
	VegeNet	Werribee, Vic	Summer	Baby cos lettuce	Larger lettuces, higher yield under net, fewer insects, shelf life unaffected.
	VegeNet, fleece, Aphid Net	Bairnsdale, Vic	Summer	Direct seeded lettuce	Higher daily maximum temperature under fleece and aphid net, slightly cooler under VegeNet, insect populations reduced, no differences in germination rate or yield.
	Insulnet, VegeNet, fleece	Robinvale, Vic	Autumn	Direct seeded lettuce	Warmer and more humid under covers, especially fleece. Slight reduction in yield under fleece, otherwise unaffected.
	VegeNet, Insect Net	Camden, NSW	Autumn	Direct seeded spinach	Higher daily maximum temperature under nets, higher overnight minimum under Insect net, insect populations reduced 60%, weed growth favoured under nets so yield reduced.
	VegeNet, Insect Net, fleece	Camden, NSW	Autumn	Direct seeded spinach	Higher daily maximum temperature and higher overnight minimums under nets, insect populations reduced 80%, weed growth favoured under nets so yield reduced.
	Fleeces	Werribee, Vic	Winter	Cos lettuce	All fleeces increased air and soil temperatures by 2-3°C and 2°C respectively. RH increased, insect populations decreased. Germination and yield increased, harvest advanced by approx. 1-2 weeks.
	Fleeces	Camden, NSW	Winter	Direct seeded lettuce	All fleeces increased air and soil temperatures. RH increased, insect

					populations decreased. Germination and yield increased, harvest advanced by minimum 2 weeks.
FLOATING ROW COVERS ON FRUITING VEGETABLES	VegeNet	Silverdale, NSW	Summer	Capsicum	Daily maximum slightly increased, higher RH. Insect damage reduced, yield similar but marketable fruit increased by 37%.
	VegeNet (3 timings)	Bundaberg, Qld	Summer	Capsicum	Temperatures reduced at >35°C, RH increased. Fruit fly catches reduced. Yield higher, more marketable fruit and advanced maturity (no. red fruit) in plants netted early in development. Little effect when plants netted 3 weeks prior harvest.
	Aphid Net, VegeNet, Vent Net	Silverdale, NSW	Summer	Chilli	Temperatures reduced at >25°C, temperatures increased at <20°C, higher RH. Aphids increased under aphid net, yield and quality unaffected overall.
	VegeNet	Bundaberg, Qld	Summer	Chilli	High temperatures reduced, RH reduced. Yield slightly reduced under netting due to increased rots, but crop damaged by heavy rain and waterlogging, trial abandoned early.
	VegeNet, Insect Net	Bundaberg, Qld	Autumn	Capsicum	High temperatures reduced by Insect Net, VegeNet similar to uncovered. Yield similar but marketable fruit increased and maturity (no. red fruit) advanced.
	VegeNet, fleece	Bundaberg, Qld	Winter-spring	Capsicum	Temperature and RH increased under fleece. Yield and quality increased under $18 g/m^2$ fleece, heavy weight fleece not durable.
	VegeNet, Aphid Net	Darwin, NT	Autumn	Eggplant	No results as yet – trial is ongoing.

2. Permanent netting or crop covers

2.1. Introduction

More variable weather, and particularly an increased frequency of heatwaves, are a key challenge facing Australian vegetable growers. Increases in average temperatures have already occurred, with the Bureau of Meteorology reporting that 2015-16 summer temperatures were 'very much above average' across much of coastal northern Australia, almost all of Victoria, all of Tasmania and much of south-east Australia.

Permanent or semi-permanent shade structures have been identified as the best way to protect vegetable crops against high temperature extremes. According to Kittas et al[1] rising air temperatures and light intensity have greatly increased the area of crops being grown under shading materials around the world. Shade cloth does not necessarily reduce air temperature around the crop; 34 to 50% shading in a structure with open sides did not affect ambient air temperatures in Greece as there was a high rate of airflow[1]. However, by reducing direct radiation, shading can reduce average leaf and soil temperatures by up to 3°C[2].

The major effects of shade net are to protect crops from sunburn and reduce moisture stress. Capsicums grown under shade are taller and have fewer, but larger leaves[2]. Despite increased leaf area, soil water content is increased, and so irrigation requirements are reduced[3]. Disorders such as blossom end rot and skin cracking are reduced by shading, as the plant is less stressed by extremes in temperature and radiation[4].

Netting not only changes light intensity, but also affects the spread of wavelengths reaching the plant. The colour of the net can influence accumulation of chlorophyll in leafy vegetables, and fruit colour in fruiting vegetables[5]. Red nets can increase leaf development, so can potentially have a positive impact on leaf crops such as spinach[6]. Yield of tomatoes is higher under red and white nets than other colour nets or the uncovered field, but lycopene

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[1] Kittas C et al. 2009. Influence of shading screens on microclimate, growth and productivity of tomato. ActaHort. 807:97-102.
[2] Diaz-Perez JC. 2013. Bell pepper (*Capsicum annuum* L.) crop as affected by shade level: Microenvironment, plant growth, leaf gas exchange and leaf mineral concentration. HortScience 48:175-182.
[3] Moller M, Assouline S. 2007. Effects of a shading screen on microclimate and crop water requirements. Irrig. Sci. 25:171-181.
[4] Lorenzo P et al. 2003. Efect on microclimate, water use efficiency and yield of a tomato crop grown under different salinity levels of the nutrient solution. ActaHort. 609:181-186.
[5] Bergquist SAM et al. 2007. Ascorbic acid, carotenoids and visual quality of baby spinach as affected by shade netting and postharvest storage. J. Agric. Food Chem. 55:8444-8451.
[6] Shahak Y. 2014. Photoselective netting: an overview of the concept, R&D and practical implementation in agriculture. ActaHort. 1015:155-162.

content may be increased under black and blue nets[7]. Capsicums were also most productive under white nets, although red nets resulted in higher levels of anti-oxidants[8].

Shading has been widely reported to increase productivity of a range of crops. However, the shading intensity needs to be suitable for both the crop being grown and the external environment. For example, in Egypt 40%[9] to 35%[10] shading maximised tomato production. Increasing shading to 51% eliminated sun-scald and increased marketable fruit compared to outside production. However greater than 51% shading reduced light below optimal levels and therefore decreased productivity. Similar results were reported from Israel for production of capsicums under shade[11]. Marketable yield was maximized under 26% shade, although results were not significantly different to 12% shade when planting density was increased. Increasing shading to 47% increased fruit size but reduced the average number of fruit per plant. In contrast, lower light levels in England mean that 23% shade is optimal for production of tomatoes[12].

It is clear that the same level of shading is not necessarily appropriate for all crops, or for use at different times of year. Retractable roof greenhouses are a relatively new technology designed to optimise shading under different environmental conditions. The sensor systems in retractable roof houses manage ventilation and shading to keep plants within an optimal environment. During cool temperatures the roof may be closed and shade curtains pulled back to warm the plants. Under more intense heat and radiation the roof and sides may be opened to allow ventilation, and reflective curtains pulled across to provide shade. Faster production cycles, major reductions in chemical use and 50% cuts in irrigation have all been reported as benefits from such systems[13].

[7] Ilic ZS et al. 2012. Effects of modification of light intensity by color shade nets on yield and quality of tomato fruits. Scientia Hort. 139:90-95.
[8] Mashabela MN et al. 2015. Bioactive compounds and fruit quality of green sweet pepper grown under different colored shade netting during postharvest storage. J. Food Sci. 80:H2612-H2618.
[9] El-Aidy F, El-Afry M. 1983. Influence of shade on growth and yield of tomatoes cultivated during the summer season in Egypt. Plasticulture. 47:2-6.
[10] El-Gizawy et al. 1992. Effect of different shading levels on tomato plants 2. Yield and quality. ActaHort. 323:349-354.
[11] Rylski I, Spigelman M. 1986. Effect of shading on plant development, yield and fruit quality of sweet pepper grown under conditions of high temperature and radiation. Scientia Hort. 29:31-35.
[12] Cockshull KE, Graves CJ, Cave CRJ. 1992. The influence of shading on yield of greenhouse tomatoes. J. Hort. Sci. Biotechnol. 67:11-24.
[13] Vollebregt R. 2004. The potential of retractable roof greenhouses to dominate greenhouse designs in the future. ActaHort. 633:43-49.

Figure 1. A retractable roof Cravo® house used to grow vegetable seedlings in Gatton, Qld.

A number of trials have examined use of netting in regions where high levels of solar radiation are likely to be an issue, at least during summer months;

- Tolga
- Stanthorpe
- Bairnsdale
- Carnarvon
- Adelaide Hills.

In addition, one trial examined yield and fruit quality of capsicums grown under a Cravo® retractable roof greenhouse in Bundaberg.

2.2. Method

2.2.1. Tolga, Queensland

The trial was conducted at a lettuce production facility at Tolga, in the Atherton Tablelands. This facility produces hydroponic lettuce for local consumption. The major production constraints are high temperatures and extreme weather events (particularly heavy rain and hail) in this region. The grower has installed two potential solutions to these challenges:

- A fully enclosed hail net house, 2.7m high and 10,000m^2, which provides some protection from the weather as well as shading for the crop
- A solo weave plastic dome type greenhouse, 6m high with extensive roof venting and roll up sides

Temperature and RH data-loggers (Hobo U23 Pro v2) were installed at the start of November 2014 to monitor temperatures.

Figure 2. Net house and greenhouse located at Tolga on the Atherton Tablelands

2.2.2. Stanthorpe, Queensland

The Stanthorpe area is highly productive, but can experience extremes of climate. It holds the record for the lowest temperature recorded in Queensland (-10.6°C) and occasionally receives sleet and even light snowfalls during winter. In summer, severe storms, including hailstorms, are a major production issue. The region usually experiences at least one major hail event between November and February each year. A number of growers have invested in hail netting as a result, including for vegetable production.

Two trials have been conducted at the Stanthorpe site. These have examined growth of baby spinach under a large hail net structure, under a floating cover (Crop Solutions UK Insect Net, 0.8mm mesh 70g/m^2) and in an open field (Figure 3).

Figure 3. Spinach growing under hail netting (left) and under a floating row cover (centre) and installation of a data logger in the open field protected by a simple PVC pipe cover

The first trial was conducted during December 2014 to January 2015. Temperature, humidity, insect populations, yield and shelf life were all recorded. Temperature and humidity were logged using Hobo U-23 external data loggers. These were protected from the elements mounted inside a vented piece of PVC pipe, open at the base.

At commercial maturity the covers were removed and twelve samples were taken of insects under the floating covers and compared to twelve samples collected from the adjacent open area. Each sample was collected using a blower-vac to suction an area approximately $2.6m^2$ for 40 seconds.

Yield was sampled from ten randomly selected positions within each treatment block. Each sampling area consisted of a 30cm x 30cm square. Spinach was harvested using a pair of scissors to trim leaves to within 10mm of the ground. Samples were weighed and then stored at $5^{\circ}C$. These were examined each day to determine the number of days until they were no longer commercially acceptable quality.

2.2.3. Bairnsdale, Victoria

The Bairnsdale region grows large quantities of babyleaf crops including rocket, spinach and lettuce, as well as more traditional lettuce varieties such as cos and oakleaf. However, high temperatures and low humidity during the summer months make it difficult to germinate seeds – especially lettuce – as well as causing sunburn, increasing water use and reducing quality of other crops.

Figure 4. White and red shade protection netting at property in Bairnsdale, and temperature + RH datalogger mounted inside a short piece of PVC pipe and placed in the seeded bed.

This trial was conducted during the summer of 2014-2015 at a commercial vegetable farm. Babyleaf spinach was planted under red and white shade netting as well as in the open field. Temperature and humidity loggers (Hobo UX100-003) were installed in the outdoor area as well as under the red and white netting. The dataloggers were protected by a radiation screen constructed from a short piece of PVC pipe and placed 20cm above the soil surface.

Comparative measurements of light intensity were taken at the time of installation using a handheld meter. Average values were calculated from a sequence of five spot measurements taken 60 seconds apart. These indicated that the white and red hail netting both provided approximately 30% shading.

Shortly before the crops reached commercial maturity, samples were taken for yield and shelf life. Five 30 x 30cm sections were harvested from each of the trial areas. Average yield was calculated for each treatment.

Three subsamples of fresh, unwashed leaves were taken from the five harvested samples from each plot area. These leaves were visually assessed then placed in separate plastic bags and stored at 5°C. A random subsample of these leaves was reassessed daily from seven days after harvest. Figures 8 and 9 illustrate a composite of typical leaves at each assessment.

Samples were considered unacceptable when >10% of the sample had signs of yellowing, leaf deterioration, or rots.

2.2.4. Carnarvon WA

Carnarvon has a hot, dry climate. Only one capsicum crop is produced each year, between February and October – December. While tomatoes and other crops are produced in the open field, capsicums are generally grown under shade netting; production is not economically viable without this protection.

Data-loggers were installed inside and outside a large, white shade house being used to grow capsicums. This was typical of structures in the area. It was several years old and quite coated with dust, which likely reduced light transmittance. Comparative measurements of light intensity, temperatures and wind were taken at the time of installation.

Figure 5. Capsicum crop grown under shade netting in Carnarvon

2.2.5. Adelaide Hills

A non-crop based assessment was conducted over the summer of 2014–2015 at Meadows, an area in the Adelaide hills. This area is adjacent to the important viticulture and horticulture region of McLaren Vale. Although only small quantities of vegetables are currently grown in this area, there is strong potential for production if the climatic constraints of high summer temperatures and limited irrigation water availability can be addressed.

Loggers were installed under a 70% shade canopy and in an adjacent uncovered area. Temperatures were monitored from 22 January to 16 February, the period when highest temperatures could be expected.

2.2.6. Bundaberg, Queensland – Cravo® house

Temperature, humidity and yield were recorded from a capsicum crop grown in the Young Sang and Co. retractable roof (Cravo®) greenhouse. This was the first crop produced inside the 4.3ha house. Temperature and humidity were monitored using Hobo outdoor data loggers (U23-100). Yield and quality were assessed when the capsicum 'king fruit' in the Cravo® house reached maturity and turned red. Data was compared to an adjacent capsicum crop planted in the field that was at a similar maturity stage. The planting dates were not the same, with the seedlings in the Cravo® house planted 1−2 weeks after the field grown crop.

Figure 6. The retractable roof Cravo® house installed by Young Sang & Co. in Bundaberg.

2.3. Results

2.3.1. Tolga, Queensland

Temperatures during the daily peak were approximately 5-7°C cooler under the hail netting compared to inside the full protected cropping structure (greenhouse). While humidity remained slightly higher inside the house during the cooler evenings, these differences were relatively minor (Figure 7).

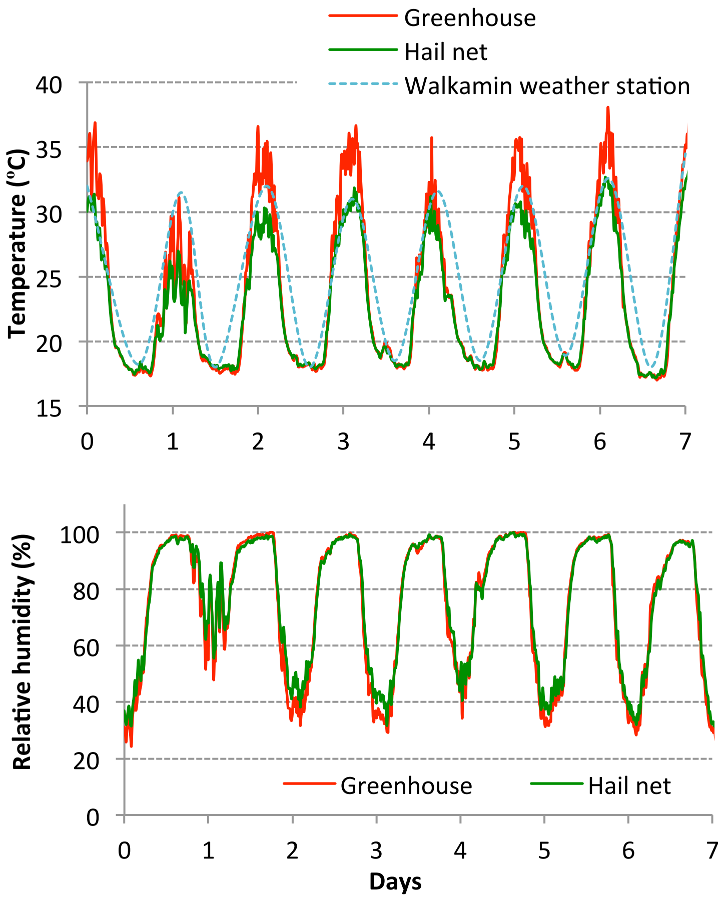


Figure 7. Temperature (top) and humidity (below) recorded at a hydroponic lettuce farm in Tolga, North Queensland during November 2014.

Data collection was limited by logger malfunction. This meant any yield data collected would have had limited usefulness.

2.3.2. Stanthorpe, Queensland

In general, temperature and humidity under the floating row cover and the hail net structures were similar to the open field. Exceptions were noted during hot weather, when daily maximum temperatures were higher under the floating row cover than the open area (Figure 8).

Under mild conditions, diurnal fluctuations in temperature were buffered by the hail net and floating cover, compared to the fluctuations in the open field (Figure 9). Similar results were found for relative humidity; in the first of these periods humidity was slightly lower in the open area, whereas in the second period RH in the open field was higher at night and lower during the day compared to the protected areas.

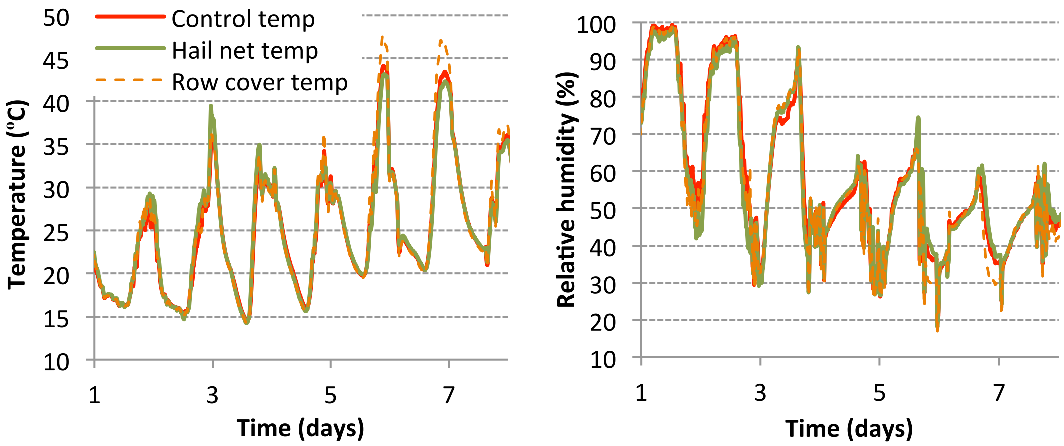


Figure 8. Temperature (left) and humidity (right) in an open field, under a floating row cover and under hail net in Stanthorpe, Qld from 5/1/2015 to 12/1/2015

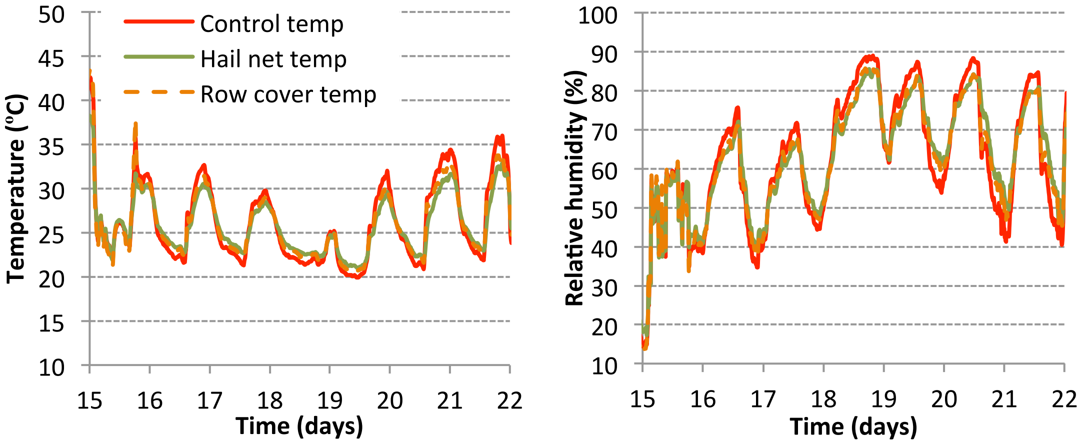


Figure 9. Temperature (left) and humidity (right) in an open field, under a floating row cover and under hail net in Stanthorpe, Qld from 20/1/2015 to 27/1/2015

These apparently contradictory results may be due to the impact of wind as well as direct sunshine, soil moisture and irrigation timing. The effect of netting on temperature and relative humidity is not straightforward, but can vary with other environmental factors.

The floating cover had a major effect on the numbers of potential contaminants in the crop. Large numbers of Rutherglen bugs were found in the open field, whereas almost none were under the floating cover. As Rutherglen bugs are a major contamination problem for baby spinach production, this represents a very positive result for the use of the netting material. The floating cover also mostly excluded beet webworm, although it was less effective against lady beetles. Although lady beetles are also a contamination issue, they may be more easily detected during packing.

Table 1.Total insects found under floating row covers compared to the adjacent field (sample size 2.6 m^2, n=12)

	Rutherglen bug	Moth /caterpillar	Beet webworm	Lady beetle
Floating cover	4	0	1	7
Open field	297	1	7	10

Yield and shelf life of spinach grown under the floating row cover was not significantly different to that grown in the open field (Figure 10).

Samples of 30 leaves were weighed to assess the relative sizes of leaves. This indicated that spinach leaves grown under the netting were approximately 10% smaller on average than those grown outside. Although yield from under the hail netting appeared to be slightly reduced, these results suggest the crop was simply slightly less mature at harvest. This limits any inference with regard to effects of growing method on total yield.

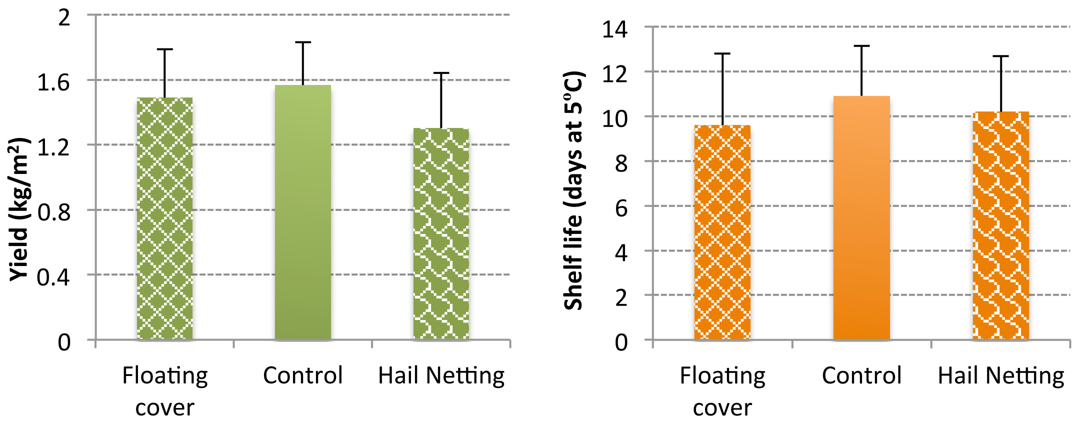


Figure 10 . Yield and shelf life of baby spinach grown under a floating net cover, under hail netting, or in the open (control). Bars indicate the standard deviation of each mean value (n=10)

Part of the reason for selecting the Stanthorpe site was because the area is prone to hailstorms during summer. While a number of hailstorms did affect the region during the trial, none impacted on the specific trial crops. The area also experienced fairly moderate temperatures during the trial period, so little information could be gathered about the impact of hail netting structures or floating covers on mitigating extreme weather events.

The most promising result is the large reduction in insect contamination of the crop by floating covers, without negatively affecting yield or quality.

2.3.3. Bairnsdale, Victoria

Although initial readings indicated that it was significantly cooler under the shade materials (Table 2), analysis of the temperature data indicated that overall temperatures were decreased by less than 1°C under the netting (Figure 11). Moreover, at higher temperatures it was approximately 1°C warmer under the red netting than it was in the uncovered field. These small differences were not statistically significantly different.

The netting did slightly increase average humidity. Although plants tended to be slightly taller when grown under the shade netting, differences in yield between the plots were not statistically significant (p=0.069).

Table 2. Differences between shaded and unshaded areas in Bairnsdale based on environmental measurements at setup.

	Air temperature (°C)	Relative humidity (%)	Soil surface temperature (°C)	Light intensity (PAR)* ($\mu mol.m^{-2}.s^{-1}$)	Plant height (mm)	Leaf length (mm)	Yield**(g/m^2)
Unshaded	38.0	38.4	31.4	1750	68	52	656
White shade	30.3	42.2	29.2	1190	74	47	489
Red shade	35.5	42.2	31.8	1242	82	48	672

* Photosynthetically active radiation

** Yield is comparative between the assessment plots but does not necessarily represent full commercial yield as the assessments were conducted prior to harvest.

