Hort Innovation

Final Report

Gap analysis and economic assessment for protected cropping vegetables in tropical Australia

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Gap analysis and economic assessment for protected cropping vegetables in tropical Australia VG16024

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Content

Summary

The project VG16024 aims to increase awareness and information about protected cropping opportunities and technology options for the vegetable industry in the tropics through the identification of gaps in information and potential economic viabilities. Protected cropping of vegetables in Australia (estimated at 1,341 ha) is by large located in temperate climate regions and in proximity to urban areas. In warm climate regions, near and north of the Tropic of Capricorn, the segment of the industry dedicated to producing vegetables using protected cropping technologies is scattered and relatively small (estimated at <80 ha). Vegetable growers in these regions would benefit from technologies that can mitigate risks linked to climate variability and that can help them address current and future market challenges and opportunities. Evidence from overseas, including in tropical regions, and demonstration plots and farmer experiences in the Australian tropics indicate that protective cropping technologies can cost-effectively mitigate the effects of extremes in air temperatures, rainfall, low and high relative humidity, wind, solar radiation, and pests and diseases, all which currently negatively affect yield, quality and consistency of supply.

In this report, four regions, two within the tropics (Burdekin dry tropics and Atherton Tablelands) and two located a short distance south of the Tropic of Capricorn (Bundaberg and Carnarvon), are selected as examples of regions where the protected cropping industry is either small or emerging, and has the potential to expand. Vegetable production in these regions is predominantly undertaken outdoors. The establishment of protected cropping enterprises would contribute to an increase in regional production that could service both domestic and export markets. This would be facilitated by the regions' proximity to road infrastructure, ports and airports but access to some of these market opportunities still need to be developed.

In the tropics the availability of medium level, cost-effective protected cropping structures that are effective in removing heat from crops is paramount. In this report, four greenhouse structure designs (high tunnels, passively ventilated greenhouses, retractable roof structures, and net houses) are discussed, and advantages and drawbacks compared. Capsicum, cucumbers, melons, and eggplants are given as examples of vegetable crops suited to warm climates and which can benefit from a protected environment and specific agronomy practices. Possible marketable yields are provided for these crops as well as estimates of production value for a range of size of areas that could potentially establish protected cropping systems.

A preliminary economic analysis was carried out for hypothetical production of capsicum crops in different protected cropping scenarios in the tropics. Under the protective structures, management practices, market prices and capsicum yields used in the analysis, preliminary results suggest that protected cropping could be a viable business opportunity for growers in the tropics. Future research investigating the heterogeneity of protected cropping enterprises would serve to further confirm these findings, especially in light of the practical implications of the technology used in a larger number of commercial sites.

Key aspects of production management in warm environments are associated with agronomy as well as economic and environmental sustainability. Areas of research and development that will support expansion of protected cropping in the tropics are suggested below:

- Vegetable crop agronomy within protected cropping systems, with specific topics that require developing recommendations for:
    - Water and nutrient management that ensure economic and environmental sustainability.
    - Soil production systems that sustain soil health through a combination of practices that growers could use and align with their market supply plan.
    - Soilless culture systems that recycle or sustainably reuse drainage nutrient solution.
    - Integrated pest and disease management systems with a large component of practices that rely on biological control options for warm environments.
    - Genetic materials suitable for warm environments as well as new types of commodities that could be of interest to domestic and export markets.
    - Technologies and crop management options to mitigate the effect of extremes temperatures on crops.
    - Crop production practices under different protective cropping structure designs that are suitable for using in the tropics.
    - Technologies that can reduce labour inputs through mechanisation and automation of operations during crop production.

- Capacity building activities that will support the current protected cropping industry and enable the scaling-up of adoption in the Australian tropics. This should target growers and related industry stakeholders.

- Development of proof of concepts through demonstrations, communication materials, and grower study tours are needed to continue to increase knowledge about opportunities, benefits and challenges of using protected cropping in warm environments through evidence-based assessments. In this process, engage the input supply industry and other vegetable industry stakeholders.

Potential users could be regional growers with outdoor farming experience and enterprises bringing knowledge and experiences from other regions. Capacity building will need to be tailored to the specific needs of potential adopters.

It is expected that in the near future protected cropping technologies will become standard vegetable production systems that will complement outdoor production in the warm regions of Australia. Information provided through this project will assist Hort Innovation prioritise future R&D investments, and Hort Innovation’s contribution towards supporting industry stakeholders with improved decision making and increased adoption.

Feasibility and economic viability studies for a variety of crops and production systems within protected cropping, as well as tailored recommendations for successfully producing in tropical environments, are still required.

Keywords

Protected cropping; climate variability; tropical environments; Northern Australia; market opportunities

Introduction

Adaptation and adoption of risk-mitigating technologies for vegetable crops in the Australian tropics could help overcome marketable yield losses caused by climate variability and extreme weather events and therefore ensure supply commitments. For some vegetable crops, protected cropping structures can potentially address many of the above issues by providing a cost-effective control of the growing environment.

