Final Report

Protected Cropping – Review of Research and Identification of R&D Gaps for Levied Vegetables

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Content

Summary

The Sector

Australia has a modest vegetable protected cropping industry. Estimates of vegetable production under protected cropping vary from 498 – 1,300 ha, with tomatoes accounting for about half the area. Low- to medium-technology structures are most common, with high technology structures increasing in recent years to meet specific market requirements. Soilless growing media is increasingly dominating the sector.

There is a large and rapidly growing international protected cropping and hydroponics research knowledge base. Australian research has contributed about 4% to this research knowledge base. A key object of any Australian protected cropping R&D investment should be to ensure that there is capacity in Australia to interpret and adapt the large international research knowledge base to local conditions.

The Review

This review is structured around four broad areas: Productivity, Technology, Plant Protection and Environment. Three questions were used to focus the review; 1. How specific is the issue/R&D area to protected cropping? 2. At what stage is the R&D area? and 3. Is international R&D relevant to the Australian protected cropping issue/R&D area?

Overall, a clear strategic research gap was identified by the review. Australia has a very high radiation load across much of the country. Radiation loads impact on the light and heat levels experience by crops in protected cropping. With much of the international research undertaken at far lower radiation levels, sometimes half that commonly experienced in Australia, this will limit the direct transfer of international research and technology. Some research is therefore required to understand and manage protected cropping systems under these high radiation loads.

Research gaps across all levels of protected cropping

To have the greatest relevance, research gaps need to be applicable to crops grown in low- medium- and high-tech protective structures. Of the potential research gaps identified the following areas have some relevance across all three levels of structures;

- Light levels and condition,
- Root zone management
- Biostimulates
- Pollination
- Real time monitoring of plant conditions
- Biological suppression of root pathogens

To deliver improved farm productivity and profitability, the six research gaps identified need to be integrated. Optimising the production systems, or designing new approaches will increasingly rely on the integration of crop physiology, control technology and plant protection models. Building industry capability to achieved this should be built into projects.

High-tech protected cropping research and development opportunities

There are three R&D areas relevant to high-tech protected cropping;

- Atmospheric manipulation
- Robotics and automation
- Energy

It is likely that the Australian high-tech protected cropping industry will rely on importing much of the above technologies. However, linkages with existing projects will help ensure that there is an Australian R&D capability which can assist developing technology relevant to Australian conditions. For example, two major research projects are currently addressing Australia's high radiation loads through smart glass technologies.

Environmental performance of the protected cropping sector

The protected cropping sector currently faces no major environmental issues around its "social licence to operate". In the longer-term pressure may come on industry from two areas; 1. water use, and 2. greenhouse gas emissions. Already there is some suggestion that water availability around cities is an issue. With this in mind, some ongoing effort into monitoring and improving the performance in these areas may be worth considering.

Extension of existing protected cropping knowledge

In collating the previous and current industry funded projects (Appendix 2) it is evident that a substantial body of Australian information exists, which has some relevance to the protected cropping sector. Consideration should be given to summarising this information, along with the international R&D knowledge, and delivering this through the Soil Wealth-ICP, VegNet and VegPro pathways. This may require additional resources to develop technical extension materials.

Keywords

protected cropping, hydroponics, capsicums, eggplants, cucumbers, light, solar radiation, solar glass, light-emitting diode, root zone, atmosphere, temperature, humidity, carbon dioxide, biostimulate, suppression, pathogens, robotics, energy, heating, cooling, pollination, plant protection, integrated pest management, integration, crop physiology, social licence, water,

Background

Protected Cropping in Australia – a brief history

The development of protected cropping in Australia has lagged much of the world due to Australia's wide range of growing environments and ability to grow "out-of-season" vegetables under field conditions. Initially, low technology plastic film based structures were used (Frodsham 2010).

The conversion from soil to hydroponics in protective cropping was the first major "upgrade" in many areas. This was driven by the prevalence of soilborne diseases and poor soil condition under the intensively cropped protective structures.

Climate control technology initially involved ventilation and cooling, with naturally ventilated structures and fogging, proving to be very effective in modifying the high temperatures experienced in many regions (Connellan, 2002).

More recently, there have been the development of high technology protected cropping structures to meet specific market requirements for continuity of supply of some key fresh product lines such as tomatoes.

Estimates of the vegetable protected cropping area varies. The international specialists in greenhouse vegetable production, Cuesta Roble Consulting provide lower estimates of area (2015-16; 498 ha, Hickman 2017) than local estimates which vary from 1,228 ha (Table 1; Biggs 2004) – 1,341 ha (PCA 2017).

Table 1. Estimated Greenhouse Vegetable Production (from Biggs, 2004).

Crop	NSW	SA	VIC	QLD	WA	NT	TAS	Total
Tomatoes	300	320		7	5		9	641
Cucumbers	165			13			0.3	178
Capsicums							0.4	0.4
Area (ha)	450	520	200	32	16		10	1,228

Crops grown under protective cropping

Most low and medium technology protected cropping systems produce cucumbers, zucchini, capsicums, egg plants, lettuces, Asian greens and herbs. However, tomatoes are the dominant crop grown under protected cropping (Table 2).

Table 2. Changes in the main vegetable crops grown in Australia under cover (Hickman 2017).

Under Cover crop area (ha)				% change
Crop	2007-08	2014-15	2015-16	2008 to 2016
Capsicum	151	149	172	+14%
Lettuce	125	52	75	-40%
Tomato	193	196	251	+30%
Total Area (ha)	469	397	498	+6%

The recent increases in protected cropping have largely been driven by the demands placed on growers to reliably meet high volume contracts and quality measures (Flores 2013). Technological developments tend to be skewed towards larger players that can afford to invest in research and development.