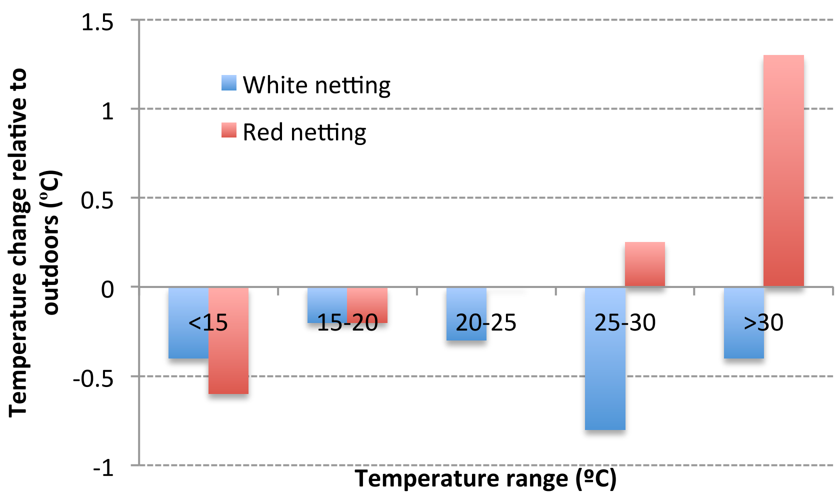
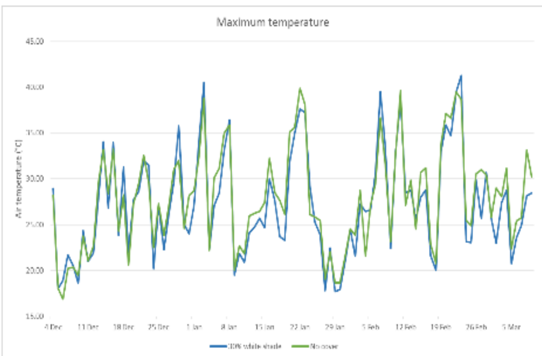


Figure 11. Change in temperature under white or red netting compared to the open field



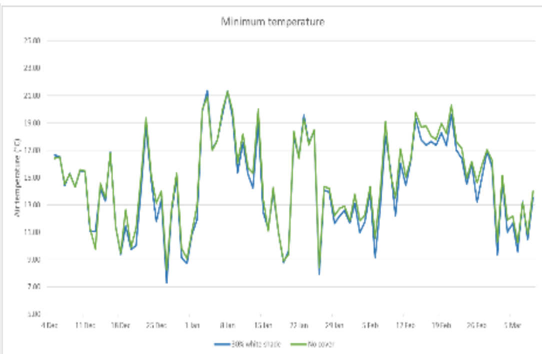


Figure 12. Daily maximum (left) and minimum (right) temperatures in an uncovered field compared to the adjacent area covered by white (top) or red (below) netting.

All three areas produced high quality leaves. The main difference between the samples which was immediately noticeable was the darker green colour of leaves grown under red netting.

All samples remained high quality until day 20. At day 21 initial leaf breakdown (<5% of sample) was evident in the product harvested from the open field (no cover). By day 23, these symptoms had increased to around 10% of leaves. At this point the product is expected to fail consumer acceptance.

Some leaf damage (<5% of leaves) was identified in the red shade product. Some of these pre-existing leaf marks became more evident by day 25. The product harvested from under the white shade was also still good quality at day 25. Initial signs of leaf breakdown in the white shade product only became evident at day 28.

Figure 13. Spinach leaves grown in the open field or under red or white netting and stored for up to 28 days at 5 °C

Estimated average shelf life was:

- Open field 23 days
- Red shade 28 days
- White shade 30 days

The 2014–15 summer was relatively mild in Bairnsdale. No major storms, hailstorms or extreme heat or cold or intense wind events occurred during the trial period. However, the results suggest that even under mild, 'normal' growing conditions light shading may slightly extend shelf life of baby spinach.

2.3.4. Carnarvon WA

Unfortunately the trials in Carnarvon were cut short by a cyclone. The loggers were not recovered and the crop was considered a total loss. The only data recorded was therefore the original spot measurements taken at installation.

Table 3. Differences between shaded and unshaded areas in Carnarvon

	Air temperature (°C)	Relative humidity (%)	Soil surface temperature (°C)	Light intensity (PAR)* ($\mu mol.m^{-2}.s^{-1}$)	Wind-speed ($km.h^{-1}$)
Unshaded	31.3	33.6	46.1	1814	7.7
Shaded	32.1	33.4	51.2	1370	3.3

* Photosynthetically active radiation

Although the effects of shade cloth on temperature and RH were minimal, it cut PAR by around 30%. It also halved wind-speed, which would likely be one of the major benefits of this system.

2.3.5. Adelaide Hills

Air temperatures were significantly reduced under the shade, particularly as temperatures became more extreme (Figure 14). At over 30°C, temperatures under the netting were up to 10°C lower than those outside. The average reduction in temperature at 35°C and higher was nearly 14%, which represents a significant potential improvement for most vegetable crops (Figure 15).

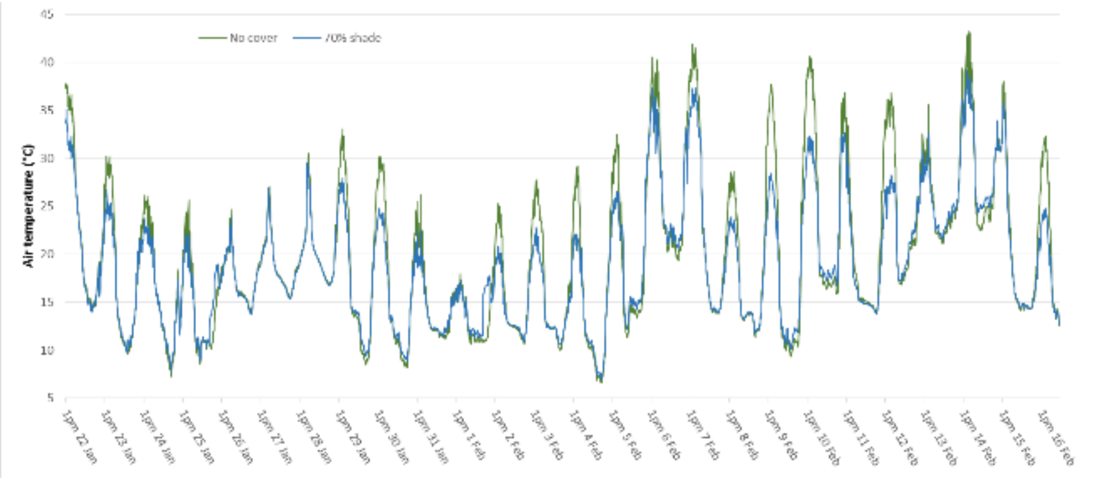


Figure 14. Temperatures recorded in the open field and under 70% shade netting during January – February 2015 in the Adelaide hills

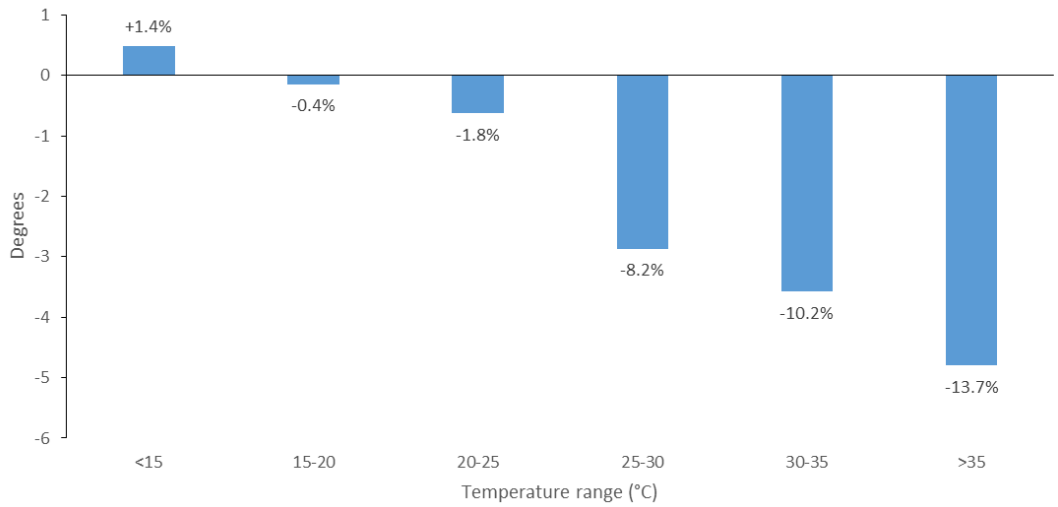


Figure 15. Impact of 70% shade on air temperature at different temperature ranges

These results indicate that shade netting could allow vegetable production during summer in a region previously considered too hot and dry for this to be viable. In this, the region resembles Carnarvon in WA, where production of capsicums and other vegetables is entirely conducted under shade netting and with drip irrigation.

2.3.6. Bundaberg, Queensland – Cravo® house

A major storm occurred in the region on 28 October 2015. Hail completely destroyed some of the outside capsicum crops, and caused significant damage to others which were already in fruit. The crop inside the house was generally untouched, although some slight damage did occur due to water ingress through the roof – it was estimated that the area received up to 150mm of rainfall, considered a 1 in 200 years rainfall event.

The storm coincided with a field day held at the greenhouse, and was effectively a major demonstration of the potential benefits of such a system. Daniel Scavo (GM, Young Sang) was quoted as saying "*You can't control the weather, but you can control the greenhouse roof*", in praise of the system.

The nearby outside capsicum crop used to assess differences in this trial had only just started to set fruit when the storm hit.

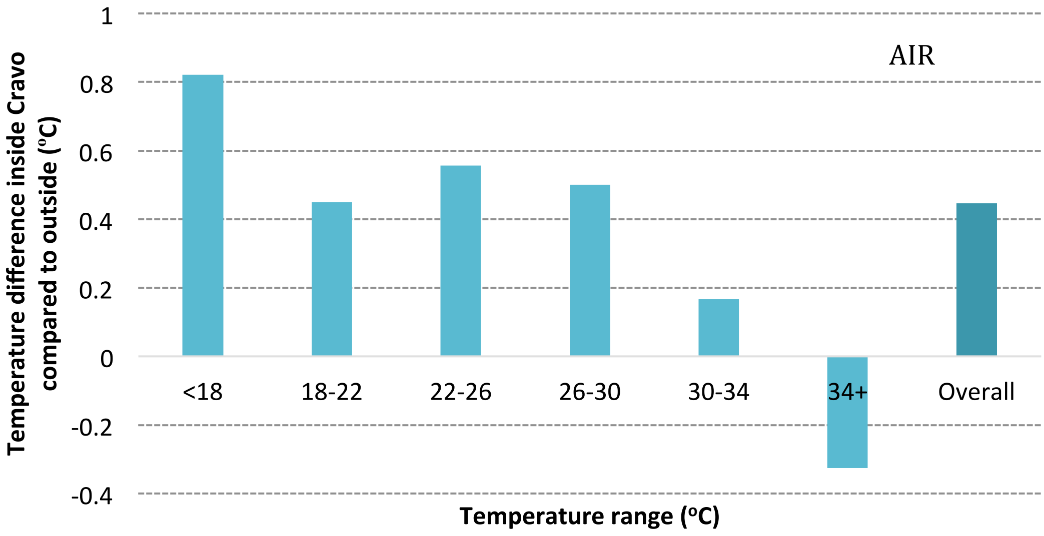
The plants inside and outside the Cravo house appeared very different, even though they had been planted at similar times. The plants inside the house had grown over a metre tall, with lush growth and very large leaves (Figure 16). Those outside the house were short, with windblown, often damaged leaves and a sprawling growth habit.

Figure 16. Capsicum crop inside the retractable roof greenhouse.

Figure 17. Field grown capsicums at a nearby field, planted 1–2 weeks prior to those inside the greenhouse.

The Cravo house provided a slightly warmer environment than the open field at air temperatures below 34°C. At higher ambient temperatures the crop was slightly cooler inside the house.

Soil temperature showed a similar pattern, although the change-over occurred at 24°C. Thus, when field soil temperatures fell below 24°C, the environment inside the Cravo house was slightly warmer. However, these differences were very small, so do not explain the large differences observed in plant growth and health.



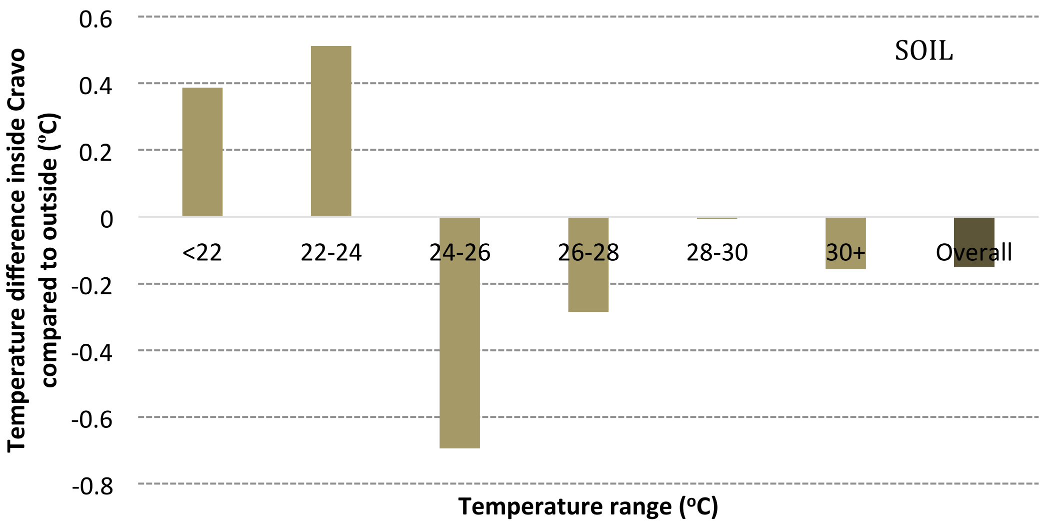


Figure 18. Air (top) and soil (below) temperatures inside the Cravo® house relative to those in a nearby capsicum crop. Below 34°C air temperature or 24°C soil temperature, the greenhouse structure provided a warmer environment for the field. However, when outdoor air temperature exceeded 34°C or soil temperatures were above 24°C, the greenhouse cooled the crop.

Large differences in yield and quality were expected between capsicums grown inside the greenhouse and field grown plants. Significant differences were found in total yield, average fruit weight and total weight of marketable size (>120g) fruit.

Table 4. Yield and quality of fruit grown inside the Cravo house compared to field grown fruit from plants of the same age. Letters indicate means that are significantly different (p<0.05, n=18).

	Total yield of fruit (g)		Total yield of fruit ≥120g		No. of Excellent fruit/plant		No. of OK to poor fruit/plant	
Field grown	1,352	a	1,085	a	3.2	a	1.3	a
Cravo house	1,692	b	1,418	b	4.2	a	0.6	a

All of the field grown capsicums were still green, whereas 26% of those inside the Cravo house were at least 50% coloured. Fruit set was extremely variable both inside and outside the house. As a result, although the number of grade 1 (excellent) fruit was higher and the number of fruit graded as “OK” or worse was halved for plants inside the Cravo house, differences were not statistically significant.

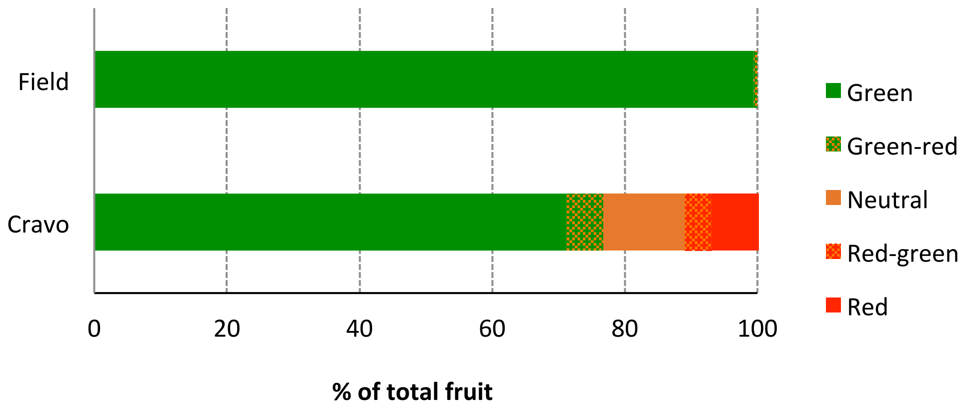


Figure 19. Percentage of the crop classified as green, mostly green, 50/50, mostly red or red from plants grown inside the Cravo retractable roof greenhouse compared with plants of the same age growing outside.

Given the health of the plants, it had been expected that differences in yield and quality would be far greater than was recorded in this trial. Although fruit set was good initially, few fruit had developed around the centres of the plants. However, the plants were flowering well at the time of evaluation, suggesting that total yield during the crop cycle could increase significantly from the figures recorded here.

As this is the first crop inside the Cravo® house, the grower is still working to optimise plant selection, nutrition and growing conditions. For example, the plants growing inside were the same variety as those in the field, which may not be the best for a protected environment. It appeared that excess nitrogen was applied during mid growth- resulting in overabundant foliage production at the expense of flowering and fruit set. The large leaves on the plants inside the house also suggest that the plants were too strongly shaded during development. It is also possible that keeping the sides of the house fully closed for an extended period during adverse weather in November may have excessively increased humidity and affected fruit set.

2.4. Conclusions

2.4.1. Effects on temperature and humidity

The results generally confirm previous published results that shade netting has minimal impact on temperatures when used only as a top over the crop. However, adding sides to the structure reduces air-flow, so can increase air temperatures even if light intensity is reduced. The red netting slightly increased maximum temperatures compared to uncovered areas, which again is consistent with published results showing higher temperatures under red netting late in the day, presumably due to increased long wavelength radiation[7].

The exception to this result was the trial from Adelaide. In this case heavy shading of 70% was tested. The result was a significant decrease in peak daytime temperatures. This site was relatively protected from wind, being located in a slight valley. This may account for the increased variation between the areas under and outside the shading compared to more exposed sites.

Humidity was also relatively unaffected by shading. Despite this, irrigation requirements under shading are likely to be significantly reduced. Adding sides to a net house reduces air movement, with the result that increased relative humidity was recorded at Tolga when comparing the net structure to a more enclosed greenhouse system.

2.4.2. Effects on yield

The trials in both Stanthorpe, QLD and Bairnsdale, VIC found no yield benefit when baby spinach was grown under white hail netting. Results were improved in the Bairnsdale trial when red netting was used. It was also notable that baby spinach grown under red netting was taller and darker green than the uncovered control. This is similar to the results reported by Bergquist[5], who also found that chlorophyll and carotenoids were increased when spinach was grown under shade netting. Darker green leaves are likely to be perceived as fresher by consumers, so are an important quality attribute. The slight improvement in shelf life that was found for spinach grown under both white and red netting is also an important positive result.

2.4.3. Protection from weather

These trials were conducted to assess how well shading could protect plants from extremes of weather and climate. Three extreme weather events occurred during the experimental periods: the cyclone in Carnarvon, a hailstorm in Stanthorpe and heavy rain in Bundaberg.

The netting in Stanthorpe completely protected the crop underneath from hail. We could easily have ended up comparing total crop loss outside the net to normal yield inside the protective structure. However, this was a highly localized storm, and in this case the adjoining control area was untouched.

Similarly, in Bundaberg, some of the capsicum crops adjacent to the Cravo® house were completely destroyed by the heavy rain during November 2015. The crop inside the structure suffered some damage, but was generally in good condition. The crop used to assess yield was approximately 2km from the Cravo® house. Although these plants were in poor condition, yield was still relatively good. However, these plants would be picked over only once or twice before the crop was ploughed in. In contrast, the Cravo® house plants were expected to continue to yield for several months. Although total yield was not assessed, it seems probable that the Cravo® house capsicums would easily overtake that from field grown crops as the season progressed.

Results would also have been improved by better nutrient and shade management of the capsicums inside the Cravo® house: this being the first crop, management was not optimal and resulted in excess leaf growth at the expense of fruit production.

Improved productivity under shading systems has been widely reported in the literature for crops such as tomatoes and capsicums, although yield of leafy vegetables such as baby spinach generally appear to be less affected. In these trials we found only moderate or no increases in productivity. However, the results do support the effectiveness of shading systems to protect crops during extreme weather events. The cost of shading must therefore be primarily balanced by the probability of total crop loss. Effects on productivity are likely to be less important, with the possible exception of systems such as the Cravo® retractable roof greenhouse.

3. Netting for summer production of leafy vegetables

3.1. Introduction

Floating covers are lightweight, permeable materials that can be laid directly over the crop without a supporting structure. Floating covers include various types of woven netting, as well as ‘fleeces’, spun-bonded materials made out of polypropylene.

Netting is primarily designed to exclude pests. Insect proof nets can reduce insecticide use, and provide an effective barrier against vectors of plant pathogens[14]. A wide range of netting materials are available, which vary considerably in light transmission, weight and mesh size. While smaller mesh sizes can help exclude more pests, they may also make control more difficult if the pest does penetrate the barrier.

For example, although fine netting can delay outbreaks of aphids, once established the aphid population can increase rapidly in the absence of predators and parasitoids[15]. One answer has been to treat the net with a long lasting insecticide, such as the pyrethroid alphacypermethrin[16]. However, this would be considered ‘off label’ use in Australia, particularly where crop contact is likely, so is not necessarily an option in Australia in the short term.

Nets also modify the microclimate around the plant. Small mesh sizes reduce ventilation, which can increase plant disease[17], but also potentially minimise moisture loss from plants and soil. Consistent soil moisture reduces irrigation requirements and may increase germination, especially for small seeds.

Although netting reduces light levels, light is more diffuse, so total photosynthesis is not necessarily affected. In addition, damage due to sunburn or heat stress may be avoided. Plant health, crop quality and yield may therefore benefit from use of nets[18]. For example, growing tomatoes under floating row covers increased total yield, marketable yield, fruit size and fruit firmness[19].

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3.2. Method

3.2.1. Robinvale, Victoria

Trials were conducted comparing the effects of Insulnet, VegeNet and Groshield on growth of direct seeded lettuce during March – April 2015. Temperature and humidity were recorded using Hobo data-loggers. Lettuces were harvested at commercial maturity, weighed and assessed for quality attributes. A random subsample of these lettuces was reassessed 7, 14 and 21 days after harvest.

Figure 20. Insulnet applied to a seeded lettuce crop in Robinvale, Victoria

3.2.2. Camden, NSW

Trial 1

Dates: 12 November to 5 December 2014

Material tested: Insulnet

Two x 50m long sections of Insulnet (Redpath, Australia) were placed over spinach plants immediately after seeding. Each piece was wide enough to cover two beds. The edges of the material were weighed down with sandbags. Adjacent beds were left uncovered.

Temperature was recorded using Hobo temperature and relative humidity (RH) dataloggers placed inside protective shields constructed of pieces of PVC pipe. Environmental conditions were also recorded using a weather station located within 1 km of the cropping area.

Figure 21. Insulnet installed over a double bed of baby spinach (left) and temperature + RH data logger inside a protective piece of PVC pipe

At commercial maturity, randomly selected 1m^2 sections of the crop under the net and in the open field were harvested (n=5). Plants were cut approximately 10mm above soil level and weighed to determine average yield/m^2.

Trial 2

Dates: 5 March to 1 April 2015

Materials tested: VegeNet and Insect Net

Three replicated 20m long sections of each type of floating cover material were placed over beds three days after seeding with baby spinach, as shown in Figure 22. The edges were secured using sandbags. Buffer areas at least 2m long were included between treatment blocks. A Hobo U23 external temperature and humidity data logger was mounted under each type of material as well as in the uncovered control area. In this case loggers were not placed in any type of protective shield but left exposed.

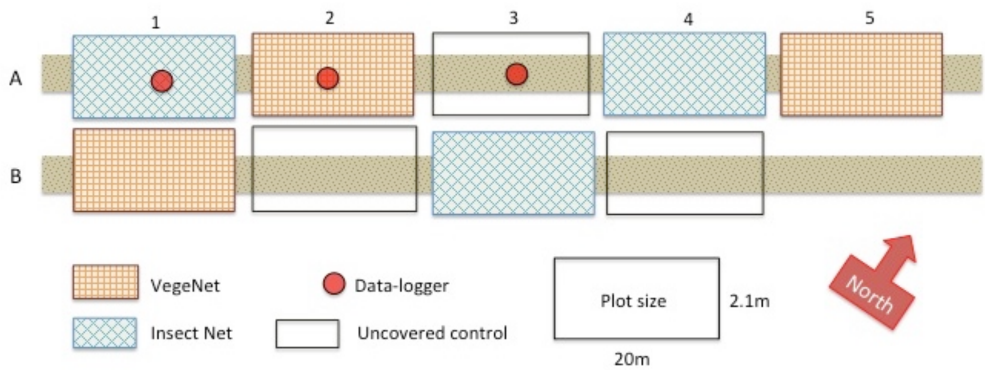


Figure 22. Trial 2 layout

Figure 23. Hobo data logger installed in the open, uncovered area of the bed and under a floating row cover

At commercial maturity each cover was removed and a blower-vac was used to sample insects from the central area of the crop. Each sample was taken over a timed 20-second period, with the operator slowly walking along the treatment block during the vacuuming procedure. Each sample was bagged for later examination of the type and numbers of insects present.

A 30cm x 30cm template was used to harvest three randomly selected sections from each treatment block (total n=9). Spinach was harvested as previously, with plants cut approximately 10mm from the ground level. Samples were returned to the lab, weighed, sorted, and segregated into units for evaluation of storage quality at 4, 7 and 10°C. Quality was assessed subjectively from excellent (4) to very poor (0) with OK (2) the limit of acceptability.

Trial 3

Dates: 16 April to 27 May 2015

Materials tested: VegeNet, Insect Net, Fleece (Agryl 22g/m^2)

Methods used were the same as those in Trial 2, with three replicated blocks of each type of material along with sections of uncovered control randomly allocated along two beds of baby spinach. Materials were applied a few days after seeding and secured with sandbags (Figure 24). A Hobo U23 data logger was mounted within each treatment type, as in the previous trial.

Figure 24. Installing three different types of floating cover on newly seeded beds of baby spinach

Insect number and presence, yield and storage quality were assessed as previously.