While there has been significant investment and expansion of protected cropping production systems in Australia, most of this growth has been concentrated in temperate regions. Almost entirely from field-grown crops, 58% of the total production of high-value vegetables (i.e. tomato, capsicum, cucumber, melon, and eggplant) are supplied from growing regions in QLD, WA and NT in the tropics of Australia. Climate variability and extreme weather events result in marketable yield losses in these regions and disrupt domestic and potential export supply commitments. This challenge could be partially overcome by adapting and adopting risk-mitigating technologies. There is evidence that using protected cropping technologies (i.e. specific inputs and management practices) tailored to mitigate key production constraints in warm climates can increase yields and minimise the risk of crop losses. Growers and other value-chain stakeholders in the tropics of Australia currently have limited knowledge regarding which protected cropping technologies would be most appropriate and cost-effective.

The intended outcome of this project is to provide vegetable levy payers, industry stakeholders and value chain members with access to information about the feasibility and economic credentials of protected cropping in the tropics. This will assist Hort Innovation prioritise future R&D investments and contribute towards supporting industry stakeholders with improved decision making and increased adoption.

The specific objectives of the project are to assist Hort Innovation and vegetable industry stakeholders:

1. identify knowledge and information gaps regarding vegetable production in protected cropping systems in tropical growing regions,
2. determine the vegetable types and protected cropping structures most suited for production in tropical Australia,
3. determine the optimum locations and scale for protected cropping structures in tropical Australia and associated volume and value outcomes for suitable vegetable crops, and
4. understand the economic viability of producing vegetables in protected cropping structures in tropical Australia production regions.

Towards meeting the above objectives, this report provides: a gap analysis and economic assessment of protected cropping technologies for vegetables in tropical growing regions; information about possible crops, technologies, and suitable regions for potential scaling up of protected cropping, with associated volumes and value outcomes for targeted vegetable commodities; and analyses of economic viabilities and overviews of marketing opportunities for protected cropping production scenarios in the Australian tropics. The information was gathered from recent R&D and demonstration plots in the tropics, expert knowledge, publications, and study tours and interviews with industry representatives.

This project contributes towards Horticulture Innovation Australia's Strategic Investment Plan by addressing issues that relate to managing risks and enabling sustainability (e.g. climate adaptability responses), stimulating productivity and driving growth (e.g. emerging technologies and innovative cropping systems), and building capacity (e.g. knowledge-sharing and people development).

Methodology

A summary of activities conducted in this project and methods used to source the information are presented in Table 1. The project also developed: a) a program logic and monitoring and evaluation plan with links to Hort Innovation and industry/fund objectives; b) a project risk register and how risks were managed, and c) a stakeholder engagement/communication plan submitted as Milestone 102 on 1 May 2017. A project inception meeting was held with three project team members and two growers on 20 March 2017 to discuss and agree on project activities. Regular weekly meetings were held with the economist consultant. Key industry stakeholders were made aware of the project and invited to participate in discussions that would assist in producing the gap analysis.

The information and analyses presented in this report were informed by discussions with protected cropping users and industry representatives; expert knowledge; current and past research outcomes from Queensland Department of Agriculture and Fisheries' (DAF) protected cropping R&D and demonstrations in north Queensland; publications; protected cropping conference presentations and discussions with attendees; and visits to production sites in Australia and in north-west Mexico. Targeted discussions with key stakeholders were held in Burdekin, Atherton Tablelands, and Bundaberg. The Burdekin region was visited regularly as part of DAF's R&D collaboration with commercial growers. In Bundaberg, challenges associated with protected cropping were discussed with key growers, some of whom had been using greenhouses for more than 15 years and others who recently had made large investments in protected cropping. The trip to Mexico was organised to visit the north western greenhouse production region of the country during May (30 April 2017 to 8 May), a time of the year when temperatures are high and comparable to locations in the Australian tropics. In addition, protected cropping industry stakeholders attending the Apex-Brinkman Protected Cropping Australia (PCA) Conference 2017 (Adelaide, SA; July 9 to 12) were consulted. Discussions were also held with a horticulture consultant in WA evaluating challenges and opportunities for using protected cropping technologies in the Carnarvon region.

Table 1. Summary of project methodology by project activity.