Australia's reliance on the international literature

This document draws on key publications from both the hydroponics and protected cropping literature. There is a large public international R&D knowledge base, which has increased rapidly since 2000 (Figure 1), with USA dominating the number of hydroponics publications. A similar trend is observed in the number of publications on protected cropping.

Australia has contributed less than 4% of publications over this period. A key object of any R&D investment should be to ensure that there is capacity in Australia to interpret the international literature and to adapt this to local conditions.

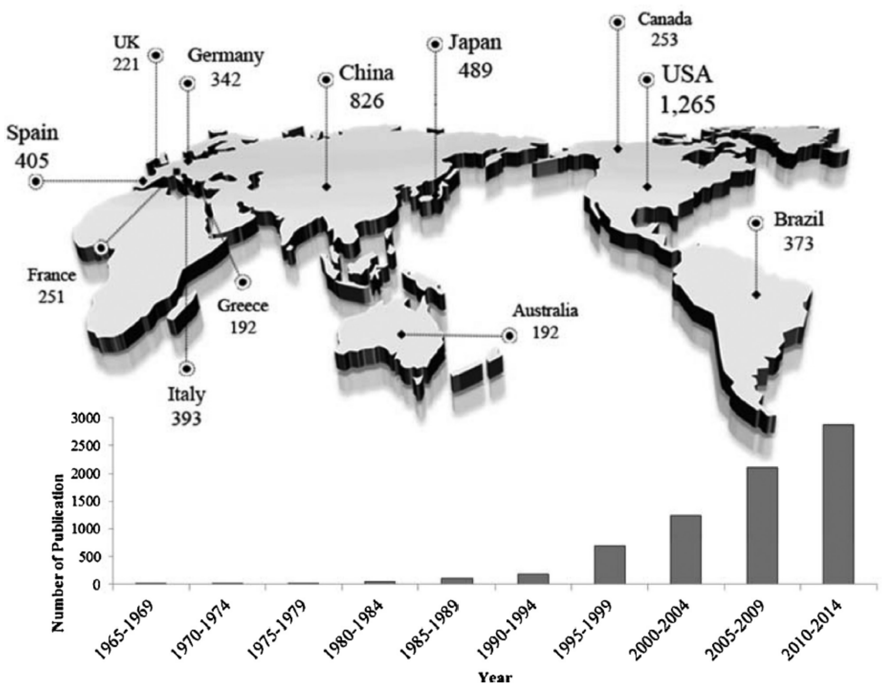

Figure 1. Hydroponic publication by country and over time clearly showing the increase in hydroponic publications. (From Lee & Lee 2015)

Scope and initial ranking of R&D areas

This review is based on current R&D knowledge and seeks to identify gaps based on the following terms of reference. "A review of the published protected cropping literature relevant to the levy paying vegetable crops will be undertaken. The review will cover the Australian and international literature. While the review will focus on the levy paying vegetables outlined above, trends in protected cropping of non-levy paying crops (e.g. tomatoes, fruit crops and floriculture) will be examined to gain insights into future directions in protected cropping of levied vegetable crops."

The ranking of R&D areas was based on the R&D knowledge rather than an assessment of industry priorities.

An initial assessment was made of research topic areas based on the three questions below. This focussed the review on areas which were most relevant to crops grown under protected cropping, where new developments were occurring, and where a local environment, market or legislative conditions required specific research.

How specific is the issue/R&D area to protected cropping?

1. Common across many industries e.g. automation, robotics,
2. Common across crops grown either in the field or under protected cropping,
3. Relevant only to crops grown under protected cropping.

At what stage is the R&D topic?

1. Mature incremental improvements in well-established area
2. "hot topic" area with rapid advances possible from the application of the new knowledge/tools
3. Blue sky emerging area.

Is international R&D relevant to the Australian protected cropping issue/R&D area?

1. International research can be directly transferred with minimal changes required
2. International R&D requires adapting to local conditions
3. Local environmental, market or legislative conditions mean only local R&D will be relevant,

The priority R&D topics are summarised in Table 3. The full list of R&D topics considered, and rankings are provided in Appendix 1.

Table 3. Priority R&D areas based on relevance to crops grown under protected cropping, where new developments were occurring, and where a local environment, market or legislative conditions required specific research.

Productivity	Infrastructure, engineering & technology	Plant protection	Environmental impacts
Lighting levels and condition	Covering material	Integrated pest management	Water
Atmospheric manipulation	Robotics and automation	Biological suppression of root pathogens	Greenhouse gas emissions
Root zone management	Energy	Market Access	Nutrients
Biostimulates			
Pollination			
Real time monitoring of plant condition			

"The whole is greater than the sum of its parts."

Protected cropping is about control. At the high-tech end of the industry this amounts to almost total control over the plants growing environment, from the root zone through to the atmosphere. The level of control, particularly of the atmosphere, decreases for medium- and low-tech protected cropping structures.

Control of the growing environment brings with it the ability to optimise climate conditions and plant properties to deliver improved productivity and profitability. For example, in the Netherlands over the last 25 years productivity (kg per m^2 of glasshouse) has increased by 90 and 35% for sweet peppers and cucumbers, respectively (Marcelis et al 2014).

To realise improvements the advances in crop physiology and control technology need to be integrated. Optimising of a single element of crop management or climate control will not deliver the productivity improvements.

Instead the "whole" will require linking crop models, which are increasingly available for vegetable crops, with environmental control systems, to drive the productivity and profitability increases of the future.