3.2.3. Werribee and Bairnsdale, Victoria

Trial 1

Dates: 14 December to 16 January 2016

Materials tested: VegeNet

Previous winter trials examining the use of netting or fleece on lettuce crops resulted in increased yield, but also in lettuces that were lighter and softer. This was thought to potentially reduce shelf life. This trial therefore examined the effect of removing the netting materials approximately one week before harvest, allowing plants to 'harden up'.

Baby cos lettuce was direct seeded at a commercial vegetable farm in Werribee in December 2015. Six sections of VegeNet were placed over the seedlings one week after planting, with netting removed either five days before harvest or at the time of harvest. Control plots were left uncovered (Figure 25).

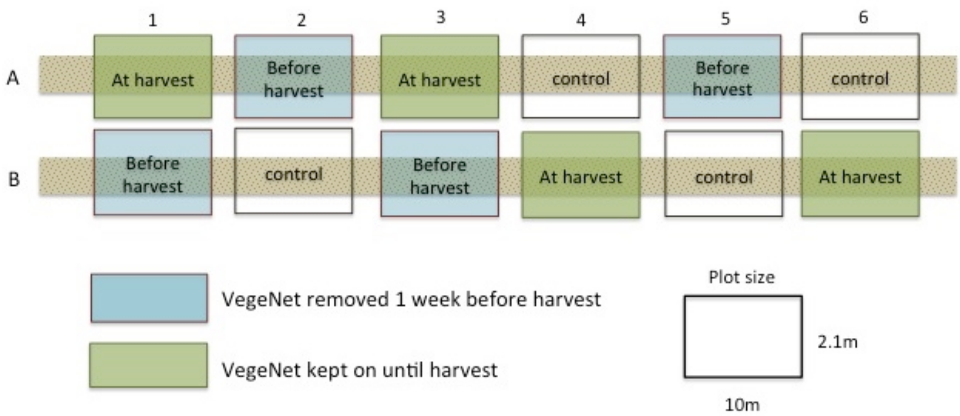


Figure 25. Trial plan for VegeNet application in Werribee

At commercial maturity, a hand-held blower-vac was run along each treatment block to collect insects present in the crop. In addition, ten lettuces were randomly harvested from the central rows of each plot. Plants were cut at the base and placed in a plastic bag. Lettuce heads were weighed, and the number of insects on each head was recorded. Lettuces were given a shelf-life score of 1-5 (1= perfect, 5=very poor) following 7 days storage at 5ºC.

Trial 2

Dates: 13 January to 23 February 2016

Materials tested: VegeNet, Groshield fleece (18g/m^2), Aphid Net

This trial aimed to test whether germination of direct seeded lettuce during summer could be enhanced using netting materials, due to more even soil moisture levels. Babyleaf lettuce (Var. Celtic) was sown in a silty clay loam on a commercial vegetable farm in Bairnsdale in February 2016. Sections of netting were placed over the beds immediately after seeding.

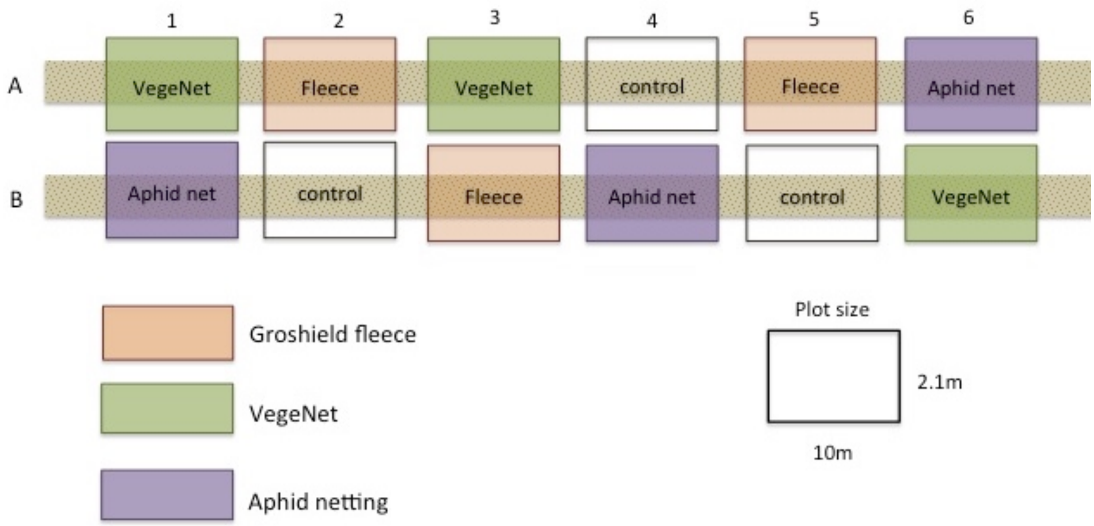


Figure 26. Trial plan for floating row covers on direct sown lettuce in Bairnsdale

At commercial maturity, a hand-held blower-vac was run along each treatment block to collect insects present in the crop. A 30cm x 30cm template was used to cut three sections from each treatment block, and the total number of seedlings was counted.

3.3. Results

3.3.1. Robinvale, Victoria

All of the floating row covers produced a warmer and more humid growing environment compared to the open field. Temperature in the open field barely exceeded 25°C and humidity stayed between 20 and 50% RH. In contrast, temperatures under the floating covers reached well over 30°C and even 35°C, while night time RH ranged up to 85-95%. The Groshield was the warmest and also most humid of all the materials, consistent with lower airflow through this material. This material increased minimum night temperatures by up to 2°C relative to the uncovered control.

Average fresh weights of lettuces grown under the Vegenet and Insulnet materials were the same as those grown in the open field, while those grown under the Groshield were approximately 30% smaller. No quality differences were observed between the lettuces, either at harvest or following postharvest storage (Figure 27).

14 days

21 days

VegeNet GroShield InsulNet Control

Figure 27. Whole lettuces grown under different types of floating row cover or left uncovered follwoing 14 or 21 days of storage at 5°C

3.3.2. Camden, NSW

Trial 1

Temperatures under the Insulnet cover were similar to those recorded in the open field. However, humidity stayed higher under the floating cover, with overnight values regularly approaching or reaching 100%RH. No desiccated plants were observed underneath the netting. However a number of dead areas occurred in the uncovered adjacent beds, where irrigation had not been sufficient to counteract hot summer temperatures.

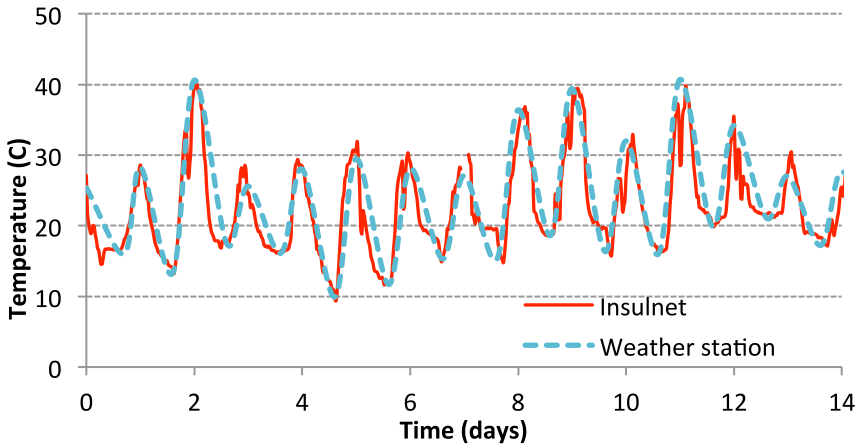


Figure 28. Temperatures recorded under Insulnet and at a nearby weather station during November 2014

Unfortunately, patchy establishment of the crop meant that yield was generally low. Yield appeared to be lower under the Insulnet cover than the open areas, although high variability meant that these differences were not significantly different (Figure 29).

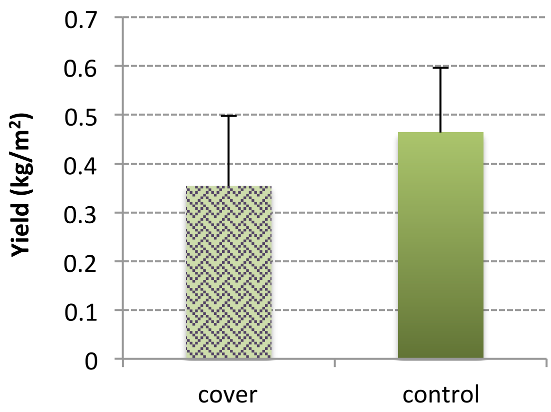


Figure 29. Yield of spinach grown under a floating row cover of Insulnet and in the open field (control), bars indicate the standard deviation of each mean value (n=5) (left) and patchy growth in the spinach crop.

Trial 2

Temperatures under the Insect Net and VegeNet were generally very similar to those in the uncovered control. However, the Insect Net did slightly mitigate against cold night temperatures, with both netting types slightly increasing daytime maximums (Figure 30). Relative humidity was slightly higher under the Insect Net but, as with temperature, such effects were marginal.

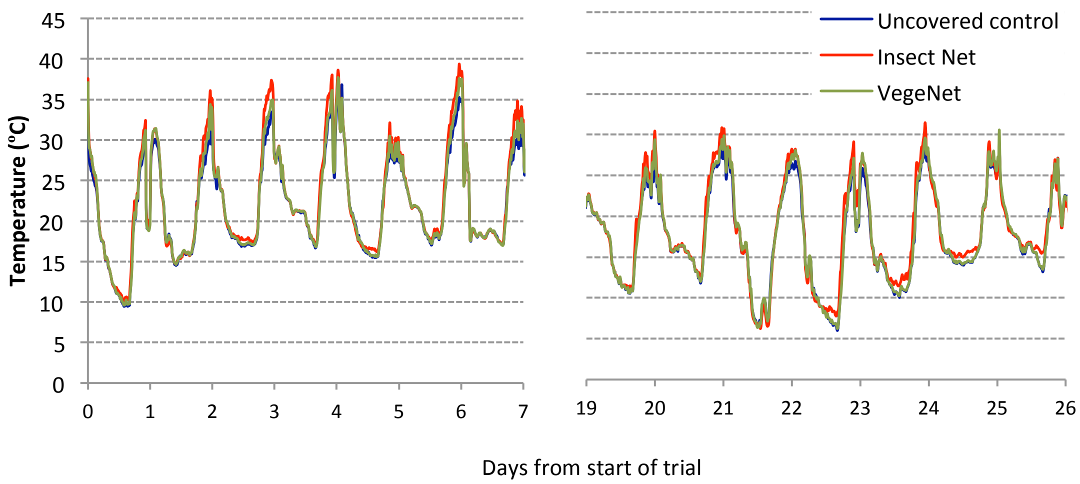


Figure 30. Temperatures during the first and last weeks of trial 2 in uncovered control plots, under Insect Net and under VegeNet floating covers

Although insects were found under both of the floating cover types, numbers were significantly reduced compared to the uncovered controls (Table 5). The ends of the nets were not very securely fastened for the trials, partly because the nets were loosened to allow for growth of the crop underneath. Had the nets been more securely fastened, results may have been improved.

Table 5. Total insects collected from the uncovered control, Insect Net and VegeNet covered crop

	Weevil	Moth	Caterpillars	Rutherglen bug	Flea beetle	Wasp / parasitoids	Thrips	Flies	Leafhoppers	Aphids	Beetles	**TOTAL**
Uncovered control	6	1	6	6	1	3	1	140	6	7	5	**182**
VegeNet	4	-	6	4	-	3	1	55	1	1	-	**75**
Insect Net	1	1	3	2	3	4	-	58	-	1	-	**73**

One potential issue noted with baby spinach growing underneath the VegeNet was that the cotyledons were narrow enough to poke through the mesh. The Insect Net mesh was too fine to allow this. When this was observed the nets were loosened and the cotyledons detached. However, this may have been unnecessary, as it was later observed that the cotyledons would naturally detach as the larger true leaves expanded under the netting.

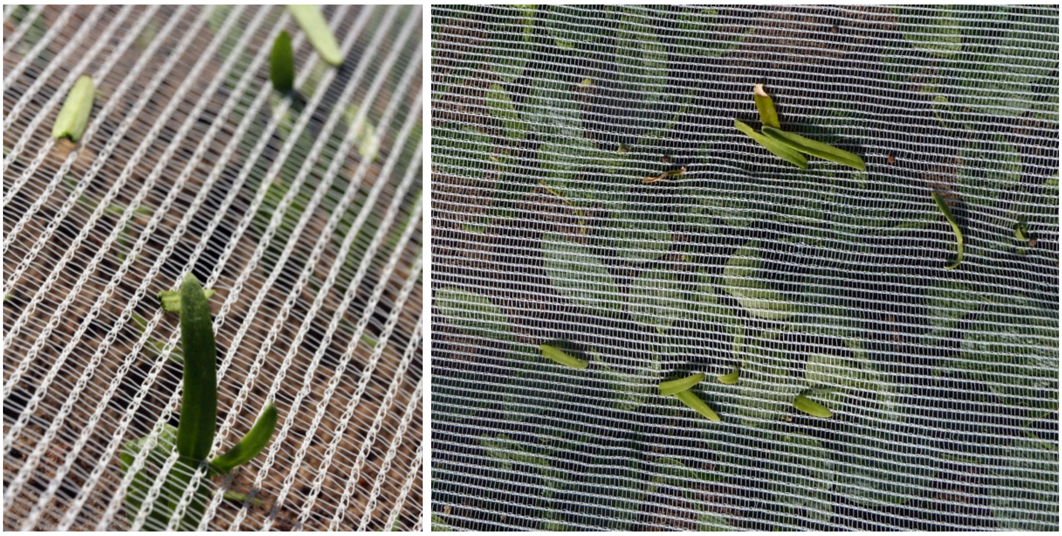


Figure 31. The spinach cotyledons could poke through VegeNet but tended to naturally detach as the plants grew

Yield results for this trial were severely affected by weeds. Although the grower had applied a pre-emergent herbicide before seeding, heavy rain the following day had clearly reduced its effectiveness. Moreover, weeds appeared to be favoured by the netting, especially the Insect Net. Yield of spinach as a percentage of total yield of vegetation was 91% in the uncovered control compared to 62% under VegeNet and only 29% under Insect Net.

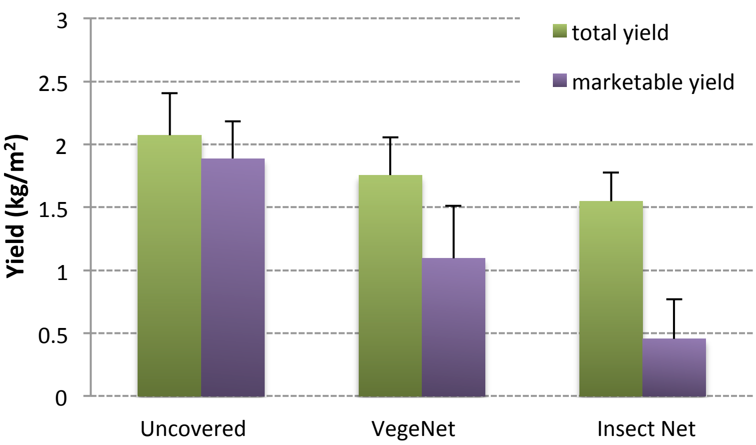


Figure 32. Total average yield of vegetation and actual marketable yield of spinach of crop grown in an uncovered bed (control), under VegeNet and under Insect Net. Bars indicate the standard deviation of each mean value.

Quality was also negatively affected by the netting materials, particularly the Insect Net. After 12 days of storage at 4, 7 or 10°C, the spinach grown uncovered in the open field remained acceptable at all storage temperatures. However, spinach grown under either type of netting and stored at 7 or 10°C was no longer marketable or consumable.

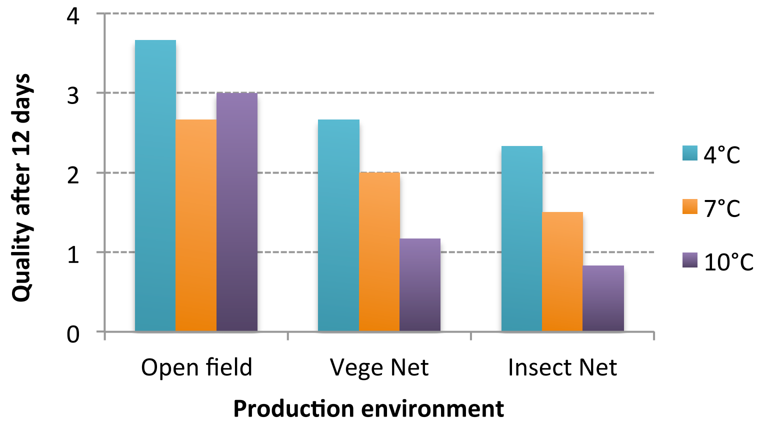


Figure 33. Average quality of spinach grown in the open, under VegeNet or under Insect Net after 12 days storage at 4, 7 or 12 °C (n=3). Quality subjectively assessed from Excellent (4) to very poor (0).

Trial 3

During the period of Trial 3, temperatures decreased and growing time increased. As the nights got cooler, differences in temperature between the different types of floating cover increased. Night minimum temperatures were up to 5°C higher under the Agryl than under the control or VegeNet. This material also increased daytime maximum temperatures, but as ambient temperatures were generally below 25°C this could have had a positive, rather than a negative effect on growth.

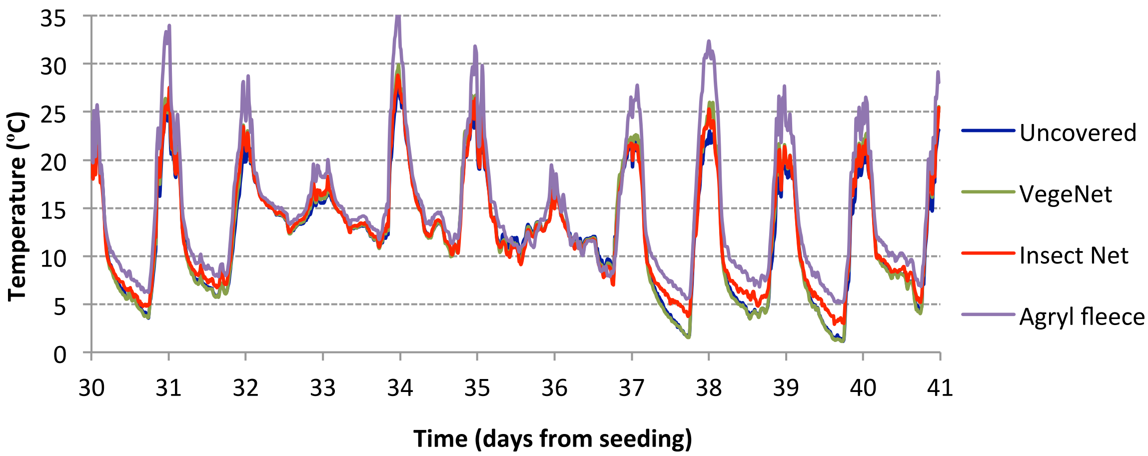


Figure 34. Temperatures during the later stages of crop growth of spinach in an uncovered control compared to under VegeNet, Insect Net and Agryl fleece

In this trial, the netting materials had been secured at the end of each block using a metal pin. There was also less pest pressure at this time compared to that in the previous trial. These factors may have helped to reduce the number of insects getting underneath, all three floating covers proving effective at reducing the numbers of insects in the crop (Figure 35).

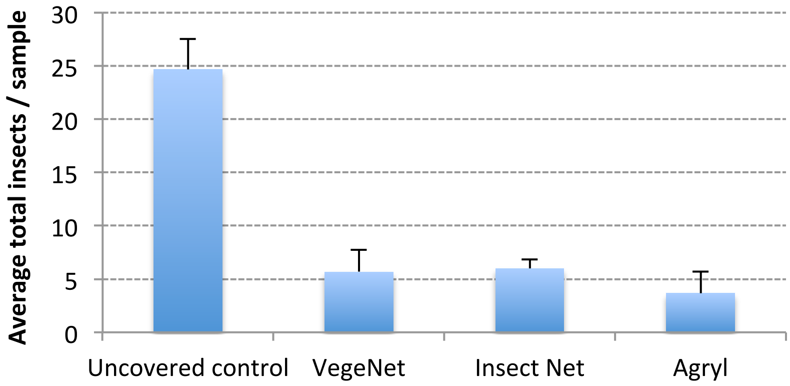


Figure 35. Average number of insects per sample (n=3) from the uncovered control compared to samples taken from under floating covers of VegeNet, Insect Net and Agryl fleece. Bars indicate the standard deviation of each mean value.

Again, growth during this trial was somewhat patchy. This was due to uneven spreading of fertiliser at planting. Also, heavy rain during the trial period leached nutrients from the sandy loam soil, with the result that plants had almost run out of fertiliser near the end of the cropping cycle. As in the previous trial, growth was also affected by weeds – particularly under the floating covers, which again had increased weed growth relative to the uncovered areas (Figure 36).

In this trial, samples from the uncovered areas contained 3.5% weed material compared to 8.8, 12.6 and 15.3% in the VegeNet, Insect Net and Agryl fleece treatments respectively.

Figure 36. Crop growth in the uncovered control (left) compared to that under fleece (centre) and Insect Net (right)

The favouring of weed growth under floating covers is an issue that will clearly need to be addressed if this method is to be used commercially. The soil under the covers was observed to be much damper than that in the uncovered areas. This was particularly the case with soil under the fleece and Insect Net. Increased soil moisture is likely to favour weeds. Reducing irrigation frequency could possibly address this issue, as well as reduce production costs.

All three floating covers reduced yield. However, as may be observed from the large error bars shown in Figure 37, results were highly variable. Spinach growing adjacent to the data logger position under the Agryl was the highest observed anywhere else in the crop (2.1kg/m^2). It was also almost entirely (97%) weed free. At this point the material was held slightly above the crop rather than resting on it, which may help explain this result.

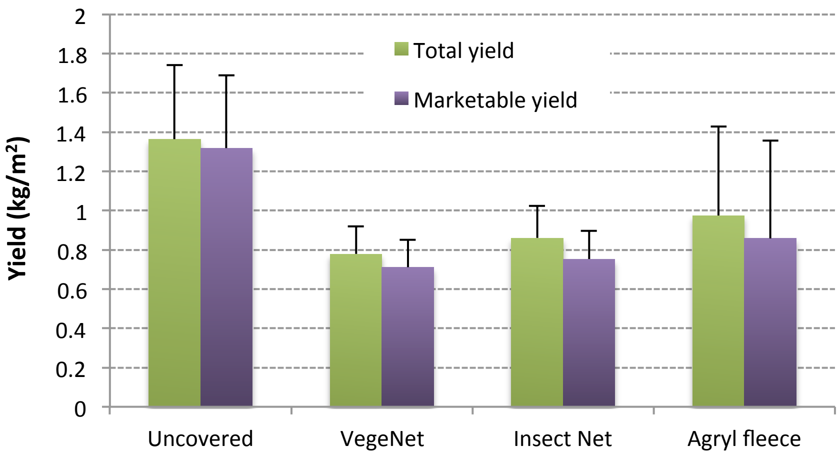


Figure 37. Total vegetative yield compared to marketable yield of spinach from the uncovered control compared to that grown underneath floating covers of VegeNet, Insect Net and Agryl fleece. Bars indicate the standard deviation of each mean value.

Although the results are not positive overall in terms of application of floating covers, they do suggest a number of refinements to the application method. The warming effect of the Agryl fleece certainly deserves further investigation for winter production. However, results may be improved if the material is slightly raised off the crop and, perhaps, irrigation frequency is reduced.

3.3.3. Werribee and Bairnsdale, Victoria

Trial 1

Lettuces covered with VegeNet were at least 29% larger than uncovered plants. This is likely due to the advanced maturity of netted plants, which appeared to be one week advanced compared to those grown in the open. Despite this faster growth under the nets, shelf life was unaffected by the netting treatments.

The results of vacuuming the crop indicated that although numbers of flies, leafhoppers and beetles were reduced in the covered crop compared to that left open, the number of Rutherglen bug was similar or increased. Although the VegeNet acted as a visual barrier, the ends of the netting were not secured, allowing Rutherglen bugs to penetrate underneath. Moreover, by excluding natural enemies, these insects may have been advantaged underneath the netting.

Despite the presence of insects under the net, the number of insects found actually on the lettuce after harvest was significantly reduced by VegeNet. This difference disappeared when the nets were removed five days before harvest.

Table 6. Effect of early removal or continuous cover of VegeNet on yield, quality and insect infestation of baby cos lettuce

	Head weight (g)	Quality (1-5)	Insects/head
Uncovered	196 c	2.2	2.4 b
Uncovered 5 days	272 a	2.5	2.0 b
Covered to harvest	256 b	2.8	1.1a
		n.s.	

Figure 38. VegeNet covers on baby cos lettuce in Werribee, and blower vac used to sample for presence of insects.

These results suggest that VegeNet improved yield without negatively impacting quality and shelf-life of baby cos lettuce. In this case yield was further increased slightly when the netting was removed several days prior to harvest. However, the potential benefits of any such removal may be counterbalanced by increased insect contamination of the crop.

Trial 2

Air temperatures reached over 40°C a number of times through the trial, which had the potential to stress germinating seedlings. Extremes in temperature were increased under the fleece, and to a lesser extent under AphidNet, whereas temperature under VegeNet was similar or slightly cooler to the control (Figure 39).