Activities	Methodology
1. Identification of regions in tropical Australia where protected cropping structures will have the greatest economic impact for vegetable production	• Targeted discussions with key protected cropping users and industry representatives (Bundaberg, Burdekin, Atherton Tablelands, and attendees of PCA Conference in SA) • Expert knowledge • Project leader's past research (evaluations of crops and management practices and use of different structure designs) • Publications • Climate data obtained from SILO[a], a repository of climate data for Australia (to report climate parameters for selected locations in the tropics) as well as the Bureau of Meteorology (BOM) • Study tour in a greenhouse production area in Mexico (to identify examples of production systems used in warm environments)
2. Identification of types of vegetables most suited to protected cropping structures in tropical Australia	• Targeted discussions with key protected cropping users who have different protective structure designs and discussions with industry representatives, including manufacturers of structures • Project leader's past research (to identify structure designs, key vegetable crops, and agronomic practices for use in the tropics) • Expert knowledge • Publications

Activities	Methodology
	• Study tour in a greenhouse production area in Mexico (to identify examples of structure designs and agronomic practices used in warm environments through discussions with operators of commercial and demonstration sites)
3. Estimation of the set up and operating costs, for a range of protected cropping structures suitable to the climatic conditions of tropical Australia	• Targeted discussions with key protected cropping users and industry representatives (e.g. industry input suppliers and marketing agents) (to obtain and calculate investment costs of selected structures suitable for the tropics) • Data from demonstration and semi commercial trials in North Queensland combined with industry knowledge (to calculate operating costs for capsicum as a model vegetable crops for the tropics) • Expert knowledge • Project leader's past research
4. Estimation of production volumes and associated values possible through producing vegetables in protected cropping systems (vs field based production) and discussions of relevant marketing and supply chains necessary to deliver product to market	• Data from trials, semi commercial plots, and demonstration sites (to estimate production and value calculated for selected crops and protected cropping systems) • Expert knowledge, past research in north Queensland (2013-2017), and publications (to estimate conservative yields in medium technology levels of protected cropping) • Discussions with commercial protected cropping operations in warm environments (to verify conservative yields levels) • Statistical data on field production volumes, value, area produced by Hort Innovation, • The indicative estimates of yields were used to relate them to potential adoption uptake and to contrast with data on field-grown crops • Targeted discussions with key protected cropping users and industry representatives, produce distributors (to identify likely drivers and barriers to adoption)
5. Investment analyses and assessment of business viabilities for protected cropping investments in tropical Australia	• Information and data estimated in Activity 3 used to conduct a preliminary economic analyses for hypothetical protected cropping enterprises in the tropics selecting capsicum as a model crop • Economic analyses and modelling using standard spreadsheet software • Assessed investment costs, production costs, overhead costs, yields and revenue in selected protected cropping scenarios using data gathered in Activity 3 and historical market prices • Calculations provided for gross margins, operating profit, return on assets (land price not included), and break-even yields and break-even prices • Price and yield risk incorporated into the analysis using a Monte Carlo simulation model to calculate probability of positive operating returns in selected protected cropping scenarios

[a]Climate data for the selected locations in regions where protected cropping could expand were obtained from SILO (Jeffrey, Carter et al. 2001), a repository of climate data for Australia. Data for the figures was extracted from the patched point dataset (PPD) which provides daily maximum and minimum temperatures from 1889 to the present. Interpolated values were inserted to maintain continuity when data were missing for some reason. Calculations were undertaken using the R statistical software (R Core Team 2015). Figures on climate parameters include standard error (SE) bars (95%).

Outputs

The overarching project output is this report, which provides a summary of the findings from the gap analysis and economic assessment of protected cropping systems for vegetables in tropical growing regions. The remainder of this section presents the key findings related to:

1. Warm climate regions in Australia where adoption of protected cropping could be used for vegetable production (examples of regions in the tropics)
2. Potential protected cropping systems tailored for warm environments (structure designs; key agronomic practices; potential vegetable crop species; and yield performance)
3. Estimates on yields and on production and value for areas of production (drivers and barriers to adoption)
4. Preliminary economic analysis for hypothetical protected cropping enterprises in the tropics

Warm climate regions in Australia where adoption of protected cropping could be used for vegetable production

The Tropic of Capricorn (with latitude is 23°26’13.3” south of the equator) is the dividing line between the Southern Temperate Zone to the south and the Tropics to the north. In Australia, this imaginary line crosses QLD, NT and WA. Examples of towns along or close to the Tropic of Capricorn are Rockhampton (QLD), Alice Springs (NT) and Newman (WA). The tropics in Australia have diverse topography and climate zones –from tropical rainforest and tablelands to inland desert and coastal areas.