This gap analysis identifies specific key areas for potential R&D investment (Table 3). The protected cropping R&D program should also ensure linkages are built between localised crop physiology models and control technology and continuous monitoring systems. Such capacity and frameworks can;

- help identify where future research can deliver the best returns for both technological and crop physiological aspects.
- optimise existing production systems.
- help design new production approaches or crop structures.

Productivity

Light levels and condition

Australia receives very high levels of solar radiation (Figure 2). As a result, both light levels and heat load can be very high, even in southern Australia. This differs from many other areas where protected cropping production and research occurs. Specific Australian research is required in two broad areas – managing high radiation loads and potential use of supplementary lighting with targeted spectrums.

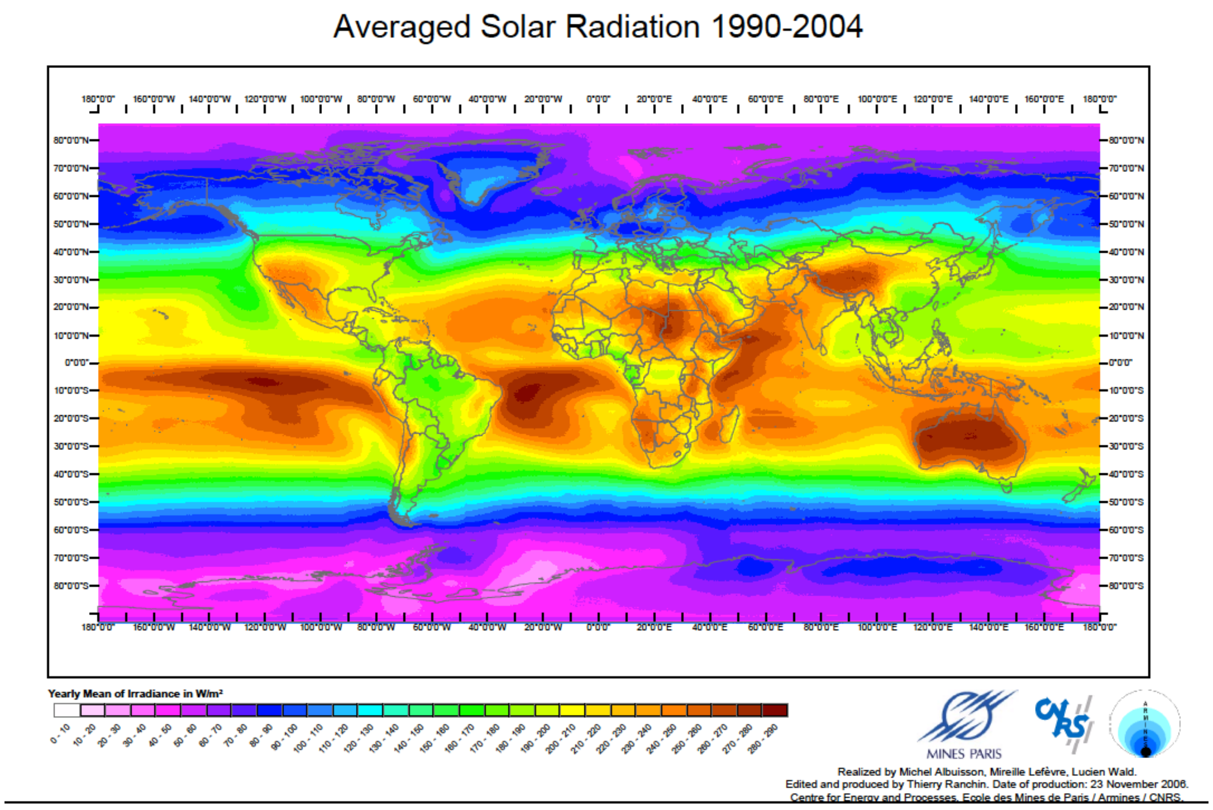

Figure 2. Global annual solar radiation levels (w/m^2).

Managing high radiation loads

Crop production can be limited by high light levels. There are a number of technologies for managing high radiation loads and the impact of these methods need to be linked to crop physiology and productivity.

The use of modern greenhouse covering materials can transform direct sunlight into diffuse light and reduce the adverse effect on crops. Experimental research with different crops (e.g., tomato, cucumber, roses) has showed improved production under diffuse light conditions, with growth rate or yield of up to 10% higher in the Netherlands (Hemmings et al 2014).

However, much of this research has been undertaken at radiation levels considerably lower than experienced in Australia. For example, Li et al (2014) looked at the impact of diffuse light on tomatoes when average light levels were only 15 MJ m^{-2} d^{-1}. By contrast, typical light levels in January exceed 24 MJ m^{-2} d^{-1} in Tasmania and 30 MJ m^{-2} d^{-1} in Carnarvon, WA.

The light conditions can also be modified by the properties of the cover material. The reflectance, transmittance and absorbance by the cover material will affect the light condition experienced by the crop (Gruda & Tanny 2015). Understanding how the light condition impacts on key crop physiology, e.g. flower initiation, can have a large impact on crop productivity.

The linking of crop physiology and technology to manage high radiation loads is a gap which is highly relevant to Australian conditions. The technology of cover material has already been identified for investment through VG15038 (Investigating novel glass technologies and photovoltaics in protected cropping; Appendix 2

Appendix 2). In addition, the Edith Cowan University's Electron Science Research Institute is developing a CRC funded trial glasshouse using newly developed “solar glass”.

Ensuring that advances in covering technology is linked to crop physiology, to optimise the protected cropping environment to the needs of the plants, is required to ensure productivity improvements.

Supplementary lighting

Light condition (quality, intensity and photoperiod) is an important environmental variable in regulating vegetable growth, development and nutrition, particularly for vegetables produced in controlled environments. In addition to the covering material discussed above, light quality can also be managed using specific wavelength lighting.