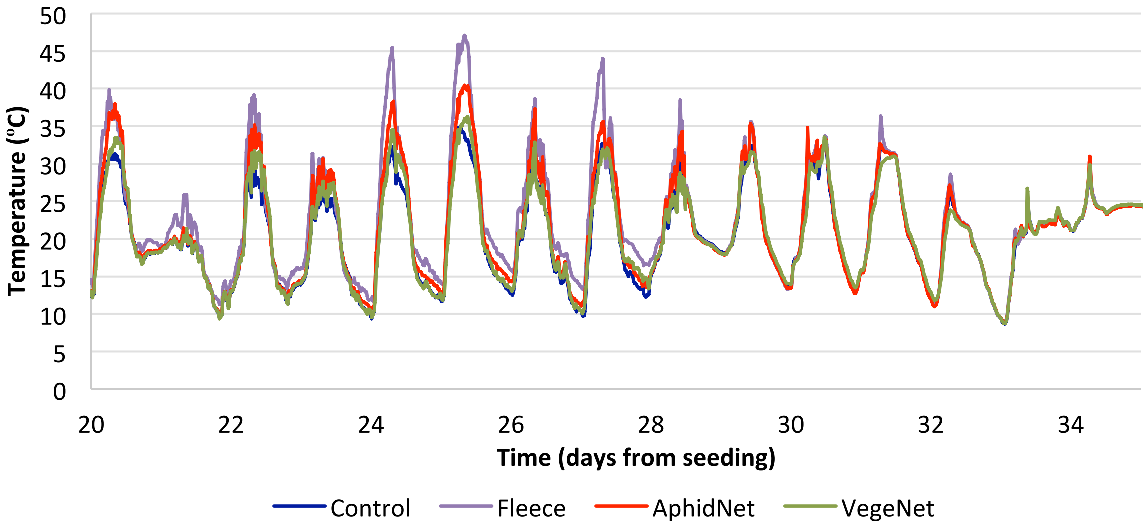


Figure 39. Air temperature in uncovered area (control) or under Groshield fleece, AphidNet or VegeNet.

Seedlings were kept very well irrigated during the trial, and were grown in a soil with a high water holding capacity. Therefore despite high temperatures which had the potential to quickly dry the soil and stress seedlings, seedling germination was very good in both netted and uncovered plots. There were therefore no differences between treatments in the number of seedlings that germinated (Table 7).

There were no significant differences between insect numbers in any treatment, although there was a trend towards fewer insects under netted treatments (Table 7). Insects were able to enter the crop because the ends of the netting were not secured, thereby allowing insects to enter.

Table 7. Establishment and insect levels in direct-seeded baby-leaf lettuce grown under floating row covers

Treatment	Insects/plot	Seedlings/m^2
Control (un-netted)	7.3	267
AphidNet	3.3	270
VegeNet	5.0	289
Fleece	2.3	264
	ns	ns

Figure 40. Floating row covers on direct-seeded lettuce in Bairnsdale, at planting (left) and harvest (right)

In this trial the crop was well managed, planted in fertile soil and provided with frequent irrigation. Despite high temperatures during the trial, floating row covers did not enhance germination. Row covers are more likely to increase summer germination of small seeded crops (such as lettuce) if the soil does not retain moisture well and/or the crop is infrequently irrigated.

3.4. Conclusions

It had been expected that the netting materials could provide some shade, reduce sunburn and maintain more even soil moisture. They could also reduce insect contamination in the crop. However, in these trials a number of issues were observed with use of floating row covers to produce leafy vegetable crops during summer.

While insect numbers were certainly reduced under the netting, insects were not prevented from entering the crop due to the ends being left open. The number of Rutherglen bugs was actually increased in one case, possibly due to these insects being protected from natural enemies by the netting. If prevention of insect contamination is a key objective, then nets must be securely fastened and left that way until harvest.

Weeds are often an issue in babyleaf crops, so thorough application of pre-emergent herbicides is essential. Where herbicide application was less than optimal, VegeNet and Insect Net increased weed growth. The warmer, moister environment under row covers can increase weed seed germination and growth rates, as well as making control with herbicide or hand weeding more difficult[20]. It is clear that effective weed control in beds prior to planting is essential if row covers are to be used.

[20] Bonanno AR. 1996. Weed management in plasticulture. HortTechnol. 6:186-189.

One of the key benefits of netting materials on vegetable beds is that soil moisture is retained, reducing irrigation requirements[21]. It is possible that irrigation requirements were reduced by using floating row covers, however this was not assessed in the current work. Positive effects of netting on seed germination were observed in trials conducted during winter. However, the results demonstrate that floating row covers are only likely to be of benefit for this purpose if other crop production factors are suboptimal. That is, if crops are being grown in sandy soil and/or irrigation is infrequent or uneven.

None of these trials resulted in significant increases in yield or quality when leafy vegetables were grown under netting. While these materials can provide some protection from insects, wind and strong sunlight, none of these factors was a major issue during the trials, and in fact the negative impacts of nets were more significant. Use of netting materials during summer for leafy vegetable crops is therefore not supported by these results.

[21] Hegazi HH, Sayed MA. 2001. Strawberry water use efficiency for different row-cover types and their economic assessment at newly reclaimed sandy soils. Alex. J. Agric. Res. 46:113-125.

4. Netting for winter production of leafy vegetables

4.1. Introduction

The main purpose of using floating row covers in summer is to protect plants from strong sunlight, dehydration and insects. In winter, the purpose is often quite different. Frost cloths, or fleece, are used to mitigate the effects of low temperatures. The slight warming these materials provide can protect plants from mild frosts, as well as provide a better growing environment for plants grown during winter months.

4.2. Method

4.2.1. Werribee, Victoria

The trial was setup at a commercial vegetable farm using beds planted two days previously with cos lettuce seedlings (Figure 41). Sections of 10m long Groshield (18g/m^2 and 30g/m^2) and fleece (50g/m^2, Elders) were laid out randomly on two seedbeds (Figure 42). The edges of the fleece material were secured using shovels of soil at regular intervals along the sides.

Figure 41. Initial trial setup in Werribee

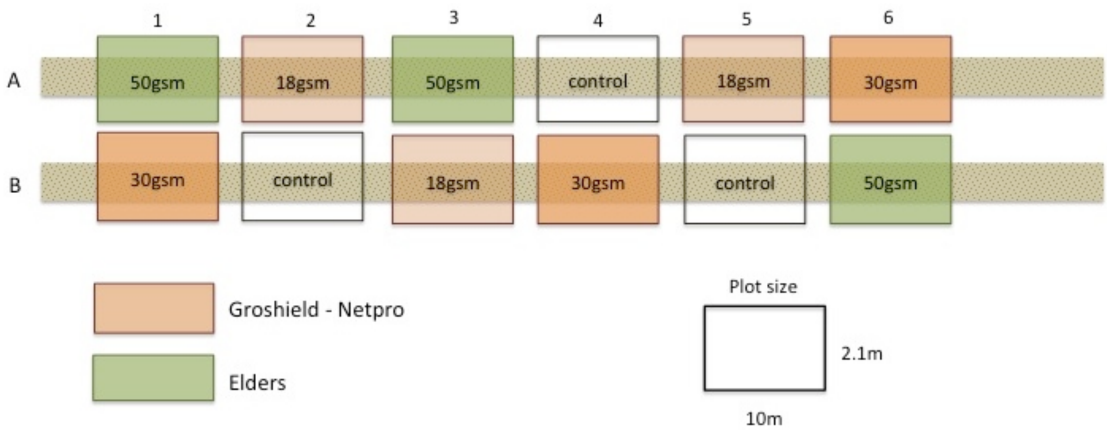


Figure 42. Trial plan in Werribee

Air temperature and relative humidity were monitored using Hobo UX100 outdoor loggers. These were fixed to short posts placed into the centres of each treatment area. Soil temperature was also monitored, using i-buttons inserted into tubes backfilled with perlite. The tubes were buried in the ground to a depth of approximately 6cm, this being the main zone of root development.

Figure 43. Installation of temperature loggers: A Hobo UX100 was used to monitor air temperature and RH, while an i-button buried inside a small tube monitored soil temperature (only lid visible at left, i-button at base of tube at right).

At commercial maturity, a hand-held blower-vac was used to collect insects present on 24 heads of lettuce. Ten lettuces were then randomly harvested from the central rows of each plot. Plants were cut at the base and placed in a plastic bag. Lettuce were weighed and assessed in terms of overall quality.

4.2.2. Camden, NSW

The trial was setup at a commercial vegetable farm using beds freshly seeded with oakleaf lettuce at a high density suitable for babyleaf production. Sections of 10m long Groshield ($18g/m^2$ and $30g/m^2$), Agryl ($19g/m^2$, $22g/m^2$ and $30g/m^2$) and fleece ($50g/m^2$, Elders) were laid out randomly on two seedbeds (Figure 44). An additional two sections of Groshield ($30g/m^2$) were also used which were lifted off the crop using inverted pots; this was trialed because of the observation during the summer trials that growth was improved where the material was lifted off the crop (Figure 45).

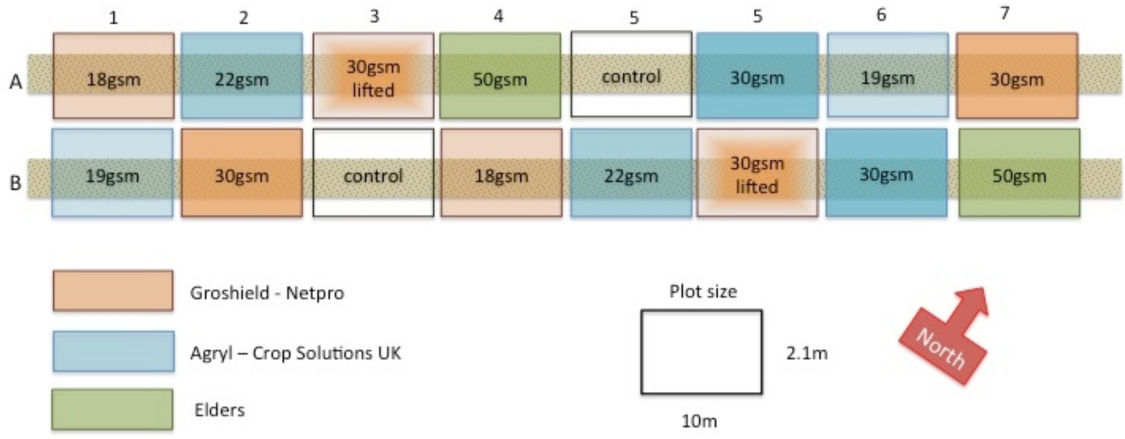


Figure 44. Trial plan in Camden

Figure 45. Initial trial setup in Camden showing sections of different types of fleece (left), and fleece lifted slightly off the crop using inverted plant pots (right).

Two harvests were conducted, at eight and ten weeks after seeding. The first was when the larger plants were just reaching commercial maturity. The covers were removed, and a hand-held blower-vac was run along each treatment block to collect insects present.

A 30cm x 30cm template was then used to harvest three randomly selected sections from each treatment block (total = 48 samples). Lettuce was harvested as previously described for spinach, with plants cut approximately 10mm from the ground level. Samples were returned to the lab, weighed, sorted, and segregated into units for evaluation of storage quality at 4, 7 and 10°C. Quality was assessed subjectively from excellent (4) to very poor (0) with OK (2) the limit of acceptability.

The second harvest was conducted two weeks after the first, when the uncovered control plants had reached commercial maturity. Another set of samples was cut from each treatment block, using areas not previously assessed. These samples were assessed in terms of yield only.

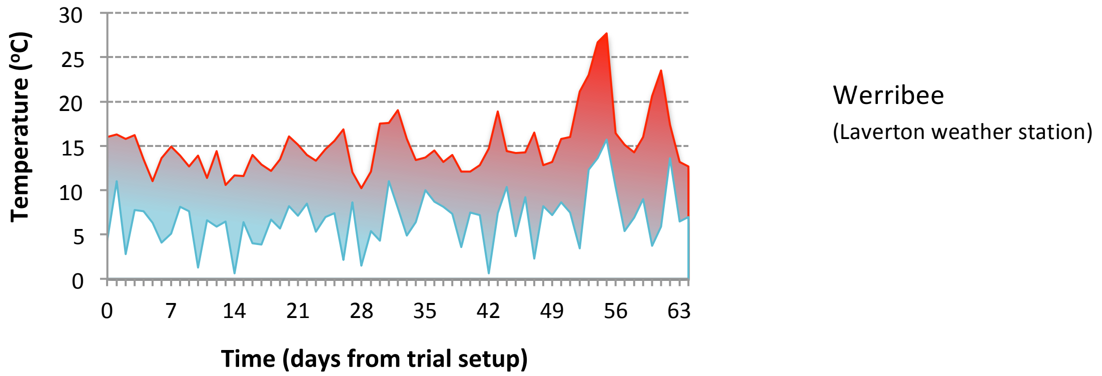
All data was analysed using CoStat statistical software. Means were separated using the Student-Newman-Keuls test for statistically significant differences at a confidence level of p=0.05.

4.3. Results

4.3.1. Temperatures

Ambient temperatures

Ambient temperatures, as measured at the nearest Bureau of Meteorology weather station, show large and significant differences between the two trial sites.



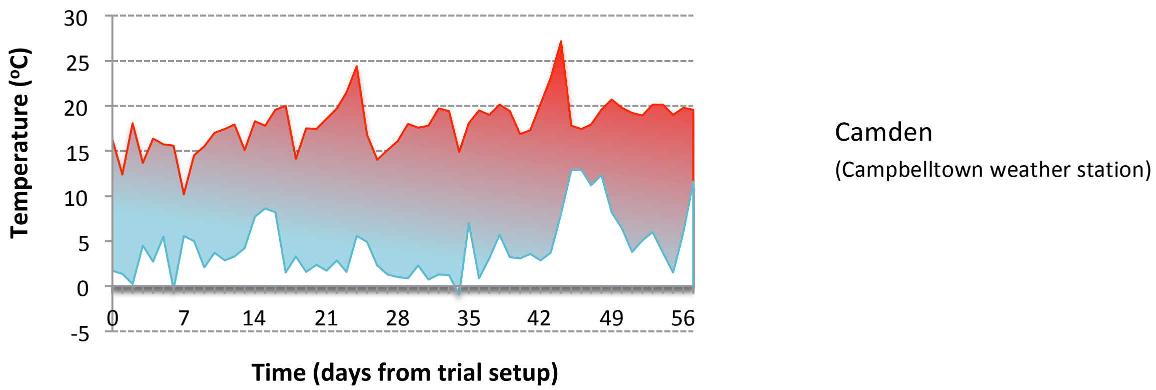


Figure 46. Daily maximum and minimum temperatures during the trial period for each of the sites, as recorded by the local Bureau of Meteorology weather station

During the trial period a number of frosts were experienced at the Camden site and two light frosts at Werribee. As expected, daily maximum temperatures were higher in Camden than in Werribee, even though night time minimums were lower.

Crop temperatures

All of the fleeces increased temperature and humidity compared to the uncovered control plots. This increase was 2-3°C overall. However, the amount that the fleece materials raised the temperature was not equal across the temperature range, being greatest at low temperatures and once ambient temperature increased to 20°C or more (Figure 47).

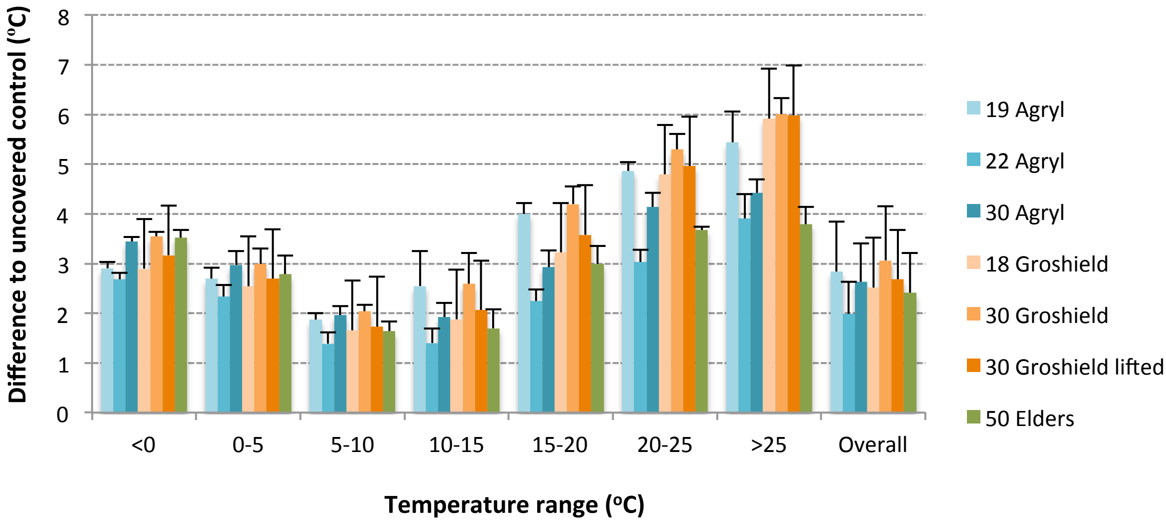


Figure 47. Difference in air temperature between the uncovered control and different types of fleeces, for temperatures recorded in 5°C bands. Bars indicate the standard deviation of each mean value.

Perhaps surprisingly, the weight of material made little difference to the resulting increase in temperature.

As with temperature, all of the fleece materials tested increased RH around the plants. This increase was greatest (although highly variable) when ambient RH was low (<70%). Overall, all of the fleece materials increased RH by around 5-15%.

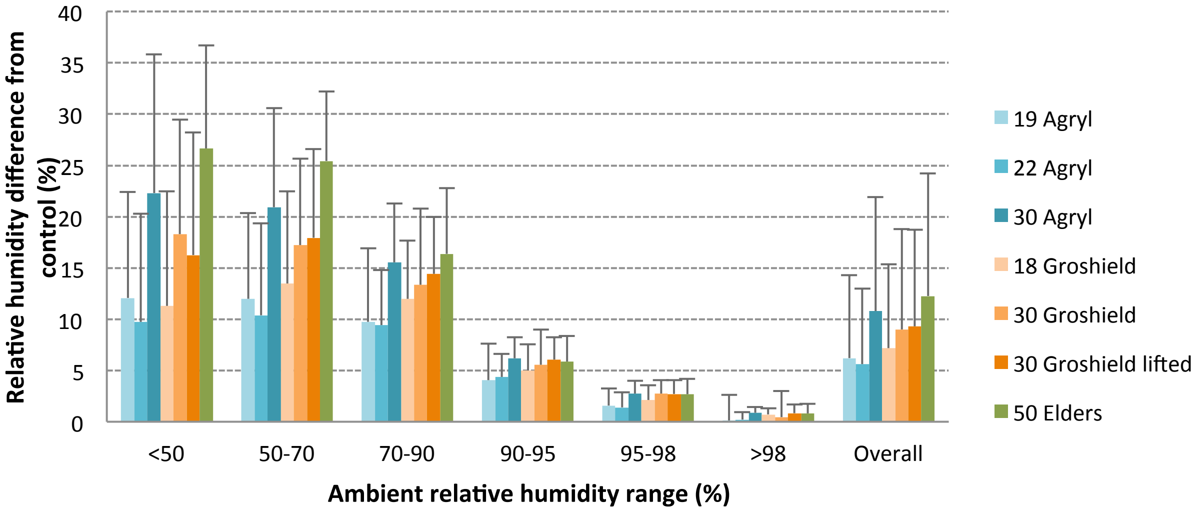


Figure 48. Difference in relative humidity (RH) between the uncovered control and different types of fleeces, for RH values recorded in different bands. Bars indicate the standard deviation of each mean value.

Soil temperatures were also elevated by all of the fleece covers. Soil temperatures generally increased by 2°C on average, regardless of fleece type or weight. The greatest increases occurred when soils were cold, being below 8°C. The exception occurred once ambient soil temperatures increased to 20°C or more. Under these conditions, the soil remained slightly cooler under the fleece, although this difference is unlikely to be statistically significant.

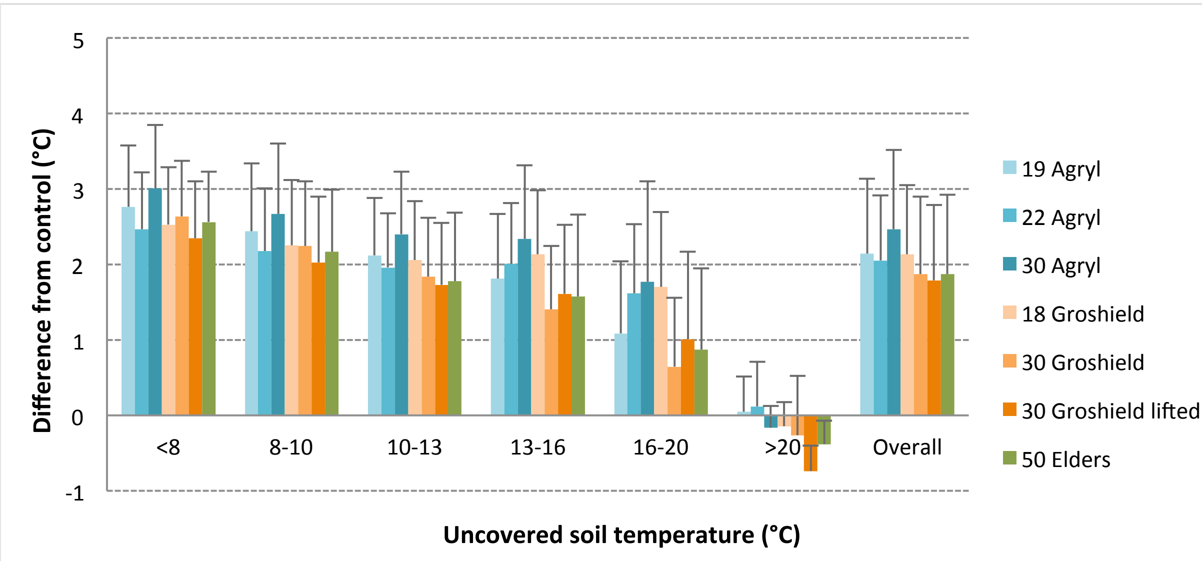


Figure 49. Difference in soil temperature between the uncovered control and different types of fleeces, for temperatures recorded in 2-4°C bands. Bars indicate the standard deviation of each mean value.

4.3.2. Yield

Werribee, Victoria

Well before harvest, there were clear differences between the lettuce grown under the fleece and those left unprotected. Yield of lettuce was significantly increased for the lettuces protected by either 18g/m^2 or 30g/m^2 Groshield compared to those left unprotected (Figure 51, Table 8). The lettuces grown under the 50g/m^2 material were intermediate. It was noted that some of the lettuces grown under this material appeared to have been damaged by the material. Some of the 50g/m^2 material came loose during the trial, due to being fractionally too narrow for the beds. This fleece had to be removed two weeks prior to harvest, as it could no longer be secured without crushing the lettuces underneath.

Figure 50. Size differences in cos lettuce grown without (left) and with (right) fleece protection materials in Werribee during winter months.

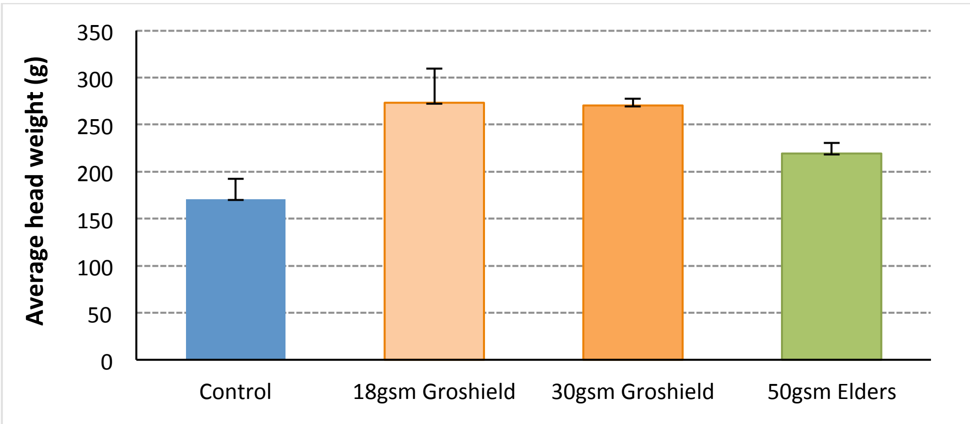


Figure 51. Average weight of lettuces grown in Werribee during winter 2015 and left uncovered, covered with 18 or 30g/m^2 Groshield or covered with 50g/m^2 frost protection material. Bars indicate the standard deviation of each mean value (n=3).

Table 8. Average weights of lettuces grown in Werribee under different frost protection materials. Letters indicate means that are statistically different ($p<0.01$)

Treatment	Weight (g)	
Control	171.6	c
18g/m^2 Groshield	273.3	a
30g/m^2 Groshield	270.7	a
50g/m^2 Elders	215.4	b

One issue experienced during the trial was loss of lettuces due to 'bottom rot' (*Rhizoctonia solani*). This appeared to increase under the 50g/m^2 covers; one of the three replicate plots was not assessed due to extensive collapse of the lettuces underneath. Incidence was similar in the uncovered controls and the plots with Groshield.

The lettuces appeared paler under the fleece materials, particularly the 50g/m^2 material. There was also some damage noted under all of the fleece materials where the covers had restricted crop growth. Loosening the covers more than once during crop growth may have avoided this damage, although over-loosening may also increase wind rub from flapping material.

Camden, NSW

Even a week after seeding, differences started to appear between the covered and uncovered plots. Germination was increased, with seedlings under the fleece materials developing rapidly compared to those left uncovered.

Figure 52. Growth of lettuces in the open compared to under fleece, one week after seeding (left) and at initial harvest (right). Poor germination and stunted growth can be seen in the lettuces left uncovered at the front of the picture, compared to the lush growth of those under the fleece (right)

The uncovered lettuce were still extremely small at harvest 1. Germination in these plots was uneven, and the lettuces themselves appeared stunted. After a further two weeks (harvest 2), they were approximately the same size as the lettuces in treated plots at harvest 1, indicating that the fleece treatments brought harvest forward by approximately 2 weeks (Figure 53).

Figure 53. Second harvest of babyleaf lettuce from the Camden site

However, during this two week period, lettuces in the plots covered with fleece approximately tripled in size. Sunny conditions, regularly reaching 20°C during the day, undoubtedly assisted this rapid growth.