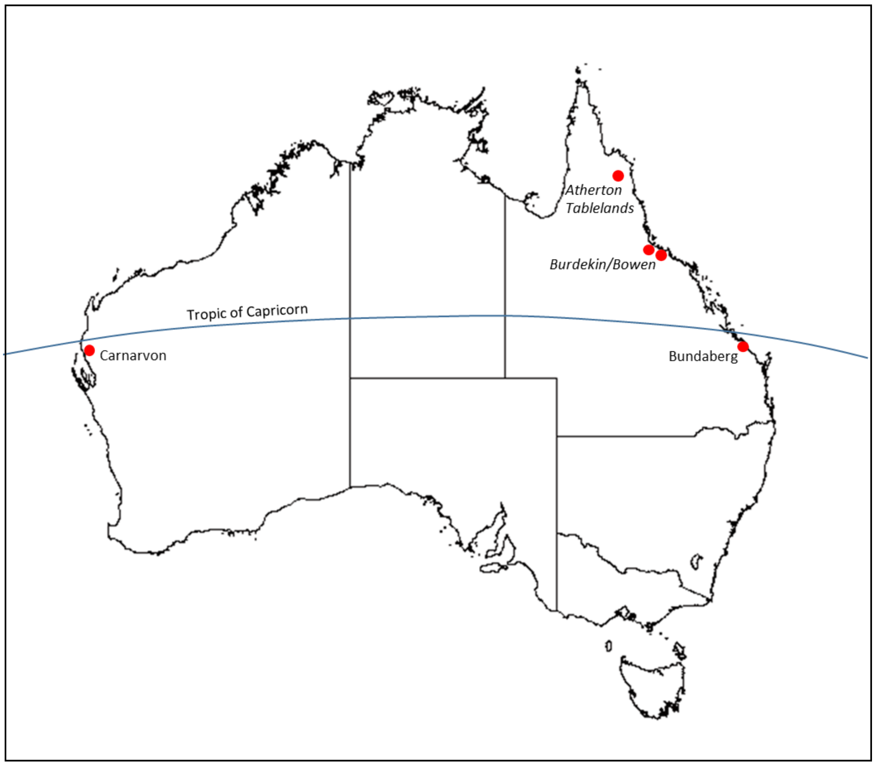
Subtropical and tropical climates in the tropics of Australia create opportunities and challenges for growing vegetables. Examples of key regions growing vegetables under warm climatic conditions exist in Queensland (eastern coastal strip regions), Western Australia (central west region) and Northern Territory (centre north region). Mostly from field cropping systems, these warm climate regions supply more than half of the total production of 793,421 t of high-value vegetables in Australia (i.e. tomato, capsicum, cucumber, melon, watermelon, and eggplant) (Hort Innovation Australia, 2016a; Hort Innovation Australia, 2016b). Field production in the tropics is seasonal because heat, rainfall, and pests and diseases impact production during summer.

The regions near the Tropic of Capricorn are characterized by seasonal or low precipitation, high solar radiation, and no or few frosts. At these latitudes (e.g. 24°), there are desert climates with high solar radiation, low air humidity and high evapotranspiration in the west of the country (e.g. Carnarvon) that differ from the climate in the east coast, where temperatures are lower and low precipitation occurs throughout the year (e.g. Bundaberg). In north Queensland there are regions with a tropical climate, some with a drier period and others where rainfall is persistent throughout the year. Where rainfall impacts field crops throughout the year, outdoor vegetable production is limited. Hot and humid environments during the summer seasons are common in most regions. In inland locations temperatures in summer months can reach >40°C; however, near the sea or on higher plains (e.g. Atherton tablelands), summer temperatures are <40°C.

For field-grown vegetable crops, more successful production is achieved in regions where dry seasons are long and more predictable. In the Dry Tropics region of north Queensland, within the subtropical and tropical zones, vegetable growers 'generally' benefit from a half-a-year of dry and warm climate (from April to Oct) which supports outdoor vegetable production with an annual gross value close to $500M (Tom Mullins, DAF pers. communication). Variability in rainfall and rain occurrences at any time of the production season still have a negative impact on vegetable production.

Four regions, two within the tropics (Burdekin Dry Tropics and Atherton Tablelands) and two located at a short distance south of the Tropic of Capricorn (Bundaberg and Carnarvon), are examples of regions where the protected cropping industry is either small or incipient, and could potentially expand (Figure 1). For this project, the following locations within these regions were selected:

1. Ayr and Bowen in the Dry Tropics, QLD (subtropical climate with distinctively dry winter)
2. Walkamin in the Atherton Tablelands, QLD (tropical climate, rainforest, monsoonal)
3. Bundaberg, QLD (subtropical climate with no dry season), in the north Burnett region, QLD (24°51′58″ S, 152°20′52″ E; located approximately 159 km south of the Tropic of Capricorn), and
4. Carnarvon, WA (desert climate, hot with summer drought), 24°52′57″ S, 113°39′25″ E, located approximately 161 km south of the Tropic of Capricorn.