With the development of light-emitting diode (LED) technology, the regulation of light environments has become increasingly feasible for the provision of ideal light quality, intensity and photoperiod for protected facilities (Zhong et al 2015). Dorais 2003 summarised the increase in yield for lettuce, cucumber, sweet pepper and tomato grown at higher latitudes.

In their review Zhong et al (2015) reported improvements in a range of nutritional aspects of vegetables, including beneficial substances such as soluble proteins, sugars, ascorbic acid, carotenoids, phenolic, and anthocyanins and harmful substances such as nitrate and oxalic acid. Supplemental light quality could be strategically used to enhance nutritional value even for baby leaf crops (Li & Kubota 2009).

Intracanopy lighting, where lamps are mounted within the canopy can increase assimilation light use efficiency at lower light levels (Trouwborst et al 2011). The benefits at higher light levels are not known.

While Australia typically has an overabundance of light, as discussed above, supplementary light targeting the growth regulation or nutritional quality of vegetables may deliver benefits. Little research has been undertaken in Australia examining the possible targeted use of the LEDs and their narrowly centred specific wavelength, which makes spectral control more flexible and feasible. Thus, LEDs can be used to provide targeted light quality to influence plant growth and development and improve production efficiency (Taulavuori et al 2017).

Atmospheric manipulation

In closed system protected cropping, manipulation of all components of the atmosphere are possible including temperature, humidity and CO_2. Experimentally, these aspects have been studied extensively (e.g. Poorter and Nagel 2000). As an industry, the high-tech end of protected cropping has been using CO_2 enrichment for decades (e.g. Mortensen, 1987).

There are also opportunities at the low- and medium-tech end of protected cropping. For example, a 19% increase in cucumber yield has been reported from CO_2 enrichment in a ventilated tunnel house (Sa´nchez-Guerrero et al 2005). There is less information on the effect of CO_2 concentration on the quality of vegetables with most publications reporting no effect on product quality (Gruda, 2005).

Any further research in atmospheric optimisation needs to focus on determining the optimal levels of CO_2, temperature and air humidity, for plant growth and quality (e.g. Duggan-Jones et al 2015).

Root zone management

In hydroponic systems, control of all aspects of the root zone is possible including the physical structure of the root environment, temperature, salinity, nutrients and the microbial community.

Management of the growing conditions, particularly the concentration of the nutrient solutions is one of the most important aspects for successful vegetable production. Several properties of the nutrient solution, such as nutrient concentration, chemical forms of the elements, temperature and pH of the nutrient solution, can affect yield and quality of the vegetables (Nicola, Hoeberechts & Fontana, 2005).

Nutritional aspects of protected cropping are a mature area of research. Further gains from optimising nutrition require integration with crop management aspects such as lighting, atmospheric modification, biostimulates and cultivars.

Root zone temperature can have a profound effect on plant growth and development, with some suggesting that temperature is as important as nutrition (Gavito et al 2001). Higher or lower growing medium temperatures can impair the acquisition of nutrients (Dalla Costa et al 2011).

A small change in the temperature can have a profound impact on physiological processes and growth of plants (Zhang & Dang, 2007. This response appears to be genetically dependent, as observed for lettuce cultivars (Economakis and Said 2002).

Again, root temperature responses are a mature research field with any further gains arising from optimising temperature in relations to changes in other crop management aspects such as lighting, atmospheric modification, biostimulates and cultivars.

Biostimulants

Bacteria that improve the growth of plants are often called plant growth promoting rhizobacteria (PGPR). There are numerous studies and reviews on the beneficial effects of the application of bacteria on yield, nutrient acquisition, hormone production and plant defences (Pii et al., 2015). However, very few studies have been undertaken in hydroponic systems.

There are some indications that root inoculation with PGPR in hydroponic systems, like e.g. *Bacillus velezensis*, can reduce the nitrate content of leaves (Balanza et al., 2012). These bacteria have been shown also to be able to reduce the contamination of Pythium sp., a pathogen causing the root rot disease, of hydroponically grown lettuce (Kanjanamaneesathian, et al 2014) and promote the fresh yield of leafy crops.

Some strains of *Azospirillum brasilense* have been shown to enhance the growth of basil plants in hydroponics (Mangmang, et al, 2015). Other effects, such as an increase in protein and chlorophyll content and a higher peroxidase activity, were measured which might be linked to a change in the capability of plants to adapt to abiotic and biotic stresses.

Humic substances are by-products of the microbial transformation of organic residues. Humic substances have been shown to affect directly plant growth, root morphology and nutrient acquisition (Nardi et al, 2002). Proliferation of lateral roots and root hairs and the simulating hormonal effects have been frequently observed in humus-treated plants (Zandonadi et al, 2007).

Most of the direct beneficial effects of humic substances have been shown using nutrient solution grown plants. This suggests that humic substances could be used to improve the productivity of hydroponic cultivation systems.

Pollination

Commercial production of solanaceous fruit crops (tomato, capsicum and egg plants) require crop pollination in protected cropping systems to ensure high quality fruit. Typically, bumble bees are used for pollination around the world. However, in Australia bumble bees are not currently commercially available either due to their absence on the mainland, or their classification as a pest species in Tasmania. As a result, crops require hand pollination (Goodwin 2012).

While there is the potential for bumble bees to be used as pollinators in Tasmania, on the mainland alternatives will be required. A recent senate committee has recommended trials of the current bumble population in Tasmania, and for the Commonwealth Government to work with state governments to fund further research into the use of native bees as pollinators (The Senate 2017). The University of Tasmania has also commenced a project looking at honey bee health and pollination in protected cropping.