The fleece treatments were all approximately similar, with the exception of the 50g/m^2 material. As noted in Werribee, this material had some negative impacts on growth, likely due to being too heavy for the plants underneath. Even after the material was removed, these plants failed to fully recover and catch up with those protected using lighter materials.

Lifting the fleece off the plants appeared to have some benefits, although these plots were very patchy according to the high and low points of the material. Results from the Agryl and Groshield were statistically similar, although a trend to increased growth under the Agryl may be observed. There appeared to be no benefits in using heavier weight materials: the lightest (and cheapest) of the materials tested gave the best results overall (Figure 54).

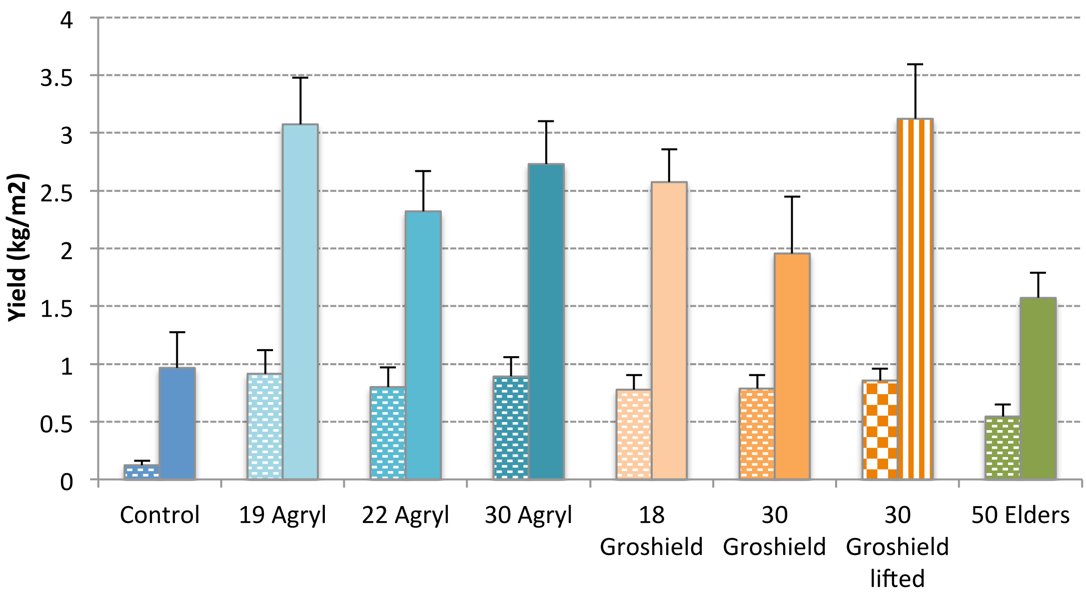


Figure 54. Yields from an initial and second harvest at Camden, harvests conducted two weeks apart using different sections of the bed. Bars indicate the standard error of each mean value (n=8)

Yield from the control plots was significantly lower than that from all the other treatments at harvest 1, and significantly lower than all except the 50g/m^2 treatment at harvest 2 ($p<0.01$) (Table 9). Stored samples were assessed subjectively after 1 and 2 weeks at 5°C. After one weeks storage the control was graded as significantly lower quality than the other samples ($p=0.01$), however after 2 weeks all samples were considered unacceptable.

Table 9. Yields from an initial (harvest 1) and second (harvest 2) harvest at Camden, harvests conducted two weeks apart. Letters indicate means that are statistically different (p<0.01)

Treatment	Yield (g/quadrant)	
	Harvest 1	**Harvest 2**
Control	11.1 b	87.0 c
19gsm Agryl	82.4 a	277.0 a
22gsm Agryl	72.0 a	209.1 bc
30gsm Agryl	80.3 a	246.0 ab
18gsm Groshield	64.6 a	232.0 ab
30gsm Groshield	70.9 a	230.8 ab
30gsm Groshield lifted	77.2 a	281.3 a
50gsm Elders	49.1 a	141.6 ab

Insects

Insects were generally low at both the Werribee and Camden sites, as would be expected during winter months.

Significant vegetable weevil larvae damage was noted in two of the plots in Werribee (30g/m^2 and 50g/m^2 fleece), although no actual larvae were found. It is possible that reduced penetration of insecticides and/or warmer conditions under the fleece might favour insects emerging from soil underneath the covers.

In total, 41 pest insects were recovered from the control plots, compared to 3, 16 and 0 insects from the 18g/m^2, 30g/m^2 and 50g/m^2 treatments respectively. Most of these were aphids, as well as small numbers of Rutherglen bug and leafhoppers.

In Camden, less than 6 insects/plot were found for all of the lettuces covered by fleece materials. Higher numbers were found in the control, which averaged 25 insects/plot. Green leaf hoppers were the dominant pest, particularly in the controls. Brown sowthistle aphids and thrips were found in all treatments, although in lower numbers under the frost protection materials.

4.4. Conclusions

All of the fleece materials tested increased yield of lettuces grown over winter. The fleeces significantly increased both air temperature and soil temperature, and slightly raised humidity around the crop.

The fleece materials also reduced the number of insects within the crop, which could affect both crop damage and contamination of packed product. It appears that the best strategy may be to use these materials over winter until air temperatures increase to a regular daytime maximum of approximately 20°C. After this time they may be removed to allow the crop to 'harden up' and possibly develop a richer colour.

There were few differences noted between the materials, with the exception of the 50g/m^2 fleece, which gave less positive results. It is notable that the lightest materials – which are also the cheapest – gave just as good a result (if not better) as heavier fabrics.

5. Netting for capsicum production

5.1. Introduction

Capsicums are a warm weather crop. They are often planted in spring and summer, with harvest extending into winter, although production can continue virtually year round in the Bundaberg region. While high temperatures increase growth, they can also result in increased blossom end rot and sunburn, both of which cause significant losses. High temperatures can also cause flowers to abort and fruit to drop[22].

Floating covers and netting have been widely reported to increase growth and yield of capsicums grown in hot climates[23]. Shading with row covers can increase marketable fruit by preventing sunburn and reducing blossom end rot[24]. They can also reduce water use[25] and even help prevent infection with certain diseases[26].

A series of trials were conducted examining the use of various floating row covers with capsicums grown in Silverdale, NSW and Bundaberg, Qld.

5.2. Method

5.2.1. Silverdale, NSW

Capsicum seedlings were planted at a commercial vegetable farm in Silverdale, Western Sydney, NSW in November 2014. Three large sections of VegeNet were applied soon after initial fruit-set. Each piece covered four rows, with two pieces 20m long, and the third piece 10m long (Figure 55). Hobo UX100 external temperature and RH data loggers were placed under the netting and in the uncovered control and recorded temperature and relative humidity for a period of the trial.

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[22] Deli J, Tiessen H. 1969. Interaction of temperature and light intensity on flowering of *Capsicum frutescens* var. *grossum* California Wonder. J. Am. Soc. Hort. Sci. 40:493-497.
[23] Rylski I, Spigelman M. 1986. Effect of shading on plant development, yield and fruit quality of sweet pepper grown under conditions of high temperature and radiation. Sci. Hort. 29:31-35.
[24] Alexander SE, Clough GH. 1998. Spunbonded rowcover and calcium fertilization improve quality and yield in bell pepper. HortSci. 33:1150-1152.
[25] Moller M, Assouline S. 2007. Effects of a shading screen on microclimate and crop water requirements. Irrig. Sci. 25:171-181.
[26] Brown JE et al. 1989. Black plastic mulch and spunbonded polyester row covers as method of southern blight control in bell pepper. Plant Dis. 73:931-932.

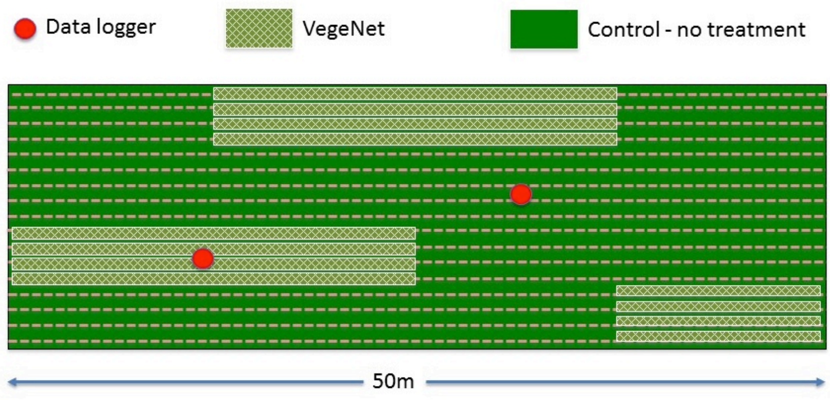


Figure 55. Trial plan of VegeNet application on capsicums grown in Silverdale, NSW.

Figure 56. VegeNet on capsicum plants grown in Silverdale, NSW. Weeds became a problem (right) soon after the trial commenced.

At harvest maturity (12 March 2015), total yield and fruit marketability was estimated using 6 plants per plot. All fruit were stripped from each plant, weighed and graded according to colour and marketability.

5.2.2. Bundaberg, Queensland

Trial 1, Autumn 2015

The trial was set up using a commercial capsicum crop. Seedlings were planted at the beginning of February 2015. The nets were installed four weeks later, which allowed time for the plants to establish. At this stage plants were approximately 40cm high and starting to flower.

Two 30m long sections each of VegeNet and Insect Net were used in the trial. As the Insect Net was relatively heavy for a floating cover, it was suspended over the plants using cloche hoops. These are used for low tunnels, particularly for cut flower production. The hoops can be unclipped on one side to allow access to the crop. The cloche hoops were placed at 2m intervals, and clamped the net quite tightly.

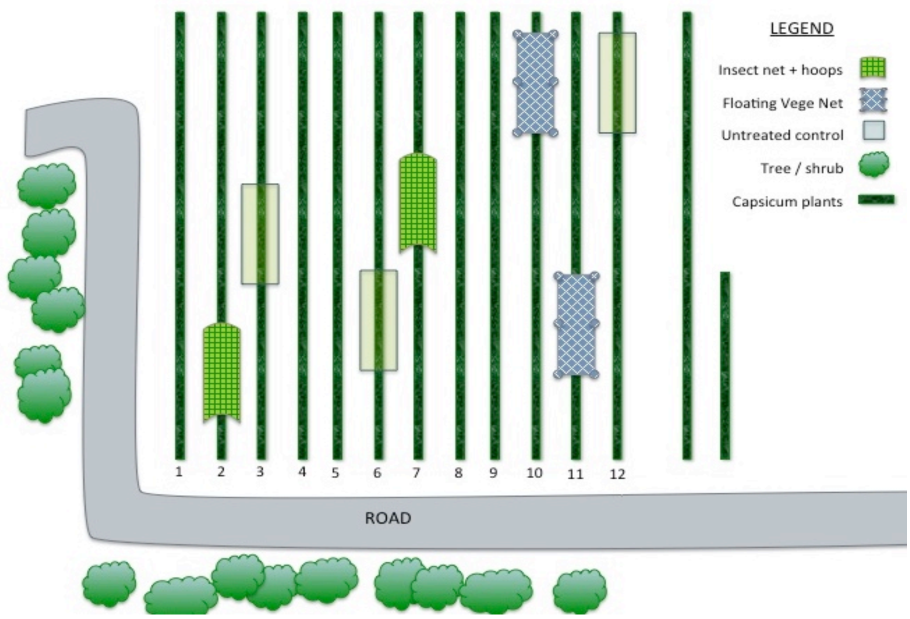


Figure 57. Trial plan for capsicums in Bundaberg

Yellow sticky traps were placed inside and outside each netting type to monitor insects. Temperature and humidity data loggers were installed within the uncovered crop and under each netting type.

Figure 58. VegeNet (left) was draped directly on capsicum plants while the Insect Net (right) was secured using low cloche hoops

Five days before the first commercial harvest the netting was removed and 2 x 5m long sections in the centre of each unit were vacuumed using an electric blower-vac. Insects were collected and kept for counting and identification (Figure 59).

Figure 59. Temperature logger installed within the crop and collecting insects using an electric blower-vac

Yield and quality was assessed using eight randomly selected plants from each treatment block (including the untreated controls). These plants were strip-picked of all fruit, including those below marketable size (n=16 / treatment). The harvested fruit were individually weighed and assessed in terms of insect damage, colour and quality. Total yield, total potential yield and marketable yield were calculated for each treatment.

Trial 2, Winter to Spring 2015

In Bundaberg, harvesting of the autumn capsicum crop usually finishes by mid-July. While the spring crop is planted at about this time, there is a break in production between August and November. While capsicum production in Bowen covers much of this period, there is a period of several weeks when supply is short in the market. Increasing the temperature around capsicum plants could bring harvest forward. Earlier maturation, particularly if it increased the number of red fruit, could be a major benefit of using frost protection materials.

Another potential benefit is the protection afforded by frost protection materials to wind. Bundaberg is prone to strong winds and storms. Previous trials with insect netting demonstrated that protecting the plants from wind resulted in healthier looking plants with improved fruit quality.

This trial therefore tested the application of different weights of fleece for advancing the maturity of winter grown capsicum in Bundaberg. Fleece material was applied in 20m sections to 1 week-old capsicum seedlings on a commercial vegetable farm in Bundaberg. Four separate rows of capsicum were used, with uncovered buffer rows in-between those used for the trial (Figure 60). As this was a winter crop, capsicums were planted in a single row, rather than a double row as is usual during warmer months. The edges of the fleece were secured with soil (Figure 61).

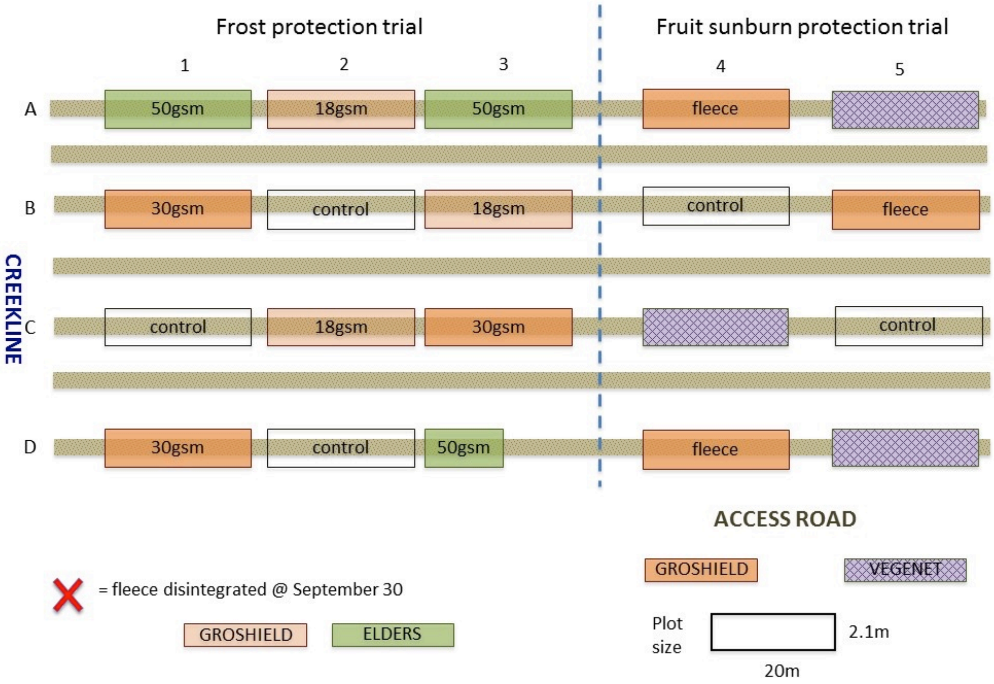


Figure 60. Winter - spring trial plan in Bundaberg

Figure 61. Initial trial setup in Bundaberg

From spring to autumn, sunburn can reduce the marketability of capsicum fruit. Therefore additional netting and fleece material was installed on adjacent areas of the same crop three weeks before harvest to test effectiveness for sunburn prevention.

Air temperature and RH was monitored using Hobo UX100 outdoor loggers. These were fixed to short posts placed in the centres of each treatment area. Soil temperature was also monitored, using i-buttons inserted into tubes backfilled with perlite. The tubes were buried in the ground to a depth of approximately 6cm, this being the main zone of root development.

A number of crop assessments were conducted in Bundaberg. This was partly due to storm and wind damage, which destroyed some of the fleece materials being tested. Assessments were:

1. 3/9/15 – Six plants per treatment unit cut off at the base. Fruit counted and weighed. Plant leaves and stems weighed.
2. 22/10/15 – Early harvest of mature green fruit. Six plants per treatment unit of remaining treatment blocks strip picked. Fruit were counted, weighed and quality graded.
3. 10/11/15– Commercial harvest of mature green and red fruit. Six plants per treatment unit of remaining treatment blocks strip picked. Fruit were counted, weighed, quality graded and colour recorded.

Trial 3 - Summer 2015

Previous trials found benefits from floating row covers including increased yield and quality of fruit, and a reduction in insect pests. However floating row covers can disrupt farm practices such as spraying. Ideally, they should be placed on the crop as late as possible, but early enough to still allow for the benefits that the row covers provide. This trial tested the application of VegeNet at three crop stages;

1. Start of flowering 11th November 2015
2. After fruit set 9th December 2015
3. Three weeks before harvest 18th December 2015

Sections of single rows 10m long were covered using VegeNet at the appropriate times. Fruit fly traps (Biotrap®) were placed in one plot per treatment and were checked fortnightly for fruit flies. Air temperature and humidity were recorded as previously.

All fruit from six plants per plot were harvested on 13 January 2016. Fruit were weighed and assessed for colour (red, red-green, neutral, green-red or green), quality grade (perfect, good, ok, and non-saleable), and defects such as rots.

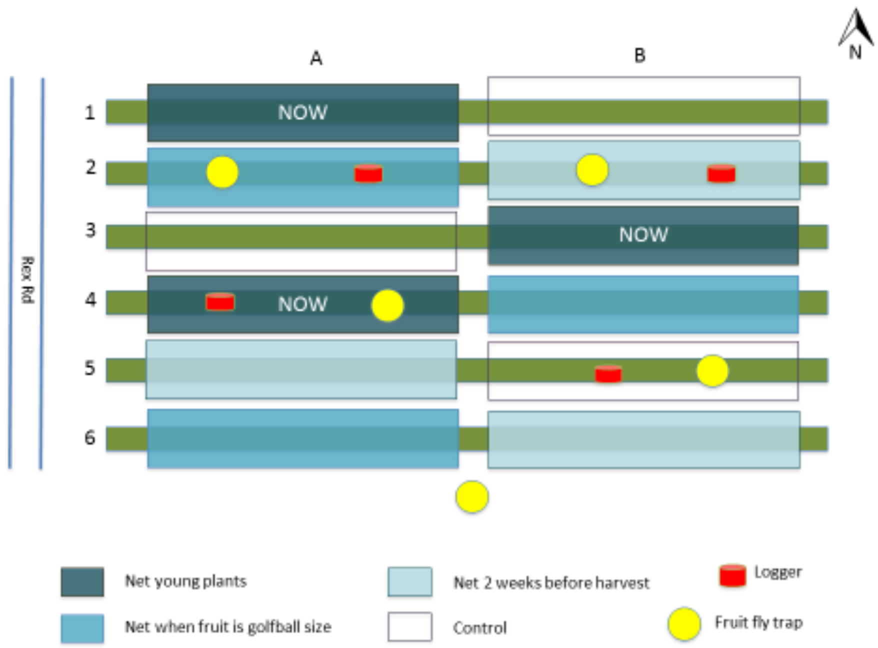


Figure 62. Trial plan for testing the optimum time for application of VegeNet to a capsicum crop in Bundaberg

Figure 63. Size of plants when nets were first installed (left, top), second installation (right, top) and fruit three weeks prior to harvest when final installation was completed (below)

5.3. Results

5.3.1. Silverdale, NSW

Maximum temperatures were slightly raised under VegeNet, which was likely due to reduced air movement around these plants. Minimum temperatures were similar between netted and uncovered plots. Minimum relative humidity tended to be higher under the VegeNet between irrigation events, as the uncovered plots began to dry out.

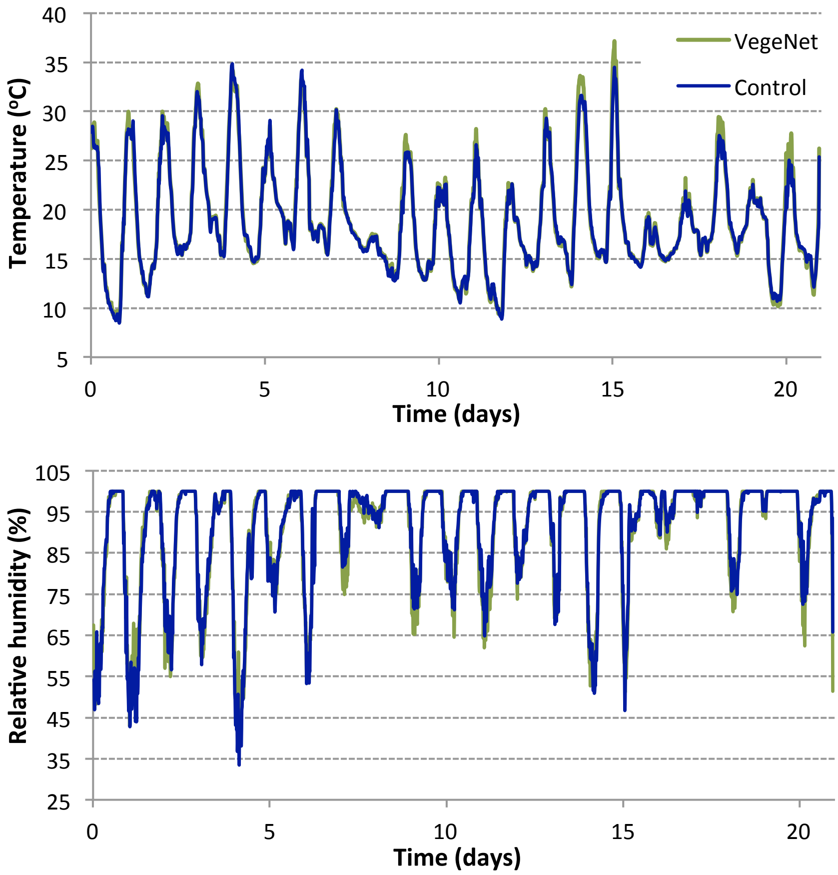


Figure 64. Temperature (top) and relative humidity (below) of capsicums grown under VegeNet or left uncovered (control)

Capsicums grown under VegeNet had a similar total yield to that of the uncovered controls. However marketable yield was 37% higher in plants grown under VegeNet (Figure 65). Common defects that deemed fruit unmarketable included sunburn, deformed fruit, and thrips damage.

VegeNet reduces fruit sunburn by diffusing strong sunlight. The plants were also protected from strong wind under the VegeNet, potentially resulting in less deformed fruit. The netting also helped to protect the plants from insects, both as a physical and as a visual barrier. This may have reduced damage by heliothis and other larger pests, and possibly even smaller insects such as thrips through acting as a visual barrier.

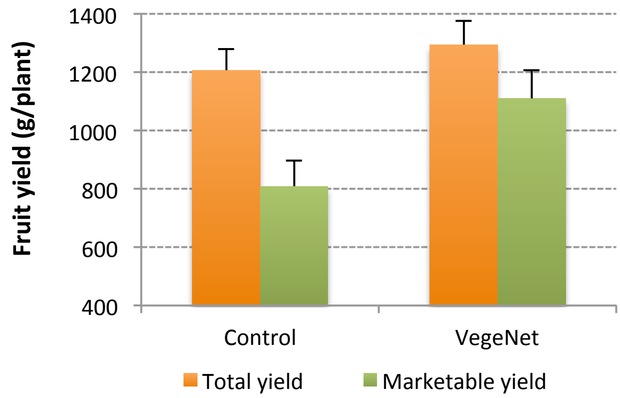


Figure 65. Total and marketable yield of capsicums grown under VegeNet and an uncovered control

5.3.2. Bundaberg, Queensland

Trial 1, Autumn 2015

Temperatures under the VegeNet were generally similar to those in the open field. In some cases night temperature was slightly (~1°C) higher under the net, but this was not always the case. Temperatures under the hoops with Insect Net were also similar to the untreated control at night. However, in this case the netting reduced daytime maximums by up to 5°C. This was particularly apparent during hotter weather (>30°C) and where there was a large swing between day and night extremes.

Perhaps surprisingly, relative humidity (RH) was slightly lower under the VegeNet than in the open field, at least during evening periods. Under the VegeNet it rarely exceeded 95%, whereas in the field, RH approached 100%. While this is a small difference, this could result in a difference in leaf wetness. It seems possible that the netting reduces overnight settling of dew on the crop, which could provide some benefits in terms of disease control.

Results from the sticky traps suggested that there was an increase in the number of thrips under the Insect Net. An average of 52 thrips/trap were recovered from under the hoops compared to 15 thrips/trap from the open field. However, aphids and jassids were found on the sticky traps in the open field whereas none were found on those under the insect net.

Similar results were found in the samples removed by vacuuming. As shown in Table 10 there was a greater diversity of insects in the open field, whereas the Insect Net with hoops system appeared to favour thrips. This may be because of reduced penetration of insecticides, or because the protected environment inside the hoops was more suitable for these pests.

Table 10. Average numbers and types of insects recovered by vacuuming a 5m section of capsicum plants

	Thrips	Whitefly	Aphid	Jassid	Click beetle	Heliothis
Open field	2	7	2	1		
Hoops	5	3				4
VegeNet	3	3			1	

While no measurements were taken to establish plant health, capsicum plants grown under either type of netting appeared to be healthier and stronger than those grown in the open field (Figure 66). The leaves were dark and undamaged, whereas those in the open tended to have curled edges and showed signs of wind / abrasion damage. It was also noticeable that although there were significant numbers of sunburned fruit in the open, none were observed under the netted areas. There were also more signs of healed insect damage in the open field (Figure 67). These benefits may be due to reduction of wind damage (the site was quite exposed and near the coast) as well as filtering of direct sunlight.