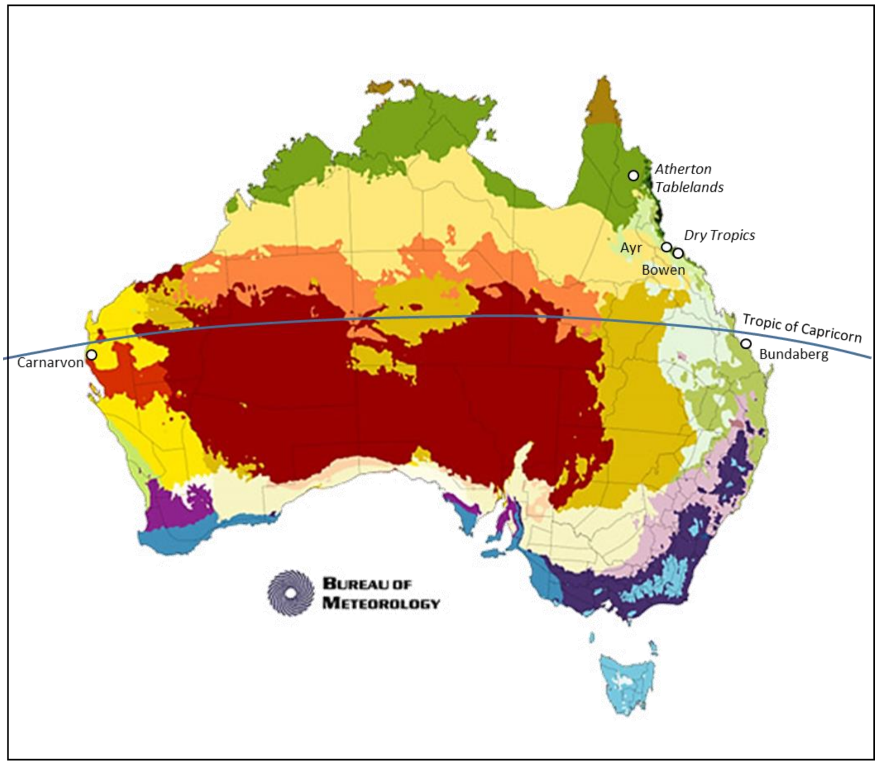


Figure 1. Selected regions in the tropics and locations near the Tropic of Capricorn used as examples where protected cropping could be expanded (Top). The selected regions and locations are overlapped with the Australian climate classification map (Bottom) of the Bureau of Meteorology (<http://www.bom.gov.au>).

The Australian Bureau of Meteorology provides climate classification maps based on different climate parameters: temperature and humidity; seasonal rainfall; and Köppen climate classification zones (<http://www.bom.gov.au/jsp/ncc/climate_averages/climate-classifications/>). For the selected locations, climatic characteristics on rainfall, solar radiation, air temperature, evapotranspiration, and vapour pressure deficit based on historical data are presented in Figures 2 to 6. Variability in Australia's annual rainfall by regions can be found in the Queensland Government website 'The Long Paddock' <https://www.longpaddock.qld.gov.au/>.

The locations listed above have an industry that produces vegetables outdoors. The challenges of climate variability impacting crops become more important when markets require consistency and certainty in volumes and quality of vegetable supply. Protected cropping systems in these regions can assist growers to respond to these market demands by modifying climate parameters such as avoiding rainfall over crop canopies and soil and reducing wind speed impacting crops. Protected cropping can also mitigate extremes in high solar radiation; high and low leaf, soil, and air temperatures; and high and low air humidity levels. Insect exclusion screens covering structures can assist reducing the impact of pests on crops.

A small protective cropping industry has been established for some time in locations such as Bundaberg (mainly using tunnels, greenhouses, and more recently a retractable roof structure) and in Carnarvon (mainly using net houses). A few small structures have also been growing vegetables in the Atherton Tablelands. Since 2014, an expansion of protected cropping (approximately 70 ha) in the Tablelands has occurred in one crop: blueberries. Protection from rain and nutrient management through soilless culture are the main reasons for using protected cropping on blueberries in this tropical region. The new technology may give vegetable growers some indication of benefits of protected cropping for managing risks in vegetable production. In the dry tropics of North Queensland, adoption has been slower, with a few small structures, some which have been used as learning and demonstration sites.

In all of these regions, protected cropping can ensure plantings are done on time even when rainy conditions exist outdoors. Production thus can then be sustained throughout the year. Nonetheless, production during the summer months is more challenging. Depending on the planting schedules, a break period between crops is required to remove old crops and implement hygiene practices that limit problems with pests and diseases. This usually occurs during the summer months.

The few protected cropping enterprises that have been operating for some time in these regions have shown that it is possible to achieve high yields and supply of high quality vegetables to local and distant markets. Other locations in the tropics could benefit from protected cropping as a means to extend the production period and improve vegetable yields and quality. For example, near Lake Bennett, south of Darwin, in the Northern Territory, there is successful production of cucumber, tomato, capsicums and Asian vegetables from a farm using protected cropping in approximately 16 ha. The use of protected cropping needs to be assessed with regard to the local environmental conditions and their advantages and constraints. In addition to climatic conditions, an assessment should include considerations associated with availability of resources, current infrastructure and services, distance to markets, and the objectives of the business in the value chain.