Given the cost of hand pollination, which has been estimated at up to $25,000/ha (Connellan & Parks 2015), the identification of suitable insect pollinators for the mainland protected cropping industry is a clear gap. Furthermore, with the rest of the world able to use bumble bees, this is a uniquely Australian issue.

Real time monitoring of plant conditions

There is an increasing array of plant sensors which have the potential to be used in protected cropping to link crop physiology and control systems.

For example, Takayama et al (2014) developed the “speaking plant approach” to maximize profit in greenhouses. This concept defines that the optimal plant cultivation conditions should be achieved by monitoring the physiological status of the plants. Chlorophyll fluorescence imaging technique is useful to evaluate the photosynthetic functions of plant non-destructively. It is also possible to monitor plant turgor pressure in real-time (e.g. Zimmermann et al 2013).

For both irrigation and nitrogen management, Thompsom et al (2015) recommended a combined prescriptive-corrective management approach. Models are used to prescribe management plans and monitoring is used to identify when adjustments are required.

Plant protection

Protected cropping environments can be conducive to pest and disease epidemics due to the favourable growth conditions, for both plant and pest or disease, intense production practices and in some systems recirculation of water and air.

A number of projects on IPM and disease management in protected cropping were delivered between 2004 – 2010 (Appendix 2). An extension project has also recently completed on integrated crop protection information (VG13078). However, this was principally focussed on field grown vegetables. More recently, there has been some RD&E deliver to the protected cropping section in VG15010 (A multi-faceted approach to soilborne disease management). In this project, sub-components have looked at grafted cucumber for managing root diseases, and biofumigants in tunnel house soil-grown capsicums.

It is evident that a substantial body of Australian information exists which has some relevance to the protected cropping sector (Appendix 2

Appendix 2). Consideration should be given to summarising this information, along with the international R&D knowledge, and delivering this through the Soil Wealth-ICP, VegNet and VegPro pathways. This may require additional resources to develop technical extension material.

Recent exotic pest and disease detections emphasise the vulnerability of the protected cropping industry. There is a clear need for the Australian industry to support a plant protection capability.

Integrated Pest management (IPM)

IPM can be used in protected structures. There are many successful uses of IPM overseas and in Australia.

Overseas, the use of bumble bees as pollinators provides a strong incentive for the use of IPM. This shift began at the end of the 1990's in Southern Europe to IPM occurred when bumblebees were used for pollination. The use of bumblebees accustomed farmers to choosing pesticides that are selective for these pollinators (van der Blom et al., 2009). Consequently, the use of broad-spectrum pesticides significantly decreased as the use of bumblebees was adopted for most tomato crops. The use of selective pesticides allowed for the release of some natural enemies in this crop, although chemical control was still the main control measure for pests (Perez-Hedo et al 2017).

In Australia, the use of IPM has been held back by the lack of experienced IPM practitioners, the lack of a strong driver, and the continued reliance on agrochemicals.

With the continual evolving of pests and diseases and crop cultivars there is an ongoing need to maintain a certain level of research capacity.

Biological suppression of root pathogens

Many pathogens can grow under hydroponic conditions due to high nutrient concentrations (Xu and Warriner, 2005). *Fusarium*, *Phytophthora*, and *Pythium* are the most common plant pathogens found in hydroponic systems (Li et al.,2014; O'Neill et al., 2014).

The management of root zone pathogens can include physical, chemical, and biological methods. Physical treatments can disinfect nutrient solution, while maintaining rhizosphere biology. But physical systems have high capital and running costs.

Chemical control strategies can suppress the growth or symptoms of plant diseases in hydroponic systems. However, toxicity of fungicides, by-products and evolution of fungicide resistant microorganisms are problems shared with soil systems.

The suppression of plant diseases in hydroponic systems are now being investigated. A range of beneficial microorganisms for vegetable crops have been trial (Table 4Table 4). These beneficial microorganisms have some potential when used as part of a whole system for pathogen management and growth optimisation.

Table 4. Beneficial microorganisms for plants grown in hydroponic systems (adapted from Lee & Lee 2015).

Microorganism		Host plant
Genus	Species	

Pseudomonas	*aeruginosa, aureofaciens, chlororaphis, corrugate, fluorescens, fulva, marginalis, oligandrum, plecoglossicida, putida, syringae*	Bean, carnation, chickpea, cucumber, lettuce, peppers, potato, radish, tomato
Bacillus	*amyloliquefaciens, cereus, subtilis, thuringiensis*	Carrot, chrysanthemum, cucumber, lettuce, pepper, tomato
Enterobacter	*aerogenes*	Cucumber
Streptomyces	*griseoviridis*	Cucumber, tomato
Gliocladium	*catenulatum*	Cucumber, tomato
Trichoderma	*asperellum, atroviride, harzianum, virens*	Bean, cotton, cucumber, maize, rice

Microflora typically develop rapidly after crop establishment in hydroponic systems, using plant exudates, compounds in nutrient solution, and dead plant materials as energy sources. The composition of the microflora in hydroponic systems may be affected by environmental factors and the source of nutrients. Some of the microflora can be plant pathogens, but the pathogens are commonly outnumbered by the population of non-pathogenic organisms (Khalil & Alsanius, 2010). *Bacillus* spp. *Gliocladium* spp., *Trichoderma* spp., and *Pseudomonas* spp., are common beneficial microbes but their beneficial effects are not always sufficient to prevent disease outbreak (Khalil & Alsanius, 2010).

Advanced molecular techniques, especially next-generation sequencing, now allows the study on whole genome identification of PGPR, and microbial community analysis in hydroponic systems. Further research is warranted to investigate the differences in microbial community between open and closed hydroponic systems and their effects on crops (Lee & Lee 2015).