Figure 66. Plants grown under netting (left) appeared healthier and more robust than those grown in an open field (right)

Figure 67. Damage observed on plants grown in the open field; sunburned fruit, healed insect damage (weevil) and leaves with dry, curled edges

While total yield was not affected by the netting, there was a significant increase in marketable yield from plants under the VegeNet compared to those from the open field. This was partly due to a reduction in sunburn and other types of damage. Thrips damage was also greatest in the untreated control fruit, while the number of fruit with rots was increased under the InsectNet. Total potential yield was also greatest under the VegeNet, with the total number of fruit increasing from 8.5 to 9.3 per plant.

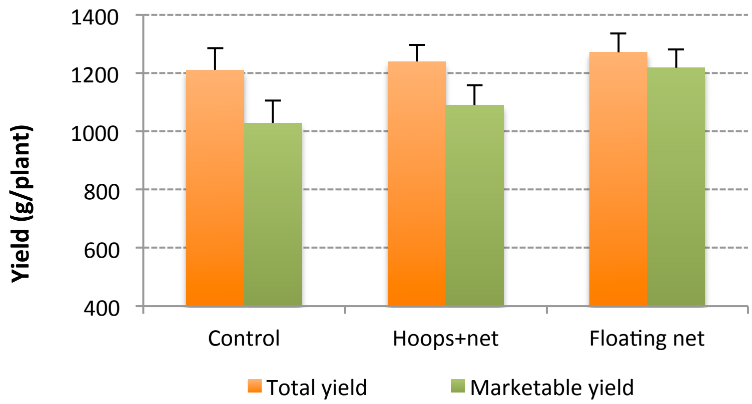


Figure 68. Total yield and marketable yield from capsicum plants grown in the open, under hoops covered with InsectNet and under a floating cover of VegeNet

While this study was limited by reliance on a single harvest (whereas commercially there may be 2 – 4), it appeared that fruit grown under VegeNet matured faster than those from other treatments, with an approximate doubling in the number of red fruit.

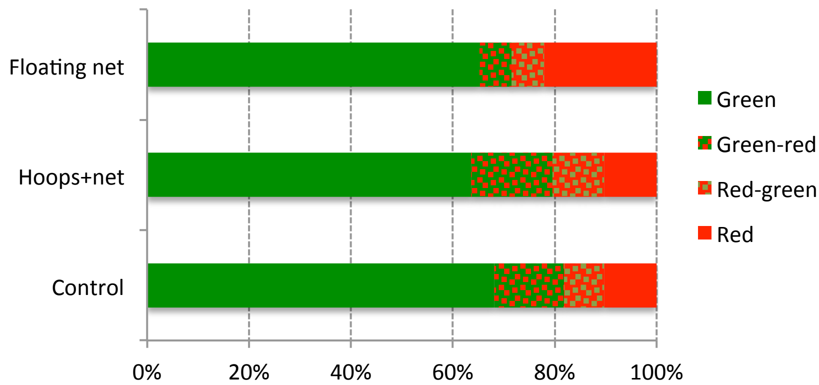


Figure 69. Proportion of harvested capsicums which were green, mostly green, mostly red or red

These results suggest that a floating row cover can improve quality and yield of capsicums. It also seems likely that insecticide and water use could be reduced under this system.

Trial 2, Winter to Spring 2015

Strong winds damaged fleece material, with some pieces completely disintegrating and others with large holes. The material that was least able to withstand the conditions was the 50g/m^2 fleece, which was completely shredded by wind and rain. Perhaps surprisingly, it was the lightest, 18g/m^2 fleece, which remained the most intact at the end of the trial.

Although all of the fleece materials significantly increased plant size (Table 11) only the 18g/m^2 fleece increased the number and total weight of fruit on each plant. It should be noted that at the time of this assessment all 50g/m^2 fleece and one 30g/m^2 fleece had been destroyed by a severe weather event, assessment was conducted approximately two weeks later.

Table 11. Mid season assessment of plants with immature fruit. Letters indicate means which are significantly different ($p<0.05$, n=18)

	Shoot weight (g)		No. of fruit / plant	
Control	295.7	a	6.7	a
50gsm fleece	419.2	b	7.8	a
30gsm fleece	406.2	b	7.6	a
18gsm fleece	419.2	b	10.8	b

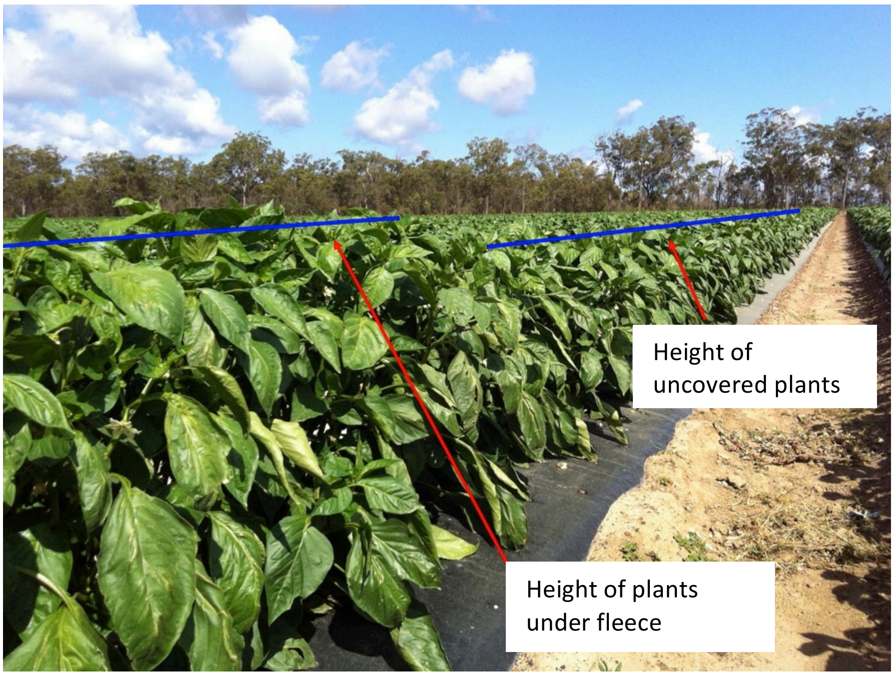


Figure 70. The plants covered by the fleece were noticeably taller than those left uncovered

No further assessments were conducted of the 50g/m^2 treatments as the covers were destroyed. One of the 18g/m^2 and half of a 30g/m^2 treatment were also damaged so as to be partly or fully ineffective.

At the early harvest of green fruit significant differences in fruit yield and quality were again found for the plants protected with 18g/m^2 fleece compared to the uncovered controls. Plants protected with 30g/m^2 fleece were intermediate. The total number of fruit per plant did not vary significantly among the treatments, demonstrating that yield differences were due to larger fruit size on the protected plants.

This difference carried through to commercial maturity. The plants covered with the 18g/m^2 fleece had both significantly more marketable size fruit (>120g) and more high quality fruit than any of the other treatments ($p<0.05$). The number of fruit graded as 3 or less was halved in the 18g/m^2 fleece.

Applying fleece or netting 3 weeks prior to harvest did not improve any of the yield or quality attributes assessed in this trial ($p>0.05$). The number of sunburned or damaged fruit was extremely low regardless of treatment. It appears possible that floating covers applied shortly before harvest could provide greater benefits during the peak of summer, when sunburn is more of an issue for capsicum producers.

Table 12. Early and commercial harvest of capsicum plants with protective covers applied to young plants (cool weather protection) or mature plants (sunburn protection). Letters indicate means which are significantly different ($p<0.05$, n=12 or 18).

	Total yield of fruit (kg)				No. of fruit ≥120g/plant				No. of grade 1 or 2 fruit/plant			
	Early		Mature		Early		Mature		Early		Mature	
Control	1.28	a	1.65	a	5.2	a	7.3	a	2.7	a	4.4	a
18g/m^2 fleece	1.83	b	2.35	b	8.3	b	10.2	b	6.1	b	8.1	b
30g/m^2 fleece	1.54	ab	1.66	a	6.4	ab	6.4	a	4.4	b	4.7	a
Sunburn - control			1.88	ab			7.5	a			4.6	a
Sunburn fleece			1.89	ab			7.7	a			4.5	a
Sunburn - VegeNet			1.95	ab			7.3	a			4.6	a

The number of red or turning fruit was slightly increased under the 18g/m^2 and 30g/m^2 fleece materials (Figure 71). However, results were highly variable between individual plants, so differences were not statistically significant ($p<0.05$). It is likely that maturity was not advanced under the fleece materials due to the higher yield of fruit on these plants.

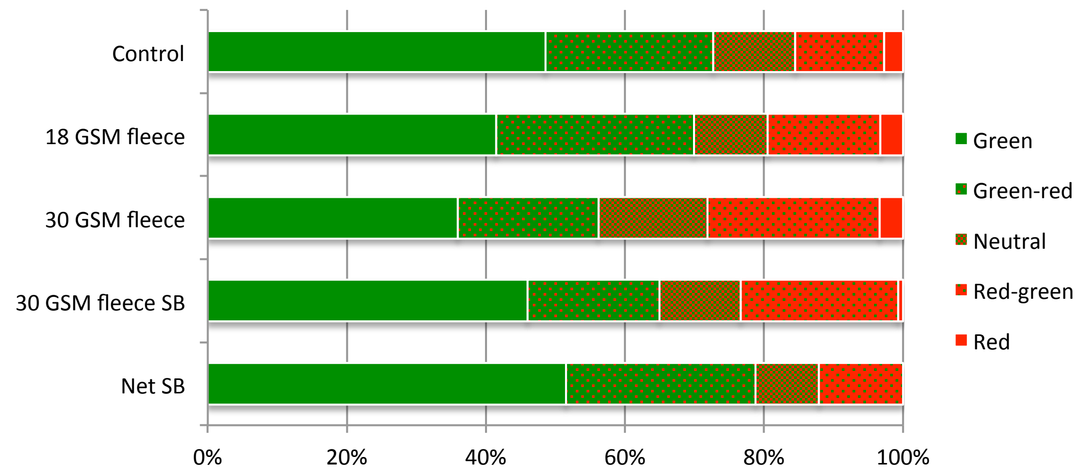


Figure 71. Percentage of the crop classified as green, mostly green, 50/50, mostly red or red from plants protected with fleece or netting early or late (SB) in crop development.

The fleece materials did not advance crop maturity as much as had been hoped. However, there were clear benefits in terms of quality and yield from placing the fleece over the crop. It is interesting to note that the lightest material also provided the best result in terms of yield, although the heavier fleece did increase the number of red fruit.

Trial 3 - Summer 2015

Plants were looking large and healthy until a severe amount of rain and wind hit the site in early January. Unfortunately this resulted in a large amount of fruit falling off the plants, as well as rotting fruit on the plants. However this did provide an opportunity to assess the performance of VegeNet under these conditions.

Temperature and humidity was altered under the netting. When air temperatures were below 35°C, temperatures under the netting were slightly higher than the control, while at temperatures above 35°C the shading effect of the netting kept temperatures lower. Humidity was higher under the netting at low humidity levels, but lower under the netting when humidity was above 75% (Figure 72).

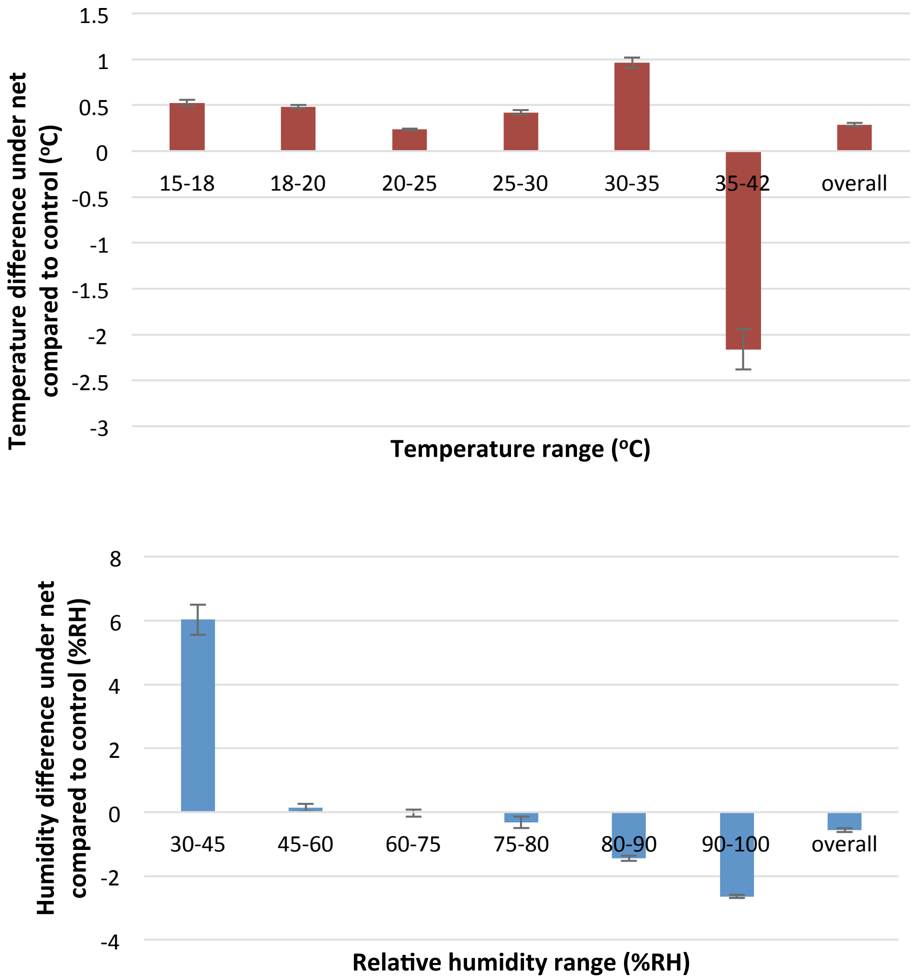


Figure 72. Effect of a floating row cover of VegeNet on temperature and humidity inside a capsicum crop

Fruit maturity was most advanced in plants that were netted the earliest, with 51% of fruit categorised as red, compared to only 34% in the uncovered control. Plants that were netted when older had slightly more red fruit than the control, while netting plants three weeks before harvest did not advance maturity (Figure 73).

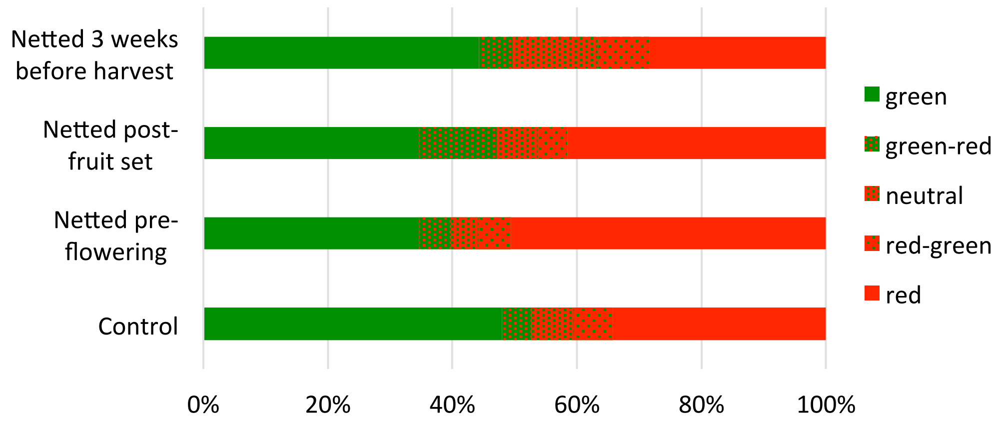


Figure 73. Colour stages of capsicum fruit covered with VegeNet at three different growth stages as compared to an uncovered control.

Total yield was higher in all netted treatments, although this was not statistically significant. Marketable yield was also higher under all VegeNet treatments, however only significantly higher (by 52%) under plants netted post-fruit set (Figure 74).

Individual marketable fruit weight was 17% higher in plants that were netted pre-flowering. There were less rotten fruit on netted plants, and plants that were netted pre-flowering had half the number of rotten fruit compared to the control. Netted plants tended to have more grade 1 fruit, although this was not statistically significant (Table 13).

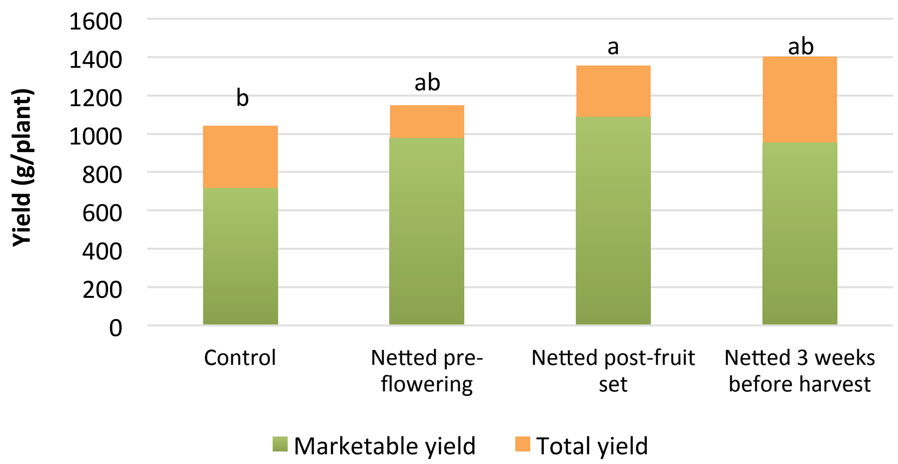


Figure 74. Marketable and total yield of capsicums covered with VegeNet at three different growth stages as compared to an uncovered control. Letters indicate marketable yields that are significantly different (p <0.05). Total yields were not significantly different.

Table 13. Quality parameters of capsicums when covered with VegeNet at three different growth stages as compared to an uncovered control. Means in columns with different letters are significantly different ($p < 0.05$).

	Average marketable fruit weight (g)	Rotten fruit (%)	Grade 1 fruit (%)
Control	177 b	38.1 a	8.5
Netted at flowering	207 a	18.6 b	17.5
Netted after fruit set	187 ab	28.6 ab	17.2
Netted 3 weeks before harvest	179 b	27.1 ab	10.8
			ns

Fruit fly populations in the uncovered control and nearby tree were relatively low in the earlier stages of the trial, but had a major increase towards the end following a wet period. Even under these significant fruit fly populations, plants netted before flowering or at the green fruit stage (young and old plants) were well protected from fruit fly. No fruit fly were trapped under the plants that were netted after fruit set although some were trapped under nets that were put on young plants, possibly as a result of the net becoming unsealed (Figure 75).

When plants were netted only 3 weeks before harvest fruit fly trap numbers remained reasonably constant well after netting application; fruit flies may already have been present in the crop.

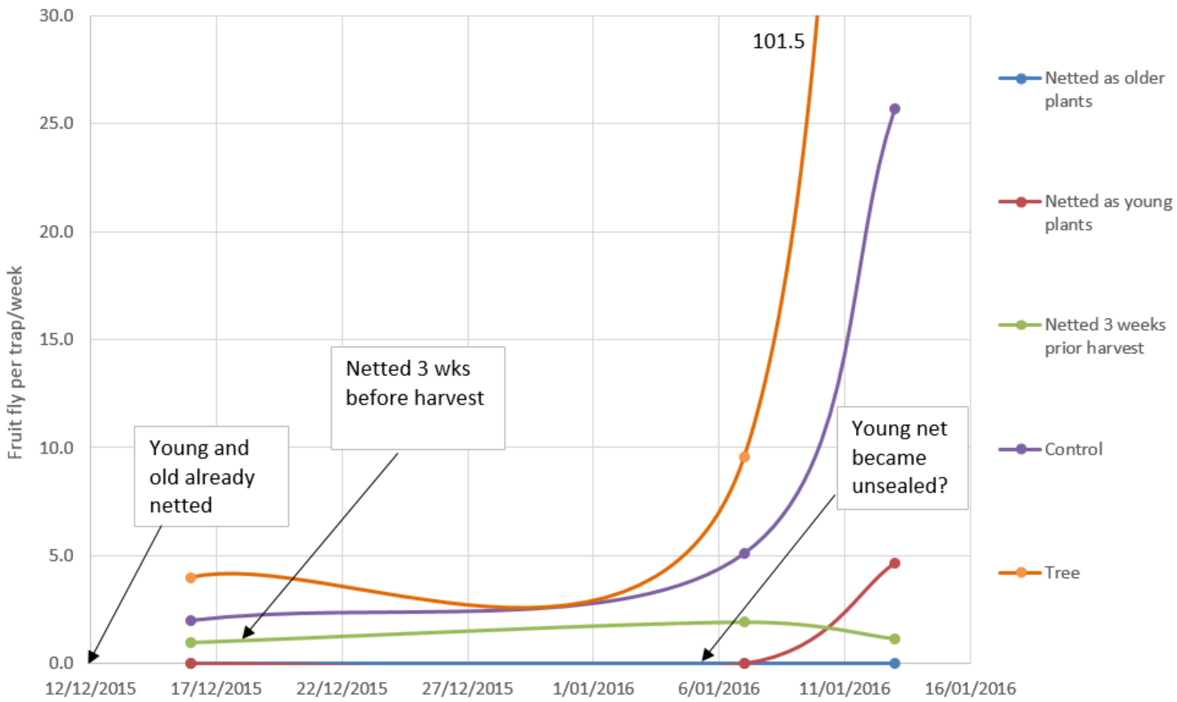


Figure 75. Number of trapped fruit flies in capsicums netted before flowering (young), at the green fruit stage (old) or 3 weeks before harvest compared to an un-netted control and nearby tree.

Application of VegeNet either when plants were just starting to flower or soon after fruit-set advanced fruit maturity and tended to increase average fruit weight and marketability of capsicums grown over the summer. Furthermore, netting applied at or before fruit-set helped to reduce the probability of infestation by fruit fly. Yield, quality and reduced fruit fly pressure benefits were maximised when netting was applied earlier, while little benefit was apparent when VegeNet was applied 3 weeks before harvest.

Fewer rotten fruit were found on plants netted earliest, although it is difficult to attribute this directly to the VegeNet. As these fruit were more mature, any rotten fruit may have detached from the plants before assessment.

5.4. Conclusions

Capsicum plants grown under a floating row cover of VegeNet had improved yield and better fruit quality. Floating row covers reduced the incidence of sunburn and could lower temperatures around the plants during hot weather by providing some shading. The results were best when the row covers were installed when plants were still young, with less significant gains when the covers were installed late in development.

Plant growth was also enhanced under fleece type materials. Although plant maturity was not brought forward by as much as had been hoped, fruit maturity was somewhat advanced under these materials. Durability was an issue, especially under the windy conditions common in Bundaberg.

Although difficult to measure, perhaps one of the most striking effects of both the fleece and the VegeNet was improved plant growth. Plants that were protected from strong light and wind had larger leaves and appeared generally larger and healthier, without the curled leaf edges and sprawling habit of plants that were grown in the open. While this did not always directly result in improved yields, it seems likely that healthy plants will be less susceptible to disease and more resistant to pest attack. By reducing losses of moisture from the soil, plants protected using floating covers are likely to need less irrigation, while all of the covers tested proved effective at deterring one of the most significant pests of capsicums, Queensland fruit fly.

6. Netting for chilli production

6.1. Introduction

Chillies are extremely susceptible to infestation by fruit flies, such as Qfly. The loss of pre- and postharvest chemical controls has left growers with few options for control of this pest. Moreover, growers using integrated pest management (IPM) techniques to control other pests are reluctant to spray insecticides which will disrupt an otherwise well functioning IPM program.

Floating row covers had proven effective at excluding Qfly from capsicums. Moreover, the increases in yield and quality helped justify the cost and labour involved. If similar results can be shown for chillies, which are a relatively high value (although labour intensive) crop, then floating covers may provide a cost effective solution to the Qfly issue. They could also help exclude other pests of chillies, including virus vectors such as aphids.

Trials were therefore conducted in Silverdale, NSW and Bundaberg, Qld, examining the use of floating covers for chilli production.

6.2. Method

6.2.1. Silverdale, NSW

A combination of Cayenne and Birdseye chilli seedlings were planted on 16 November 2015 at a commercial vegetable farm in Silverdale, south-west Sydney. Following the issues with weeds the previous season, the seedlings were planted in single rows through black plastic mulch. Ideally plastic mulch would be combined with drip irrigation. However, as this system was not available plants were irrigated with overhead sprinklers. This proved effective as the soil on site has a high content of clay and organic matter, so excellent water holding capacity.

Establishment was initially slow due to high temperatures stressing the young seedlings. The netting materials were therefore not installed over the crop until 19 January 2016. At this stage plants were flowering, but had not yet set fruit. Three x 20m long sections of VegeNet, Insect Net and Vent Net were draped over the plants in a randomised design (Figure 76) and the edges secured with shovels of soil (Figure 77). A Biotrap fruit fly trap with Cuelure wafer was installed under each section of netting as well as in the control blocks. A temperature and RH datalogger (Hobo, UX100) was placed under one of each of the four treatments, and set to record values every 15 minutes.