Remoteness is a key issue to consider in the tropics. Long distances to markets and export centres (airport and ports) by road inevitably increases costs of inputs and services and may impact the shelf life quality of high value vegetables. On the other hand, some isolation from field production systems can be beneficial as this minimises insect and disease pressure. When considering soilless production systems, the selection of location will be independent from the soil quality required for agriculture. Access to consultants and extension and research officers with experience in protected cropping is also critical.

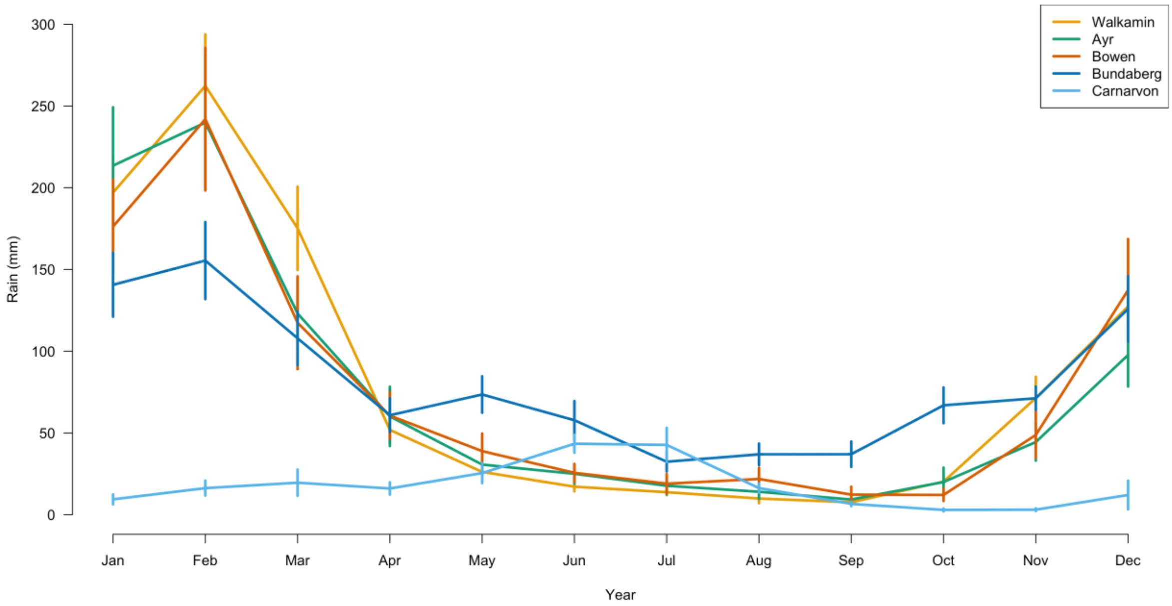


Figure 2. Monthly rainfall (Mean±SE) for selected locations in the tropics and near the Tropic of Capricorn where protected cropping could be expanded.

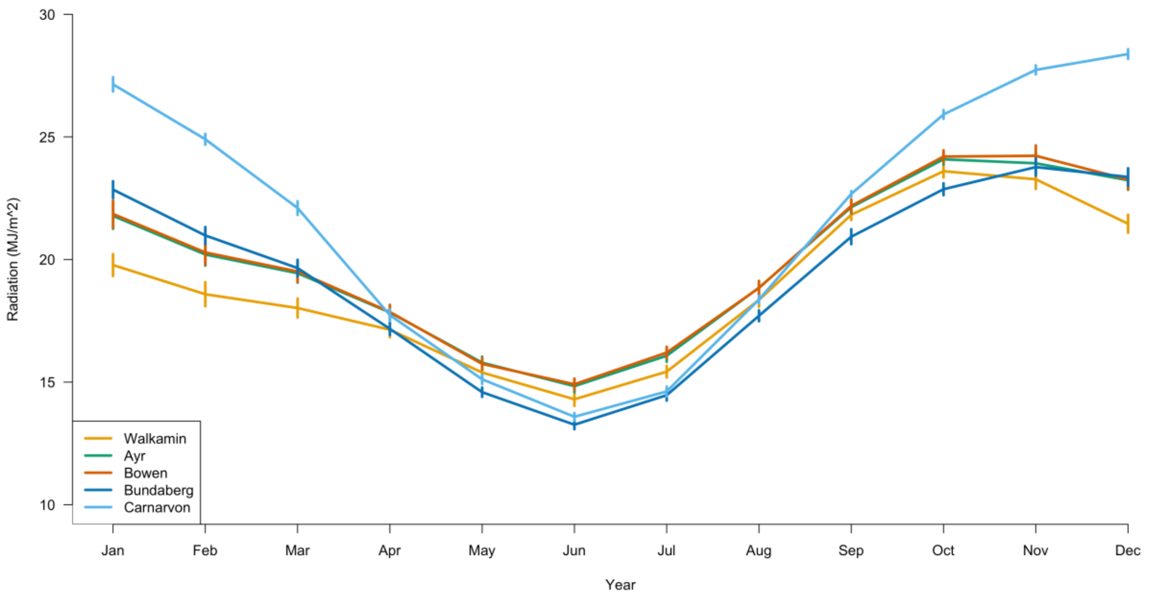


Figure 3. Monthly solar radiation (Mean±SE) for selected locations in the tropics and near the Tropic of Capricorn where protected cropping could be expanded.