Recycling nutrient solutions offers potential savings in water and fertilisers, and reduces environmental pollution. The challenge to the protected cropping industries is to include effective, economical and appropriate disinfection systems, as there are several important bacterial and fungal plant pathogens that are spread in water.

Market Access

Excessive pesticide residues have been shown to be a significant issue in greenhouse cucumber and hydroponic lettuce production. This is probably due to a lack of product registrations for certain important pests, reduced chemical breakdown in the protected cropping environment and potential for pesticides to move into hydroponic solutions and be taken up by roots (Smith & Dal Santo 2011). There is a distinct lack of registered microbial pesticides that would reduce reliance on conventional pesticides.

This is a world-wide phenomenon and is largely due to restrictive and expensive registration requirements despite the development of certain microbial products.

Infrastructure/engineering/technology

Protected cropping structures are capital intensive, with a high level of supporting infrastructure required. For the high technology production facilities, there is a strong reliance on expertise from northern Europe, and north America. This also applies to much of the research and development that occurs in the engineering and technology areas.

Because the leading edge of the greenhouse industry is technology-driven, there will always be new developments that will have a positive impact upon production efficiency. Automation and access to improved cultivars are two examples where the industry is well placed to adopt new overseas developments.

This process has been facilitated by good international relations to European parent companies of those supplying the local industry. Overseas study tours and active cultivar evaluations by seed companies have also assisted this uptake.

There are two areas which Australia has some R&D leadership in relations to vegetable production in protected cropping.

Covering materials

As previous identified, Australia has a high radiation load compared to most of the areas where glasshouses are developed. Two major research projects are currently addressing both the challenges, in terms of heat and light load, and the solar energy harvesting opportunities.

Edith Cowan University's Electron Science Research Institute is working on an advanced glazing system for solar energy harvesting and radiation control. The group has recently been funded through the CRC system to develop a trial greenhouse, with two PhD Scholarships.

Swinburne University of Technology is leading VG15038 (Investigating novel glass technologies and photovoltaics in protected cropping). The project will trial smart glass which can adjustable light intensity and spectrum in addition to semi-transparent photovoltaic glass that could simultaneously generate electricity from some of the light and allow the rest to pass through.

Robotics and automation

Greenhouse production is a intensive activity which requires a high amount of labour, especially during crop establishment and harvest. The environment in the protected cropping structures can be challenging with high temperatures and humidity. Exposure to pesticide is also a significant issue with greenhouse workers at greater risk than outdoor agricultural workers (Kittas 2014). These factors have driven the interest in robotics and automation in protected cropping.

Sydney Universities Horticulture Innovation Centre for Robotics and Intelligent Systems is undertaking R&D on robots for field cops. However, there is considerable international developments in robotics and automation. It is likely that Australian high-tech protected cropping will rely on importing robotics technologies. However, there is the potential to adapt locally developed robotics for protected cropping.

The advancement of sensors technology, in conjunction with that of wireless communication technologies, have led to the development of cheap, relatively easy to install and operate, wireless sensor networks (Ferentinos et al 2015). This has seen increase experimentation with automatic monitoring system to understand the greenhouse environment and state of the crops, and optimize growth conditions and crop diseases prevention e.g. Park & Park (2011).

Energy

Growing vegetables under cover is more energy intensive than other farming methods. Past projects have focussed on assessing energy use and demonstrating two alternate energy sources; containerised phase change material (PCM) and hydronic heating system linked to a geothermal heat pump and heat exchange loop (Jarvis 2014).

The use of "solar glass" technologies to reduce energy costs are driving the interest in new cover materials. Like all protected cropping investment, this will require good benefit:cost ratios to drive uptake.

Environmental impacts

Protected cropping industry data on area, crops and value varies considerably (e.g. Table 1). This will hamper the ability of the industry to measure and manage the environmental impacts. Improving industry data would also help guide industry development and future investment in R&D.

The horticultural sector has previously invested in over $38 million environmental RD&E between 2005 and 2011 (Muller at al 2012). The vegetable industry dominated this investment, however only pesticide and nutrient issues in protected cropping were directly addressed. As the protected cropping sector matures there will be a need to review the environmental impact with reference to the threats outlined below.

Social licence to operate

The protected cropping sector currently faces no major issues around its "social licence to operate". This contrasts with some agricultural sectors, such as cotton, where the industry is required to invest considerable resources in both monitoring, reporting and improving resource use (e.g. Cotton Australia 2008). In the longer-term pressure may come on the protected cropping industry from two areas; 1. water use, and 2. greenhouse gas emissions. With this in mind, some ongoing effort into monitoring and improving the performance in these areas may be worth considering.

Water

Protected cropping and associated hydroponic irrigations systems are very efficient users of water. Fruit and vegetable growing generally uses about 38L of water per dollar of value produced, whereas hydroponically-produced vegetable crops use only 0.6L of water to produce the same value (Rogers & Montagu 2013a). While water use efficiency is typically high, the protected cropping sector can have a high dependence on urban potable water supply – or "blue water" (Falkenmark & Rockstrom 2006). By contrast field production of vegetables uses a mix of blue (irrigation) and green (rainfall) water which reduces the water resource impact of field produced vegetables.

The dependence on potable town water may explain some of the resistance of urban areas to protected cropping (Smith 2017). Reducing the impact of protected cropping on water resources include water harvesting and recycling. Information on these practices are available (e.g. Smith 2011). A small project collating information on the use of water, its source and productivity (e.g. kg/L) under protected cropping could be considered.