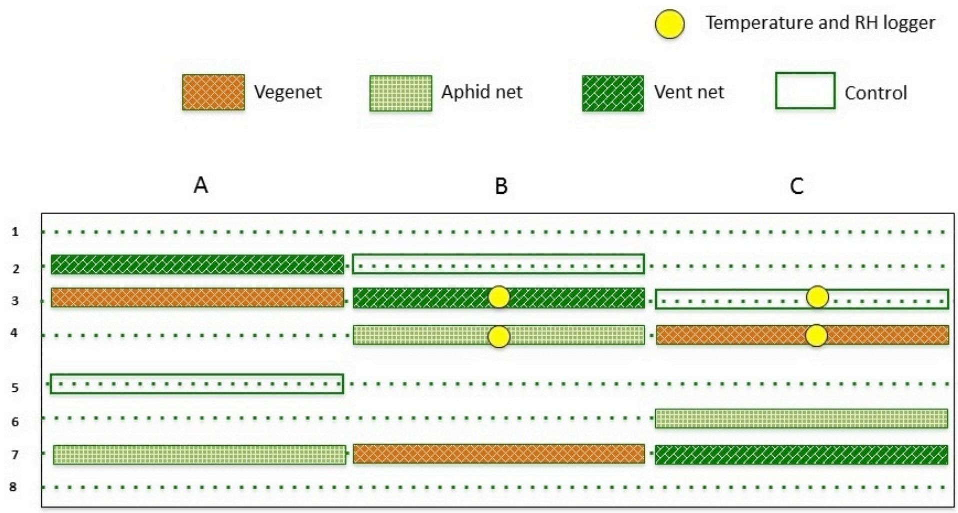


Figure 76. Chilli trial plan in Sydney. Total block length approximately 60m, outer rows used as buffers only.

Figure 77. Aphid net (L, top), VegeNet (R, top), Vent Net (L, below) and a Biotrap located in the crop.

Although Queensland fruit flies (Qfly) are endemic in the area where the trial was conducted, the lack of suitable natural hosts means that populations generally remain low. We therefore conducted a number of inundative releases of Qfly to test whether the netting materials were effective at excluding this pest. The flies were obtained from the Macquarie University Department of Biological Sciences, reared from pupae supplied by the NSW DPI fruit fly colony at Camden. Approximately 2,000 fertile adult (minimum 10 days from pupal emergence) male and female flies were released on four occasions between February and April, 2016.

Catches in the traps were recorded weekly. While each release resulted in a spike in trap catches, by the end of the trial there appeared to be a resident population of flies present in the crop.

Yield and quality of Birdseye and Cayenne chillies were assessed on 18 March and 31 March respectively. Three plants per treatment unit were cut off at ground level and all the fruit stripped from the plant. The fruit were then weighed, sorted by colour and scored for marketability.

6.2.2. Bundaberg, Queensland

Two or three-week old Cayenne chilli plants in a commercial planting in Bundaberg were covered with 10m lengths of either VegeNet or 18g/m^2 fleece on 10 December 2015. In each of the two and three week-old plants there were two replications of each treatment. Temperature and RH were monitored as previously.

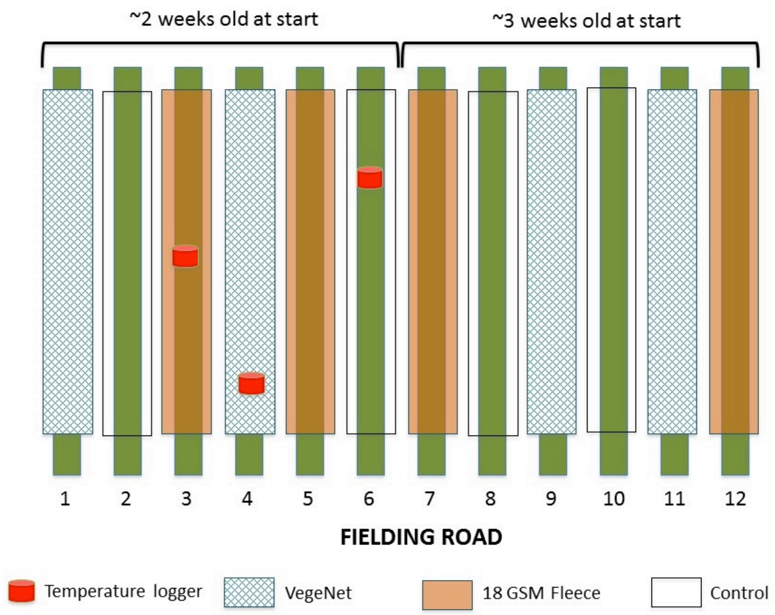


Figure 78. Trial setup for Cayenne chilli plants in Bundaberg

Yield and quality were assessed on 10 February 2016. Six plants from each treatment plot were cut at soil level, with whole shoot weight, fruit weight, fruit colour and other quality attributes recorded.

Figure 79. Trial setup on unsprayed Cayenne chillies in Bundaberg, QLD.

6.3. Results

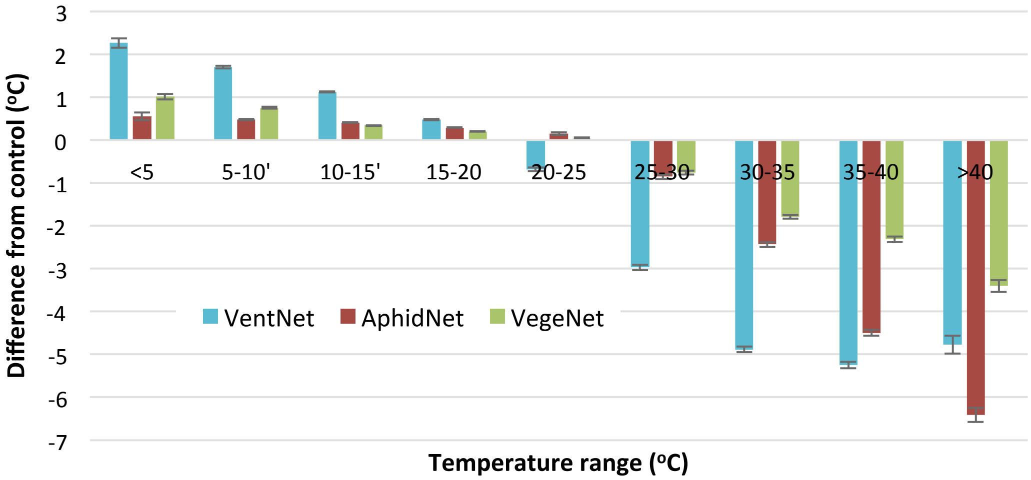
6.3.1. Silverdale, NSW

Temperatures were increased slightly under netting when ambient conditions were 20°C or less. Perhaps surprisingly, this effect was most noticeable under the Vent Net, even though this might be expected to have a higher rate of air movement than the other materials tested. Above 25ºC, temperatures were markedly lower under netting, with Vent Net and Aphid Net reducing temperatures by up to 6ºC. Relative humidity was increased under netting, most notably below 70% RH (Figure 80).

Yield varied considerably between plants. As a result, differences between the netting types were not significant (Figure 81). Differences in fruit maturity were also relatively small, and not significant, although there was a slight trend to increased numbers of red Cayenne chillies in the uncovered controls and Vent Net treatments.

Between 4 February and 27 April a total of 2,963 flies were captured by the three traps located in the uncovered control areas. This compares to 839 flies under the Vent Net, 26 flies under the VegeNet and 7 flies under the Aphid Net. However, 22 of the flies captured by traps under the VegeNet were in a single trap in the last three weeks of the trial. At this time inter-row weeding had damaged the net, and some gaps had been opened up. Over the majority of the fruit production period, only four flies were caught inside the VegeNet material.

Also in the last few weeks of the trial, large aphid populations were found underneath the Aphid Net. This is consistent with previous research, which has indicated that populations of aphids can increase rapidly under permanent nets because the net acts as a physical and visual barrier against predators and parasitoids[16]. These increases were not observed in the larger mesh size materials or in the controls, indicating that natural biological control agents were able to keep the aphids under control under these materials.



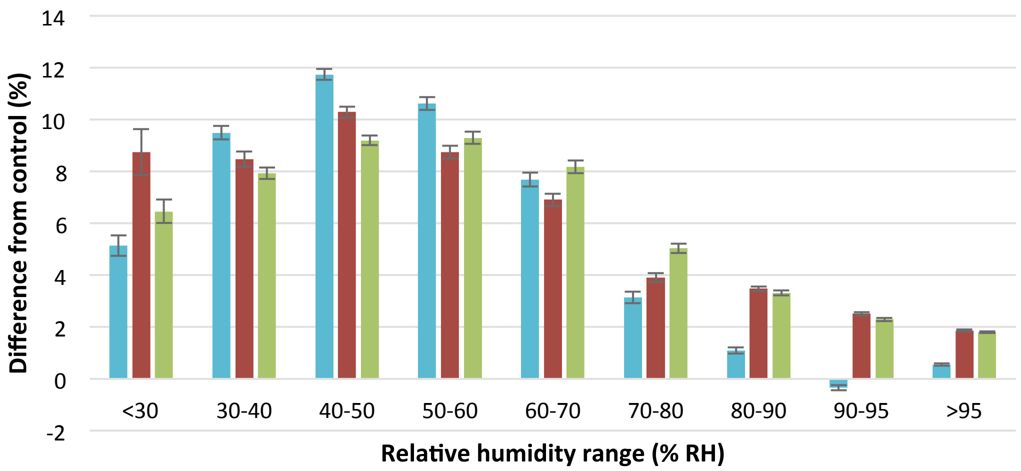


Figure 80. Temperature (top) and RH under different types of netting compared to the uncovered control plots. At temperatures above 25°C the netting cooled the chilli plants, whereas at temperatures below 20°C they provided some slight warming. Relative humidity was higher under the nets than in the ambient environment, especially between 30-70%RH.

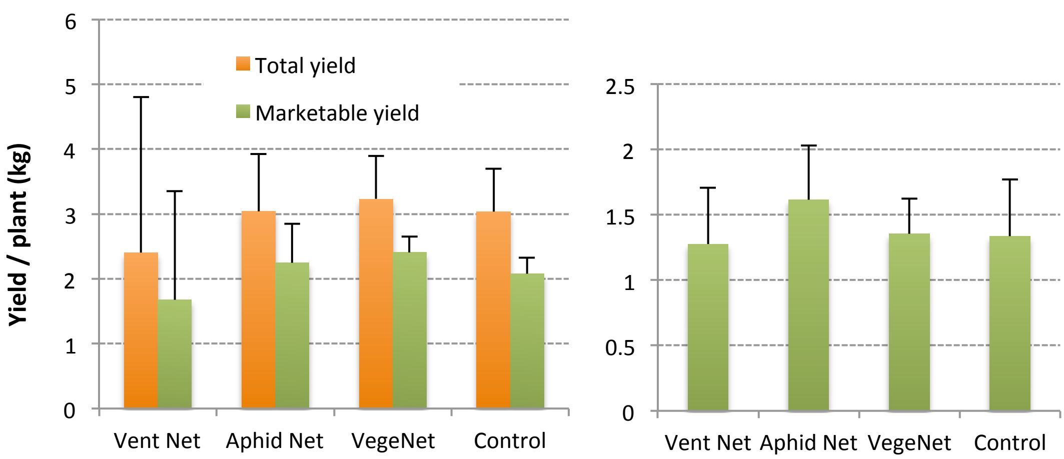


Figure 81. Total and marketable yield per plant of Cayenne chillies (left) and Birdseye chillies (right). Bars indicate the standard deviation of each mean value (n=9)

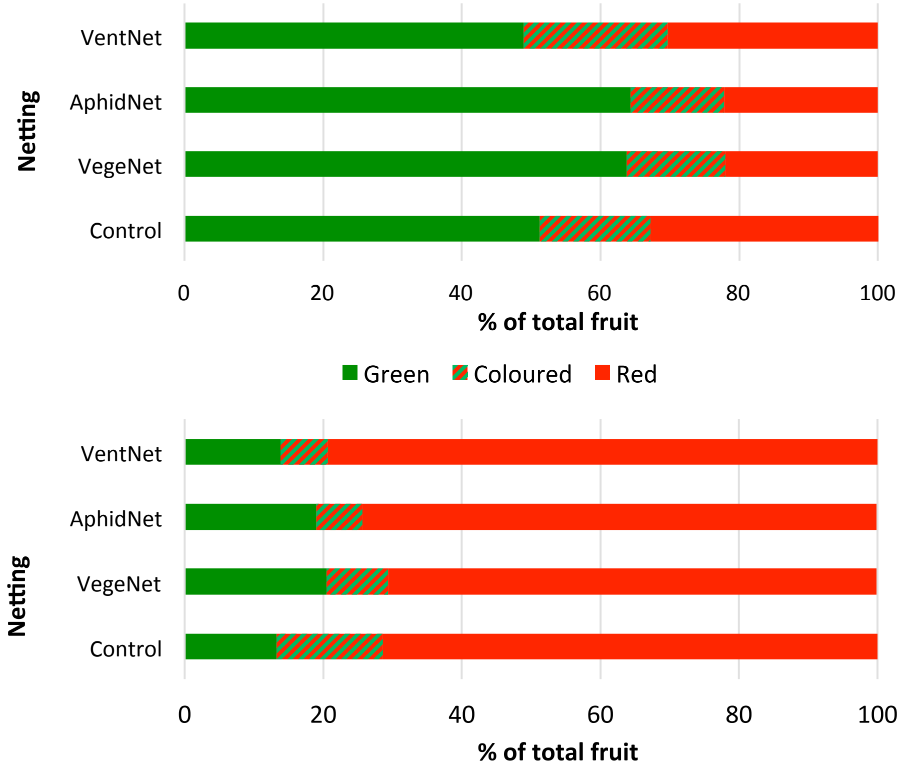
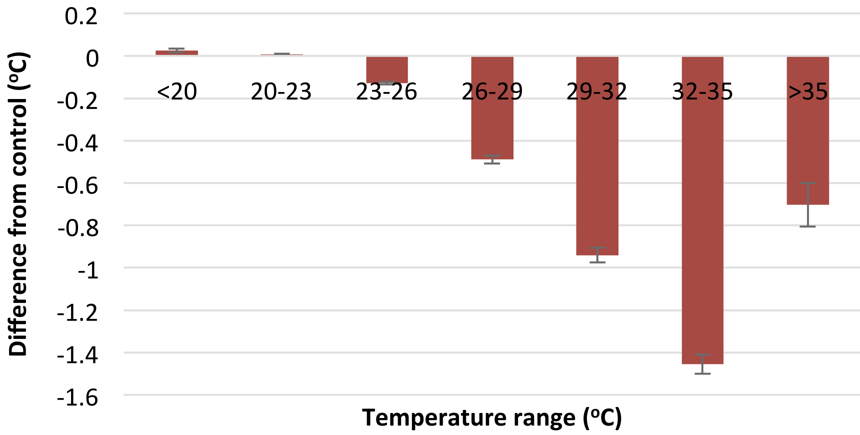


Figure 82. Percentage of Cayenne (top) and Birdseye (below) chillies that were green, red, or partially coloured at yield assessment

Figure 83. Aphids infested the chilli plants that were under the Aphid Net by the end of the trial

6.3.2. Bundaberg, Queensland

The chilli plants grew larger than the capsicum plants that had previously been studied. As a result the fleece material proved too narrow, and could not be effectively secured to the ground. The VegeNet remained on the crop, although it became very tight near the end of the trial. The VegeNet reduced both temperature and RH compared to the uncovered control, particularly when the air was relatively dry or temperatures exceeded 26°C.



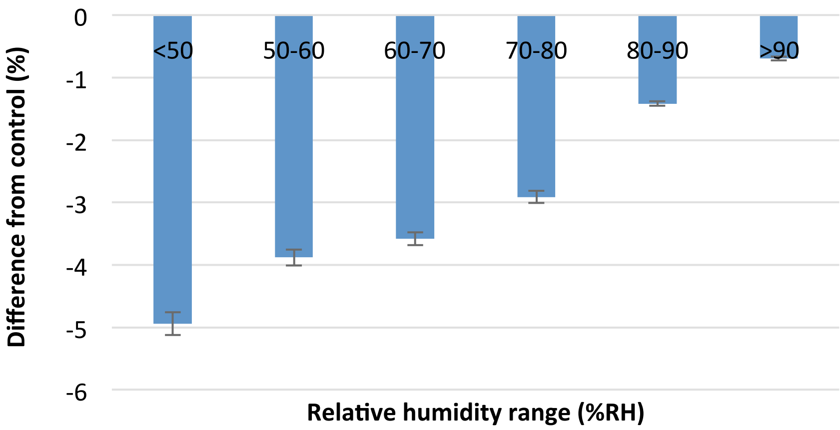


Figure 84. Temperature (top) and RH (below) under VegeNet compared to the uncovered control. At temperatures above 26°C the netting provided shading, while RH was reduced by the netting, especially when humidity generally was low.

Bundaberg was affected by heavy rain during January. More than 300mm of rain fell over only a few weeks, resulting in severe waterlogging of the crop. Large amounts of fruit rotted and fell from the plants. Although yield results suggested that there were more rotten fruit under the VegeNet, and that yield was reduced, the amount of rotten fruit means that this result cannot be reported with confidence. There was also little effect on fruit maturity, with similar percentages of red fruit found in the control and the netted plants.

The chilli plants covered with VegeNet did not perform as well as the uncovered plants. This is different to the results with capsicums, where yield and quality was improved and maturity advanced.

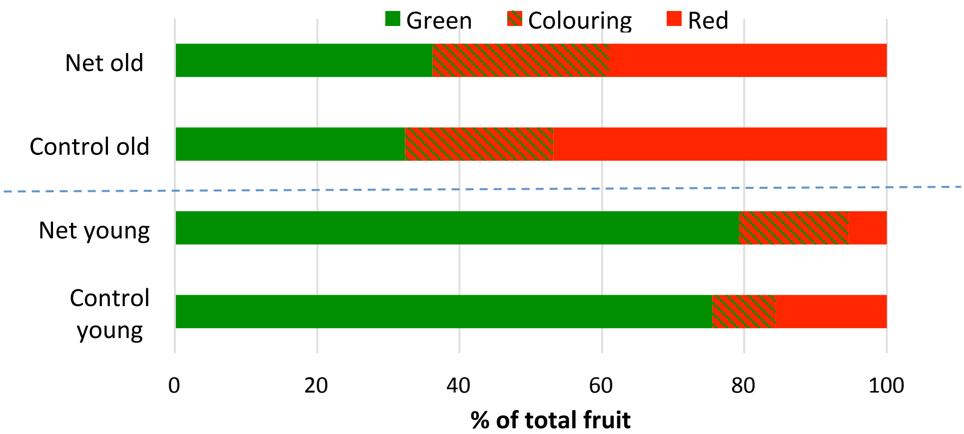


Figure 85. Maturity of chillies at assessment when VegeNet was placed over seedlings planted 2 (young) or 3 (old) weeks prior, compared to uncovered plants (controls)

6.4. Conclusions

Capsicums responded well to floating row covers. Increases in yield and quality were found, as well as reductions in pests and protection from sunburn.

The same effects, however, were not observed for chilli plants protected by fleece or netting. No increases in either yield or quality were observed for Cayenne or Birdseye chillies grown with floating covers. The large size of the plants and more frequent harvests also made use of floating covers more problematic for chili production. The major benefit of using floating covers for chilli plants was protection from fruit fly. This is not insignificant, as control of fruit fly is particularly problematic on chillies, which are an excellent host.

Although the same species as capsicum, there are clear differences in the response to floating covers by these two crops.

Blankets for vegetables

Using frost cloth to protect plants from weather

Integrated Crop Protection
PROTECTING CROPS

Background

Cold winter temperatures are a problem for many vegetable growers. At the least, they reduce growth and yield and extend the time to harvest. However, if temperatures fall below zero the consequences can be devastating. While some crops can recover, for others even a brief period at -1°C or lower can result in total crop loss.

Frost is most likely on calm, clear nights, especially if humidity is low. Under these conditions there are no clouds to reflect heat back to the earth, and no wind to mix the descending cold air with ascending warm air. Temperature changes more quickly when humidity is low, which is why temperatures drop so quickly after sunset in desert areas.

Frost damages plants due to water turning into ice. Formation of ice crystals inside plant tissue ruptures cell membranes, causing the contents to leak out. Even if frost only settles on the surface of the leaf it can draw moisture out, so dehydrating it (Figure 2).

Young, growing foliage is the most susceptible to cold damage. The effects of a frost will be more severe if there was no cold weather to "harden off" – effectively slow down growth – of plants before the cold weather hits.

Stopping plants freezing

The traditional way to stop frost settling was to light 'smudge pots'. Smudge pots burn oil, giving off heat but also smoke, water vapour and other particles. Heat produces air movement by convection, while the smoke forms a kind of 'blanket', insulating the crop.

Orchards and vineyards in frost-susceptible areas sometimes install overhead irrigation systems or wind turbines to protect their crops. Even a small amount of air movement or warmth from irrigation water can prevent cold air pooling and forming a frost.

Another way to protect crops is by using a frost cloth. Home gardeners can use sacking or even a cotton sheet

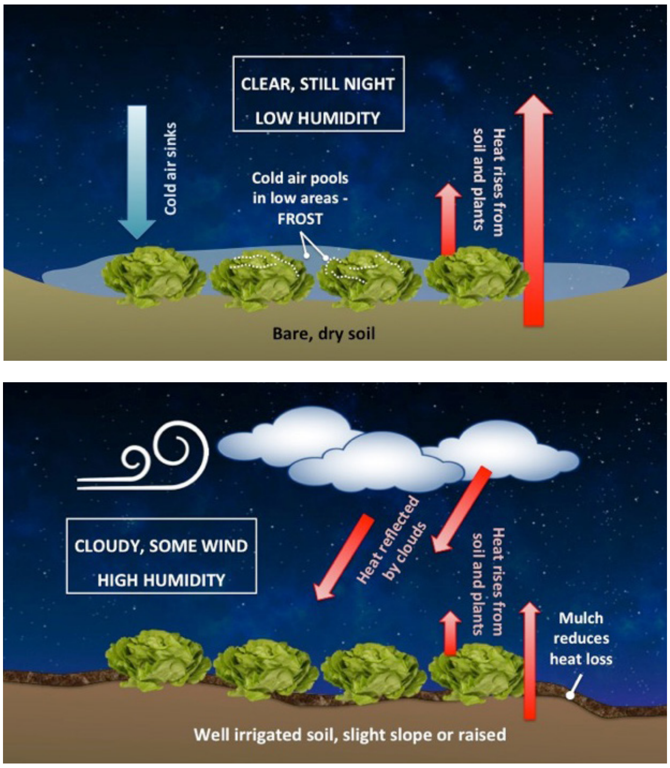


Figure 1. Conditions that make a frost likely (top) and conditions that reduce the chance of frost damaging crops (bottom).

Figure 2. Frost pulls water out of plants (left), while formation of icicles inside the plant tissue break cell membranes, allowing contents leak out (centre). This leaves dark, water-soaked areas on damaged leaves (right).

ICP1/027/1603

This project has been funded by Horticulture Innovation Australia Limited using the vegetable levy and funds from the Australian Government.

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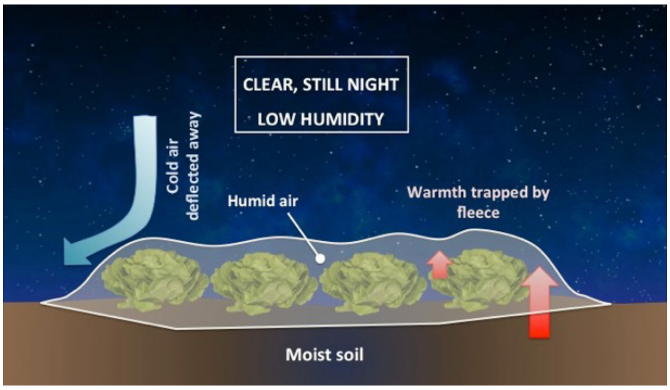

Figure 3. Fleece can prevent frost damage, acting like a blanket over crops.

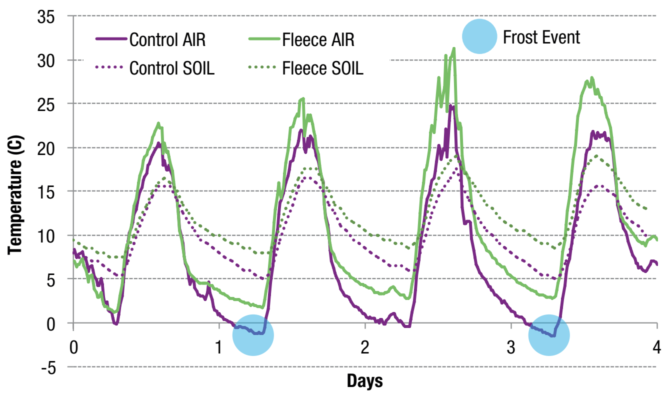

Figure 4. Air and soil temperatures recorded in a vegetable crop protected by 18gsm fleece or left uncovered (control). The fleece increased air temperature by up to 5°C, which was enough to prevent frost damage on days 1 and 3. See explanation of cloth thicknesses (gsm) below.

as a frost cloth, but these have to be removed each morning. Commercial frost cloths are called '**fleece**'. Made of spun bonded polypropylene, fleece remains in place throughout the cropping cycle.

Unlike insect netting, which is a woven material, fleece does not have holes, so presents a continuous barrier to air movement. Fleece therefore acts like a blanket, trapping warmth radiating from the soil, increasing humidity and deflecting sinking columns of cold air (Figure 3).

Keeping plants warm

Fleece can provide benefits even if temperatures stay above freezing because it can raise temperatures in both the soil and the air around plants (Figure 4). Higher temperatures – particularly in the root zone – can increase plant growth rates, especially during colder months.

Table 1 shows average temperature increases under fleece applied directly onto a bed, as it would be to lettuce or babyleaf crops; or draped over a taller crop, such as capsicum plants.

The effect of fleece is most predictable at low temperatures; at temperatures up to 10°C fleece will increase the temperature around the crop by 2–5°C and the soil temperature by 2–3°C.

Under warm conditions the effects are more variable. During a hot day the material can increase air temperatures around the plant by up to 8°C *or* decrease temperature slightly due to shading. The effects vary according to crop, sun strength and wind.