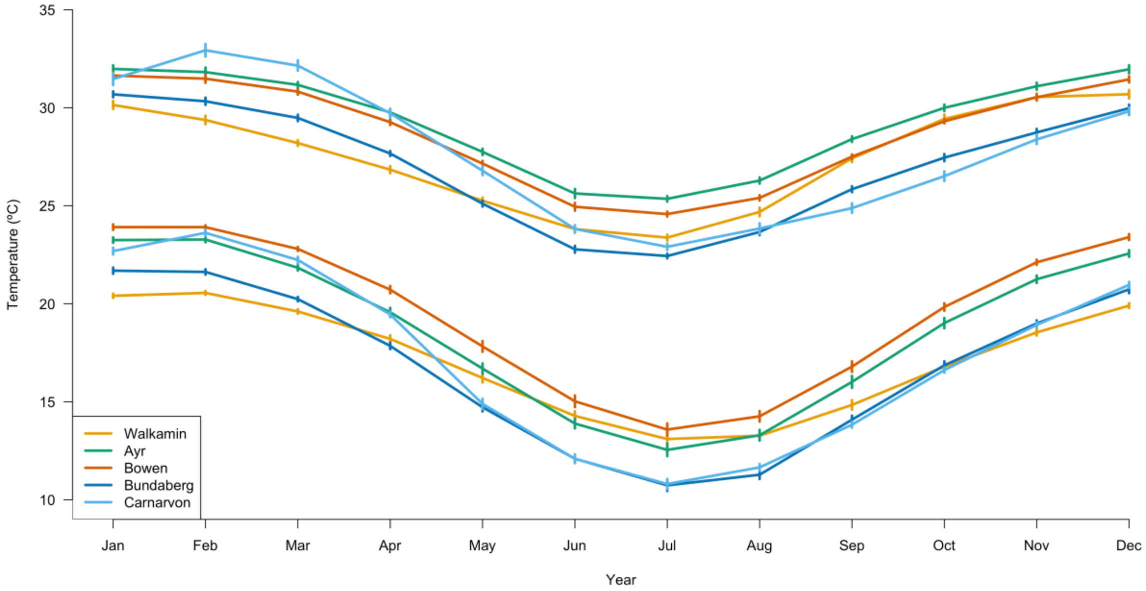


Figure 4. Monthly maximum and minimum daily air temperatures (Mean±SE) for selected locations in the tropics and near the Tropic of Capricorn where protected cropping could be expanded.

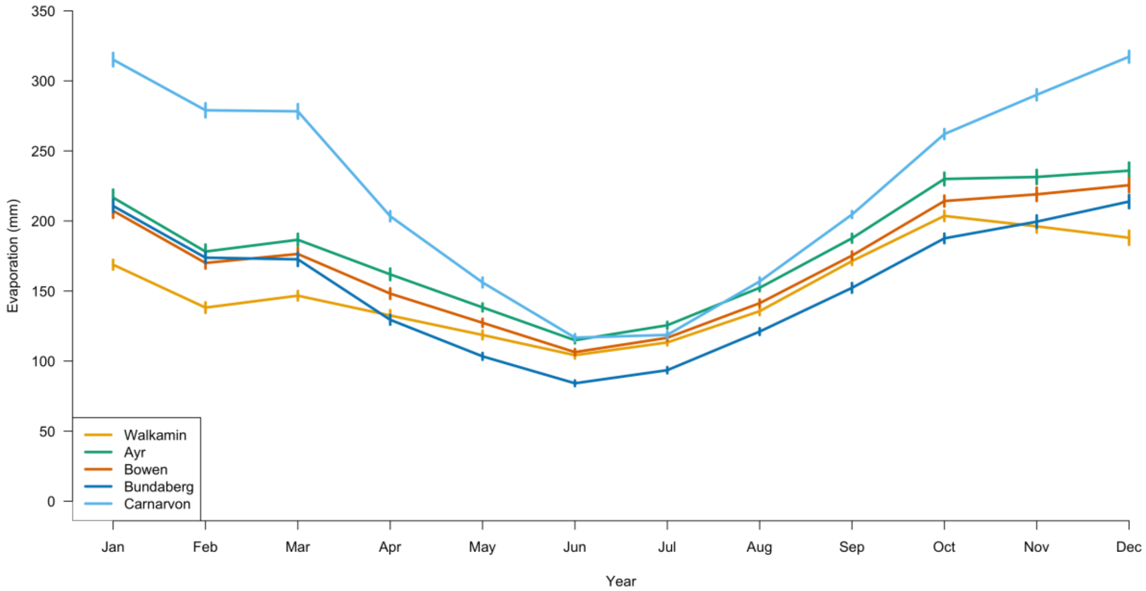


Figure 5. Monthly evapotranspiration (Mean±SE) for selected locations in the tropics and near the Tropic of Capricorn where protected cropping could be expanded.