Greenhouse gas emissions

Energy use and subsequent greenhouse gas emissions are the most significant environmental impacts of protected cropping. While agriculture has been excluded from any direct greenhouse gas account system (Rogers & Montagu 2013b), the uncertainty of Australia's climate policy and the increasing emphasis on voluntary reporting suggests that the protective cropping industry should be proactive in both understanding their emissions profile and putting in place processes to reduce the impact.

A small project collating information on greenhouse gas emissions, their source and emission intensity (e.g. kg product/kg CO_{2e}) under protected cropping could be considered.

Regulatory requirements

Nutrients

Free-draining hydroponic systems and the subsequent discard of nutrient rich waste water are potentially harmful to the environment. The nutrient load needs to be managed on farm or a closed, recycling system used. A project was delivered in 2009-2010 to facilitate the use of closed, fully recycling systems in protected cropping (Smith 2011).

A small project could be considered to follow up on Smith 2011 to determine if nutrient management across the protected cropping sector is minimising environmental impacts. Included in this could be an industry evaluation of the system to manage diseases in recycling systems.

Conclusion

This review is structured around four broad areas: Productivity, Technology, Plant Protection and Environment. Three questions were used to focus the review; 1. How specific is the issue/R&D area to protected cropping? 2. At what stage is the R&D area?, and 3. Is international R&D relevant to the Australian protected cropping issue/R&D area?

Overall, a clear strategic research gap was identified by the review. Australia has a very high radiation load across much of the country. Radiation loads impact on the light and heat levels experience by crops in protected cropping. With much of the international research undertaken at far lower radiation levels, sometimes half that commonly experienced in Australia, this will limit the direct transfer of international research and technology. Some research is therefore required to understand and manage protected cropping systems under these high radiation loads.

Research gaps across all levels of protected cropping

To have the greatest relevance, research gaps need to be applicable to crops grown in low- medium- and high-tech protective structures. Of the potential research gaps identified, the following areas have some relevance across all three levels of structures;

- Light levels and condition,
- Root zone management
- Biostimulates
- Pollination
- Real time monitoring of plant conditions
- Biological suppression of root pathogens

To deliver improved productivity and profitability on farm, these six research gaps need to be integrated into the whole protected cropping system. Optimising the production systems, or designing new approaches will increasingly rely on the integration of crop physiology, control technology and plant protection models. Building industry capability to achieved this should be included into projects.

High-tech protected cropping research and development opportunities

There are three R&D areas relevant to high-tech protected cropping;

- Atmospheric manipulation
- Robotics and automation
- Energy

It is likely that the Australian high-tech protected cropping industry will rely on importing much of the above technologies. However, linkages with existing projects will help ensure that there is an Australian R&D capability which can assist developing technology relevant to Australian conditions. For example, two major research projects are currently addressing Australia's high radiation loads through smart glass technologies.

Environmental performance of the protected cropping sector

The protected cropping sector currently faces no major environmental issues around its "social licence to operate". In the longer-term pressure may come on the protected cropping industry from two areas; 1. water use, and 2. greenhouse gas emissions. Already there is some suggestion that water availability around cities is an issue. With this in mind, some ongoing effort into monitoring and improving the performance in these areas may be worth considering.

Extension of existing protected cropping knowledge

In collating the previous and current industry funded projects (Appendix 2

Appendix 2), it is evident that a substantial body of Australian information exists which has relevance to the protected cropping sector. Consideration should be given to summarising this information, along with the international R&D knowledge, and delivering this through the Soil Wealth-ICP, VegNet and VegPro pathways. This may require additional resources to develop technical extension materials.

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Appendices

Appendix 1. Ranking of R&D topic areas based on How specific the issue is to protected cropping, the R&D stage and how readily international research can be applied to Australia. Overall ranking uses equal weighting for each criterion.

R&D topic area	*Q 1. Specific to protected cropping*	*Q2. R&D Stage*	*Q3. Relevance of International R&D*	***Overall rating***
Productivity				
Lighting control	3	2	2	**7**
Benchmarking	3	1	3	**7**
Pollination	3	1	2	**6**
Atmospheric manipulation	3	1	2	**6**
Root zone management	3	1	2	**6**
Plant Pruning and Training	2	1	2	**5**
Temperature control	3	1	1	**5**
Critical nutrient requirements	3	1	1	**5**
Nutrient use efficiency	3	1	1	**5**
Cultivar development	2	1	1	**4**
Partitioning	2	1	1	**4**
Infrastructure, engineering & technology				
Lighting control	3	2	1	**6**
Labour efficiency	3	1	2	**6**
Automation/mechanisation	1	3	2	**6**
Energy efficiency	3	1	2	**6**
Temperature control	3	1	1	**5**
Substrate control	3	1	1	**5**
Waste management	2	1	2	**5**
Harvesting	3	1	1	**5**
Handling	1	2	2	**5**
Greenhouse design	3	1	1	**5**
Hygiene	3	1	1	**5**
Pest exclusion	3	1	1	**5**
Nutrient control	2	1	1	**4**
Irrigation improvements	2	1	1	**4**
Logistics	1	1	1	**3**
Packaging	1	1	1	**3**
System design	1	1	1	**3**

Plant Protection				
Biocontrol systems	3	2	2	**7**
Market Access	2	1	3	**6**
Root zone management	3	1	2	**6**
Residues	3	1	2	**6**
Pesticide management	2	1	2	**5**
Diagnostic tools	2	1	2	**5**
Nutrition	2	1	2	**5**
Hygiene	1	2	1	**4**
Genetics	2	1	1	**4**
New chemicals	2	1	1	**4**
Environmental impacts				
Greenhouse gas emissions and emissions intensity	3	2	2	**7**
Water use/recycling	3	1	3	**7**
Agrichemical runoff	3	1	3	**7**
Food safety	3	2	2	**7**
Lifecycle analysis	3	1	2	**6**
Energy efficiency	3	1	2	**6**
Nutrient efficiency & management	3	1	2	**6**
Co-generation of electricity	1	2	2	**5**
Waste management	1	1	2	**4**

Appendix 2. Completed and current projects between 2004-2017 funded through Horticulture Australia Ltd. and Hort Innovations with relevance to protected cropping vegetables.