As a general guide, temperature increases under fleece are likely to be halved at particularly windy sites.

AIR TEMPERATURE (°C)	AVERAGE INCREASE UNDER FLEECE (°C)	
	LAID FLAT ON BED	DRAPED OVER PLANTS
-2 – 0	3.0 ± 0.5	ND
0 – 5	2.5 ± 0.5	4.5 ± 1.5
5 – 10	2.0 ± 0.5	4.0 ± 2.5
10 – 15	2.0 ± 1.5	3.0 ± 2.5
15 – 20	3.5 ± 1.5	2.0 ± 2.5
20 – 25	4.5 ± 1.5	2.0 ± 6.0
25 – 30	5.0 ± 2.0	1.5 ± 8.0

SOIL TEMPERATURE (°C)	AVERAGE INCREASE UNDER FLEECE (°C)	
	LAID FLAT ON BED	DRAPED OVER PLANTS
0 – 5	2.0 ± 1.5	ND
5 – 10	2.5 ± 1.5	ND
10 – 15	2.0 ± 1.5	4.0 ± 1.0
15 – 20	1.5 ± 2.0	3.0 ± 2.0
20 – 25	1.0 ± 1.5	2.0 ± 3.5
25 – 30	ND	1.0 ± 4.0

Table 1. Average increases in air and soil temperature gained using fleece laid flat on the bed, e.g. lettuce, or draped over plants, eg capsicum. The ± values indicate the range for 95% of readings.

Protecting plants from weather

Wind causes physical damage as well as pulling moisture out of plants. Fleece is an effective wind-stopper, which is another reason it increases shoot growth. For example, young capsicum plants grown under fleece were 42% larger than those grown in the open. The leaves were larger and appeared cleaner and healthier.

Decreasing air movement around plants and over the soil increases humidity and reduces evaporation (Figure 5). This effectively reduces irrigation requirements, supports even growth and lessens plant stress. If a severe frost does occur, well hydrated plants will be less susceptible to the dehydrating effects of ice crystals on the leaves than plants that are already wilting.

Keeping soil moist after seeding optimises germination, particularly for small seeded crops. Fleece has been shown to increase germination of lettuce when placed over freshly seeded beds.

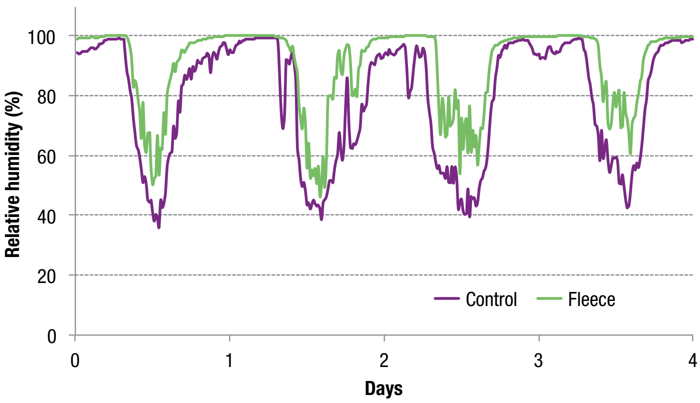

Figure 5. Relative humidity (RH) recorded in a vegetable crop protected by 18gsm fleece or left uncovered (control). During the day, average RH was 12% higher under the fleece compared to the uncovered cropping area.

Which thickness of fleece should I use?

Fleece comes in various thicknesses, ranging from 17g to 50g for 1m^2 (expressed as grams per square metre or gsm). Thinner materials are lighter, cheaper and more translucent. Although very lightweight fabrics tear easily when handled, they offer less wind resistance, so can prove surprisingly durable under windy conditions.

Thickness has little effect on the insulating properties of the material; temperature around the plants is increased due to restriction of air movement, so the thickness of the barrier itself is less important. Heavier materials may increase soil temperatures slightly compared to light materials, but the benefits of increasing the weight of the fleece are small.

When and how do I apply fleece?

Installing fleece early in the cropping cycle will optimise its effectiveness. As the material protects young plants from wind and dehydration, it helps them to establish more quickly.

In Europe, large areas are covered. These materials are rolled off large spools mounted on tractors (Figure 6). They can be retrieved using machines, which tension and roll up the material. Small areas can be installed by hand, although several sets of hands are needed.

There are a number of options for keeping the cloth in place:

- Plastic pegs are a fast way to secure fleece, but are likely to tear the material unless the site is very well protected and the peg is put through a double layer of material. They also add cost and must be retrieved after use
- Sandbags can work well if the material needs to be lifted regularly (eg for weeding), but are heavy and add significant labour
- Shovels of soil every few metres are generally the easiest and cheapest method

Figure 6. Fleece laid over direct seeded lettuce beds (L). Fleece can be laid over large areas using mechanised systems Source: Crop Solutions UK

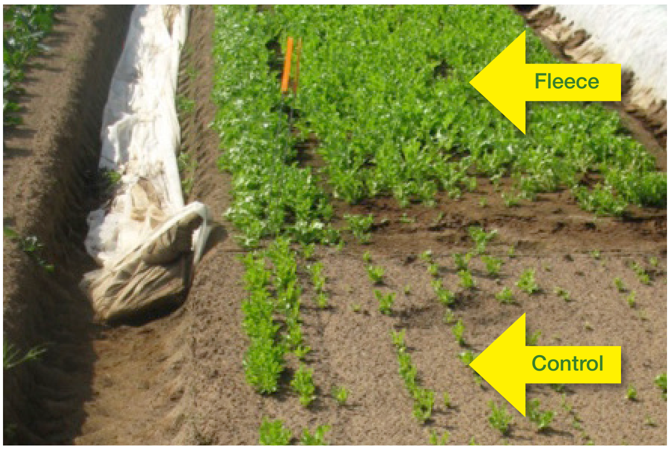

Figure 7. Growth of babyleaf lettuce under fleece compared to the uncovered control. Crop grown during winter in south-west Sydney.

Fleeces are usually removed just before harvest. However, for some leafy crops, it may be better to remove the material a week before harvest. This allows plants to harden up, potentially increasing post-harvest storage life.

In most situations, fleece is single-use because it is too fragile to withstand multiple cropping cycles. Also, recycling fleece could infect a new crop with disease, weed seeds or pests.

The cost of disposing of used fleece therefore needs to be included in any analysis of the cost:benefit of this system.

What are the effects on yield and quality?

If growing conditions are adverse, the effects on yield of babyleaf crops can be dramatic. For example, in one trial in Camden, NSW, a number of frosts occurred during production (Figure 7).

- Germination was greatly increased under all the fleeces tested

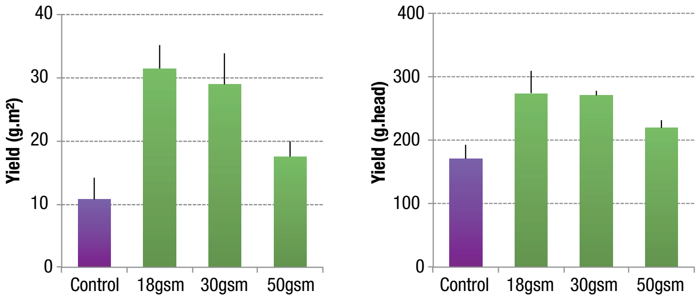

Figure 8. Differences in yield between uncovered (control) lettuce and lettuce grown under different thicknesses of fleece. Multiple frosts occurred in Camden (L), whereas temperatures in Werribee (R) did not drop below 1.6°C.

- Lettuce under the frost protection material was ready for harvest two weeks before the uncovered plots
- Total yield almost tripled

If weather is mild then the benefits of fleece will be less marked, but may still be significant. For example, yield of winter-grown head lettuce in Werribee was increased by almost 60% under fleece, even though night temperatures rarely fell below 4°C (Figure 8).

Applying 18gsm fleece to young capsicum plants in Bundaberg increased yield by 29%. Heavier materials had less effect.

One major additional benefit may be the reduction in pest and non-pest insects. Contamination with insects such as Rutherglen bug and plague soldier beetle can be major issues at certain times of year (Figure 9). A thoroughly secured fleece can exclude such pests, ensuring the harvested product is insect free.

For more information, visit the AHR website at www.ahr.com.au or contact Dr Jenny Ekman on 0407 384 285.

Figure 9. Rutherglen bug infestations can be dealt with effectively by excluding them with barriers such as fleece.

This project has been funded by Horticulture Innovation Australia Limited using the vegetable levy and funds from the Australian Government.

Managing insect contaminants in processed leafy vegetables: A best practice guide

Integrated Crop Protection
PROTECTING CROPS

Introduction

Insects are potential contaminants of processed leafy vegetables. Pest and beneficial species, in both the juvenile and adult stages of their life cycles can become unwanted contaminants if they make their way from the field into the final packaged product and to the end consumer.

This best practice guide summarises the key findings of a project conducted by Applied Horticultural Research and Harvest Fresh Cuts. The focus of this project was to find ways to control contaminants and assess their impact in processed leafy vegetable products.

To determine which insect groups were of most relevance, and how to reduce insect contamination of packaged produce, the project started at the customer level and worked back through the supply chain, examining where information was lacking, and where commercial improvements could be made.

Which insects get the most complaints?

Reviews into historical commercial data from customer complaints about manufactured leafy vegetable mixes found that moths and soldier beetles were the most reported insect contaminant. Insects referred to as moths in the data included Diamondback Moth (*Plutella sp*.), Heliothis (*Helicoverpa sp*.), Cabbage White Butterfly (*Pieris rapae*) and Beet Webworm (*Spoladea mimetica*.) Other insect groups were represented in the data at lower levels. Spiders, Rutherglen bugs, red and blue beetles and beneficials such as lady beetles made up only a small proportion of customer complaints.

Different insect species can show up in customer complaints data, and the regularity at which insect pests appear differs widely between species. The moths group (the order Lepidoptera) includes moths and butterflies. Lepidoptera pests—while seasonal—are quite regular. Soldier beetles, (*Chauliognathus sp.)* on the other hand, are a very sporadic contaminant. Rutherglen bugs (*Nysius sp.)* do not create severe contamination issues unless in plague proportions

Figure 1. Soldier beetle

in the field. Large scale commercial washing and processing lines have the capacity to remove the majority of insect contaminants.

Wanted – Dead or alive

In the factory

The project investigated whether the moths in customer complaints were reported as being dead or alive. Most moth complaints were from consumers reporting the presence of live moths, even though factory product inspection reports showed that both live and dead moths were making it to the factory.

The live moths were more likely to result in customer complaints.

Factory trials recorded the overall removal rate of live and dead moths from the wash line and it was confirmed that dead moths are easier to remove from leafy vegetables in the processing line than live moths.

Figure 2 shows the where insects are removed in the wash line, and how the first and second cleaning drums are much more effective at removing dead moths than live moths.

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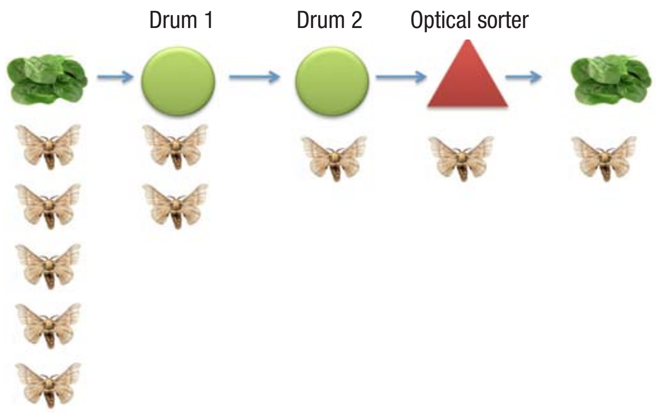


Figure 2: Diagram showing the points in the processing line where insects can be removed.

The first drum removed 42% of the dead moths, but only 15% of the live moths. The second drum removed another 24% of the remaining dead moths but only 13% of the remaining live moths (Figure 3).

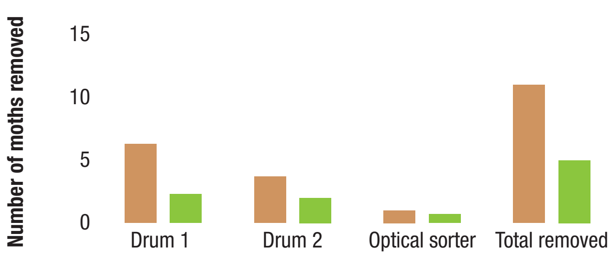
It is clear that a dead insect is much more likely to be removed in the washing process and that live ones are more likely to end up as a customer complaint.

In the field

In Australia the majority of our leafy vegetables are grown in the open field, and it common for pest and beneficial insects to be present in these crops.

There are several ways to reduce the number of insects in a crop:

- Control insects in the crop
- Control insects outside the cropping area
- Make the cropping environment unattractive to insects
- Lure the insect away from the crop



	Drum 1	Drum 2	Optical sorter	Total removed
Dead moths	6.3	3.7	1.0	11.0
Live Moths	2.3	2.0	0.7	5.0

Figure 3. Live and dead moths extracted from baby leaf spinach at various stages of the washing line.

- Exclude insects from the crop using a barrier
- Remove insects at the point of harvest

Remember: Dead insects are easier to remove in the wash line than living insects.

Control insects in the crop

Our single largest group of insect contaminants, the Lepidoptera group, are significant pests in their larval stages of growth in leafy vegetable production. Leafy vegetable producers aim to control these pests in their larval state. However, little consideration is given to the adult moth that lays the egg that becomes the caterpillar that causes the damage. Spray programs target freshly laid eggs and the early larval instar stages.

With the further adoption of more recently developed 'soft' chemistry, fewer broad spectrum insecticides are being used. Investigations examined how effective different groups of chemistry were in controlling adult heliothis moths. Other studies looked at the timing of 'knockdown' sprays in relation to harvest.

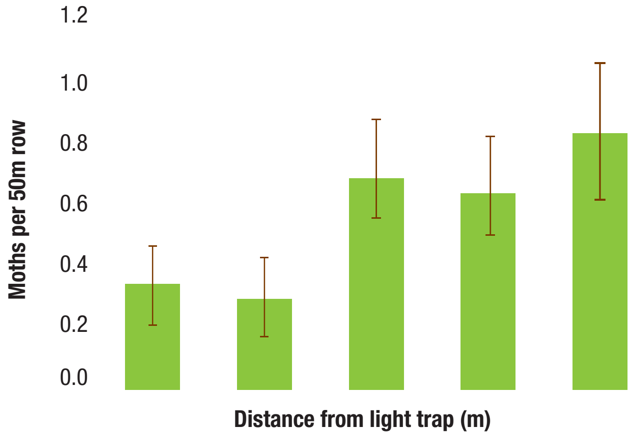
Preliminary trials were conducted on the use of moth attractants mixed with insecticide to lure adult moths to treated parts of the crop or to non-crop areas. The results were encouraging however the appropriate permits or label registrations approvals will need to obtained before these methods can be used.

Make the cropping environment unattractive to insects

Plant based extracts such as chilli were also tested. These products initially appeared to have some impact on target insect species, however in most cases the use of a deterrent such as chilli had little effect. When mixed with natural pyrethroid, the effectiveness of chilli increased slightly. Once overhead irrigation is reapplied almost all effects appear to be lost on species like Rutherglen bug and lady beetles. Overall chilli sprays appear to have little effect on adult Lepidoptera species.

Lure the insect away from the crop

The Vortex insect trapping system was trialled over two seasons with very good results. In a small cropping situation this device was able to greatly reduce moth numbers in baby leaf spinach up to 50m from the trap. Figure 4 show the light trap and its effect on the number of Heliothis moths found in spinach crops. For more information visit http://www.vortexics.com.au/insects.htm



	5	50	100	150	250
Heliothis	0.35	0.3	0.7	0.65	0.85

Figure 4. Vortex light trap and impact of the light trap on moth numbers in a baby leaf spinach crop in SE Qld.

Exclude insects from the crop using a barrier

The project investigated the use of floating row covers to exclude insects. There are many different styles of cover and their effectiveness in excluding most insect species was very high. There are agronomic challenges to consider if row covers are to be used as a control option as floating row covers perform other functions, with insect control an additional benefit.

Figure 5 shows that floating row covers can be very effective in keeping both beet webworm and Rutherglen bugs out of baby leaf spinach crops. They were less effective on lady beetles. It was observed that some beneficial eggs were laid on the row cover itself and the very small juvenile lady beetles may have found a way through the row cover after hatching (Figure 6).

Readers are also directed to a separate study which evaluated the use of floating row covers for the production of babyleaf lettuce[1].

Figure 5. Floating row covers.

1 The production of baby-leaf lettuce under floating crop covers. Horticulture Australia project number VG09188 (2013)

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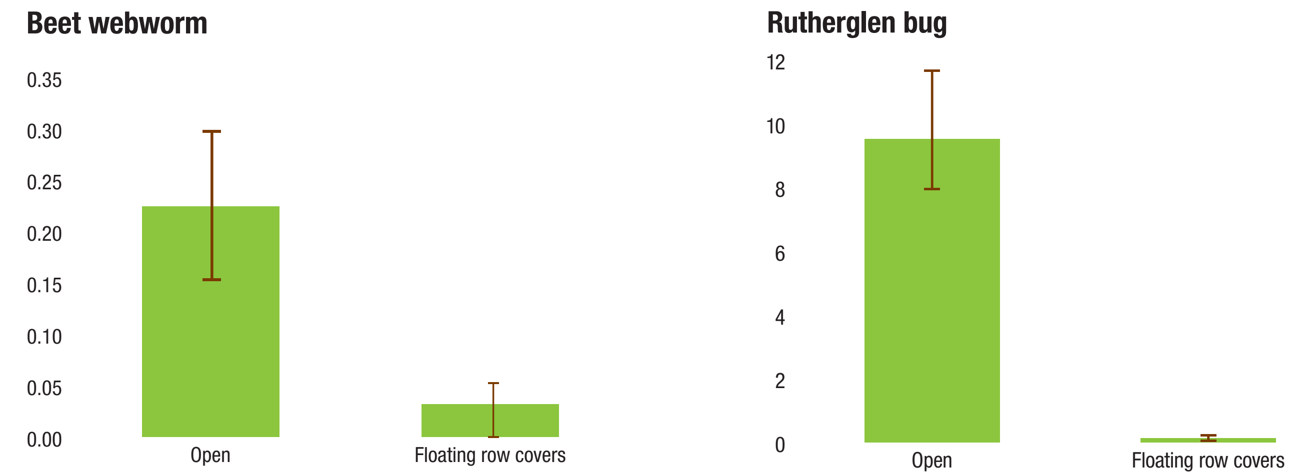


Figure 6. The effect of floating row covers in the numbers of live Rutherglen bug and Beet webworms in Spinach, Stanthorpe, Qld.

Remove insects at the point of harvest

The harvester modifications have shown promising results in field trials carried out as part of this project. The modification evaluated were:

- Fans at the front of the tractor to blow insects out of the crop just before it is harvested.
- Chains attached to the front of the harvester and dragged through the crop to dislodge insects (Figure 7).
- A perforated conveyer belt, which carries the harvested product from the cutters. The perforations allow foreign material such as insects to fall through the holes.

Trials showed that modifications worked best when they were all used together, i.e. fans + chains + the perforated belt. They were especially effective at reducing Rutherglen bug numbers in harvested baby leaf spinach. Used in combination, the modifications were able to reduce overall insect contaminate levels in spinach (Figure 8).

Figure 7. Chains in front of the harvester to dislodge insects

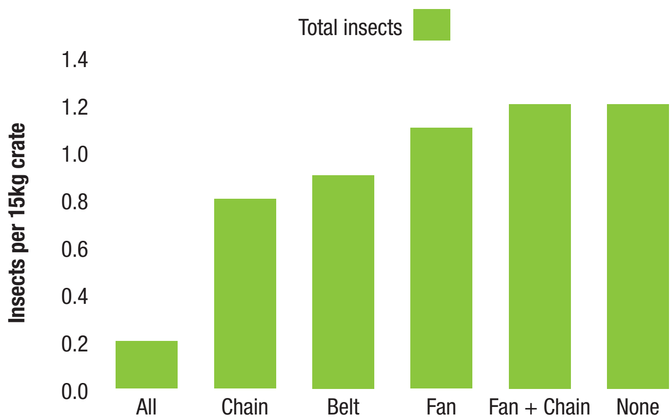


Figure 8. Effect of harvester modification on the level of insect contaminants in spinach, February 2013. The insects reported included Rutherglen Bug, flies and beetles.

For more information, visit the AHR website at www.ahr.com.au or contact Brad Giggins on 0427 014 990

This project has been funded by Horticulture Innovation Australia Limited with co-investment from Harvest Freshcuts Pty Ltd and Applied Horticultural Research and funds from the Australian Government.

Thursday 22nd October 2:30-5:30pm

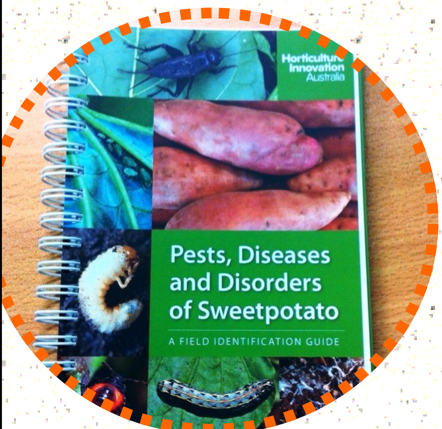
Quarterly Bundaberg Agronomic Group Meeting

Venue:

<u>Spotted Dog Tavern</u>

Bourbong Street, Bundaberg

This is our final meeting for the year so please stay around for networking drinks and wood fired pizza following the meeting



Speakers:

Dr Paul Horne IPM Technologies
Control of invertebrate pests
Insecticide resistance issues
Training opportunities for next meeting

Jenny Ekman Applied Horticulture Research
Trial update on floating covers
Controlling internal rot in capsicums
Field Pest ID Guides

Please RSVP to the BFVG Office on 07 41533 007, email bree.grima@bfvg.com.au or click 'join' in your calendar request. We look forward to seeing you there.

Bundaberg Fruit & Vegetable Growers

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Integrated Crop Protection Information Session

Integrated Crop Protection
PROTECTING CROPS

Get the latest information and advice on controlling insect pests in vegetable crops

Controlling insect pests in vegetable crops is always an issue for farmers and advisors. The problem pests are similar each season but how to control them is not always the same. Insecticide resistance management is something to be considered carefully and using all the available cultural controls is something that is often overlooked. Preparing well for the coming season can help to avoid problems rather than try to solve them during the life of the crop.

Speakers include:

- **Dr Paul Horne**, Director / Entomologist, IPM Technologies Pty Ltd on preparing for the season ahead
- **Brad Giggins,** Director, Total Horticultural Consulting on improving the management of insect contaminants in processed leafy vegetables.

Hurry places are limited

Contact Lynn Christie at **lynn@ahr.com.au** or call **02 9527 0826** to attend.

Further information

Please contact Anne-Maree Boland **03 9882 2670** or Gordon Rogers **0418 517 777**

Details

Date: **2 October 2015**

Time: **4:30 – 6:30pm**

Place: **Wanneroo Villa Tavern**
18 Dundebar Rd
Wanneroo WA 6065

Free refreshments and parking provided.

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Further information

Please contact Anne-Maree Boland **03 9882 2670** or Gordon Rogers **0418 517 777**

Details

Date: **Wednesday 9 September 2015**

Time: **2:00 – 4:00pm**

Place: **Lindenow Hotel**
(Farmers Home Hotel)
167 Main Rd, Lindenow VIC 3865

Refreshments provided

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Details

Date: Friday 11 September 2015

Time: 2:00 – 4:00pm

Place: Bear House Restaurant
110 Sladen St
Cranbourne VIC 3977

Refreshments provided

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Integrated Crop Protection Information Session

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PROTECTING CROPS

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Speakers include:

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- **Brad Giggins,** Director, Total Horticultural Consulting on improving the management of insect contaminants in processed leafy vegetables.

Details

Date: 26th August 2015

Time: 3pm – 5pm

Place: Gatton Research Station, Warrego Highway, Lawes, 4343

Free BBQ tea and parking provided

Hurry places are limited

Contact Lynn Christie at **lynn@ahr.com.au** or call **02 9527 0826** to attend.

Further information

Please contact Anne-Maree Boland **03 9882 2670** or Gordon Rogers **0418 517 777**

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Soil Wealth
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NSW GOVERNMENT Local Land Services Greater Sydney

SOIL WEALTH FARM WALK

Thursday
28 April 2016
2:00 pm – 4:00 pm

You are invited to a vegetable farm walk hosted by Ed and James Fagan at Cowra, NSW.

AHR invite you to a talk and farm walk focusing on the use of cover crops in vegetable production to improve soil health and grow better crops.

The afternoon will start with a talk summarising what the Soil Wealth team has learnt about cover crops through working together with leading growers and advisors across the 12 demonstration sites — www.soilwealth.com.au/demo-sites **Meet at DPI Agriculture Research Station, 296 Binni Creek Road at 1:45pm**

Using examples from the demo sites we will share how cover crops have impacted on crop yield and quality and practical lessons on integrating cover crops into vegetable production (when and how), managing the transition from cover to cash crop, specialised cover crops (eg biofumigants), and pest and disease considerations.

The talk will be followed by a farm walk at the Cowra Demo site to look and discuss:

- Tillage radish
- A range of cover crops and mixes
- Nitrogen management and cover crops
- What's new in irrigation, technology and practice
- Blankets for vegetables — frost and insect protection

Demonstration Site Hosts
Ed and James Fagan, Cowra NSW
'Mulyan' North Logan Road, Cowra

You can watch the site "live" on Facebook at 'Soil Wealth Cowra'. Afternoon refreshments provided.
To RSVP please send your details to Marc Hinderager at **marc@ahr.com.au** or on **0409 082 012**

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Australian Government

Horticulture Innovation Australia