Project	Title	Lead Provider
VG04012	Biocontrol of hydroponic lettuce root r	NSWDPI
VG04019	Assessing nitrate and nitrite levels in vegetables	NSWDPI
VG04032	Integrated management strategies for pests and diseases of Asian vegetables	NSWDPI
VG05034	Improving cucurbit immunity to powdery mildew	UWS
VG05054	Management of powdery mildew in field and greenhouse cucurbits	QDPIF
VG05084	Integrated management of greenhouse vegetable diseases	NSWDPI
VG05093	IPM for greenhouse vegetables	NSWDPI
VG05094	Sustainable integrated control of foliar diseases in greenhouse vegetables	SARDI
VG05095	Pathways to production, a skilling initiative of the Australian protected cropping industry	AHGA
VG06003	Enviroveg manual new sections - hydroponic, greenhouse and organic production	AusVeg Ltd
VG06009	Management of vegetable diseases with Silicon	University of Tasmania
TL00137	Integrated disease management strategy for tomato spotted wilt virus in protected crops	DAWA
TL00127	IPM Onfarm – Protected Cropping (Training Course Workbook)	NSW DPI
TL00137	Integrated disease management strategy for tomato spotted wilt virus in protected crops	DAWA
TL00268	Growing cucumbers in protected cultivation in Western Australia	
VG06010	The sustainable use of pesticides (esp spinosad) against WFT in vegetables	NSWDPI
VG06011	Determining the level of resistance to silverleaf whitefly in cucurbits	Dept. Ag. & Food WA
VG06014	Revegetation at property scale – designing the 'right' biodiversity for sustainable vegetable production	SARDI
VG06022	Developing and communicating strategies for controlling virus diseases in vegetable cucurbit crops	Dept. Ag. & Food WA
VG06024	Phase II: Native vegetation to enhance biodiversity, beneficial insects and pest control in horticulture systems	CSIRO Entomology
VG06028	Alternative fruit fly control and market access for capsicums and tomatoes	QDPI&F
VG06066	LOTE program for the vegetable industry	AusVeg Ltd
VG06071	Greenhouse Study Tour Canada	Australian Hydroponic & Greenhouse Association

Project	Title	Lead Provider
VG06094	A scoping study of IPM compatible options for the management of key vegetable sucking pests	QDPI&F
VG06142	Leadership development enabling growers to attend national greenhouse conference	AHGA
VG06146	Feasibility study for the introduction of Bombus terrestris in Australia	AHGA
VG07003	Development of IPM strategies and tools for WFT in hydroponic lettuce	NSWDPI
VG07076	The delivery of IPM for the lettuce industry	NSWDPI
VG07074	European greenhouse study tour October 2007	AHGA
VG07082	Post harvest treatment of hydroponically grown Asian vegetables	NSWDPI
VG07087	Vegetable biosecurity & quarantine gap analysis	Scholefield Robinson Hort. Serv. Ltd
VG07095	Program approach to plant pathology	HAL
VG07118	Build capacity of greenhouse growers to reduce crop loss through adoption of preventative disease management practices	NSWDPI
VG07119	Identification and monitoring of resistance in vegetable crops in Australia	NSWDPI
VG07125	Best-practice IPM strategies for control of major soilborne diseases of vegetable crops	VDPI
VG07128	Integrated viral disease management in vegetable crops	QDPI&F
VG07136	Review of *Diseases of vegetable crops*	QDPI&F
VG07137	Vegetable pathology program – workshops and coordination	HAL
VG07144	Improving greenhouse production practices	SARDI
VG07145	Improving greenhouse systems	NSWDPI
VG07153	Nutrient management of Asian vegetables	NSWDPI
VG07165	Pesticide residues in hydroponic lettuce	NSWDPI
VG08045	National greenhouse industry business and productivity analysis system	NSWDPI

Project	Title	Lead Provider
VG08064	Developing demonstration sites for simple hydroponic systems in protected cropping	SARDI
VG08072	Hydroponics, greenhouse vegetable and olive tour of Peru, Spain and Portugal, Aug 2008	SARDI
VG09068	European greenhouse study tour – October 2009	Australian Hydroponic & Greenhouse Association
VG9073	National Greenhouse waste-water recycling project.	Graeme Smith Consulting
VG09112	Protected Cropping Grower Tour Europe 2010	SARDI
VG09121	Neutralising pesticides in recirculating water systems within a protected cropping system	Graeme Smith Consulting
VG10078	The addition of root and hydroponic vegetables to the Belt (flubendiamide) label for the control of Lepidoptera sp.	Bayer CropScience
VG14010	Management and detection of bacterial leaf spot in capsicum and chilli crops	The Department of Agriculture and Fisheries (DAF)
VG13052	Confirmation of ultra filtration as a viable low cost water disinfection and nutrient solution recycling option	Primary Principles
VG13075	An investigation of low-cost protective cropping	AHR
VG13078	Extension of Integrated Crop Protection information	RMCG
VG15010	A multi-faceted approach to soilborne disease management	AHR
VG15038	Investigating novel glass technologies and photovoltaics in protected cropping	Swinburne University of Technology
VG16024	Gap Analysis and Economic Assessment for Protected Cropping Vegetables in Tropical Australia	Queensland Department of Agriculture and Fisheries (DAF)