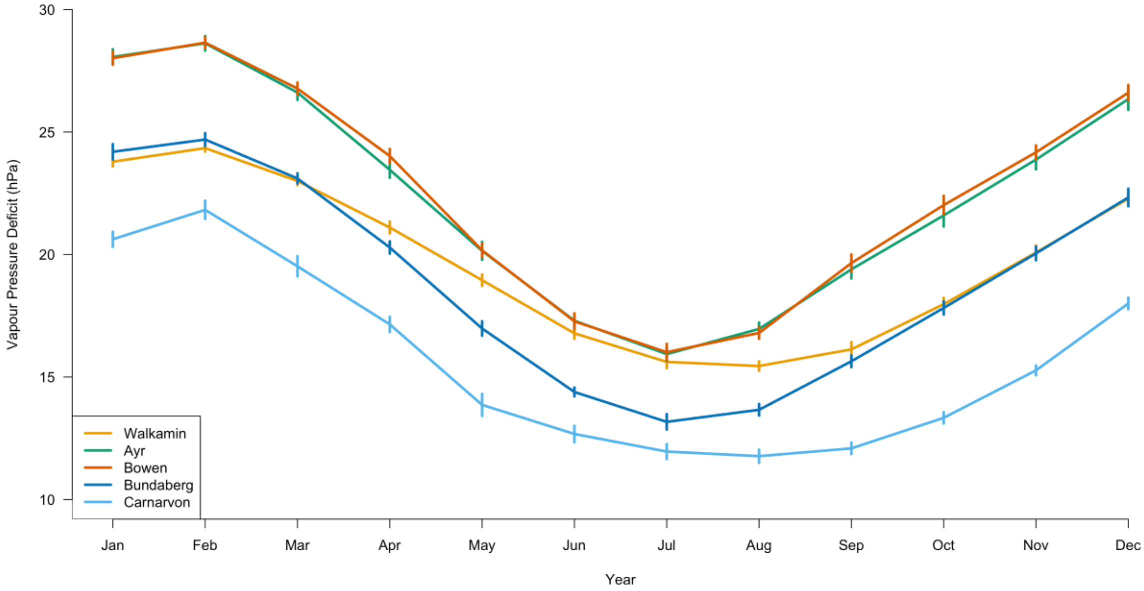


Figure 6. Monthly vapour pressure deficit (Mean±SE) for selected locations in the tropics and near the Tropic of Capricorn where protected cropping could be expanded.

Tropical cyclones

Tropical cyclones are of a concern to farmers who are using or considering the use of protected cropping systems in the tropics. Wind speed is the core aspect of tropical cyclones that will impact protective structures. For the purpose of selecting and setting up a structure design (and based on descriptions in Australian Standards AS/NZS 1170:2:2002), most of the coastal areas fall into the Wind Region C (e.g. Ultimate Design Wind speed will be 232 km/h for a Terrain Category 2, and 10 m Reference height) with some areas along the west coast of Australia falling into the Wind Region D (Ultimate Design Wind speed of 316.8 km/h, Terrain Category 2, and 10 m Reference height). When locations are inland, the wind regions change to B and A (Ultimate Design Wind speed of 186 km/h and 148 km/h, respectively). Terrain and reference height will affect the design wind speed values. A map with wind regions in Australia derived from Australian Standards AS/NZS 1170:2:2002 can be found in the publication 'Wind loads, Structural provision and loading' as part of the Toolbox: Greenhouse Construction and Safe Operation factsheets developed in the Hort Innovation project VG16004 *Developing technical guidelines and a best practice extension toolbox for greenhouse construction and safe operation* (https://static1.squarespace.com/static/58087866f7e0abd4e560f57d/t/590329b546c3c42efb8c4e55/1493379526316/7_Factsheet_Wind+loads_v1.pdf).

With destructive winds, damage to frames is more likely to occur when film and screen materials are left attached to the frame. Sometimes it is feasible to remove or retract the covering materials in order to avoid or minimise deformation of the frame (as the structure will be able to sustain higher wind speeds). In general terms, resistance to destructive winds will be very low in high poly-tunnels and will be superior in structures such as passively ventilated greenhouses and retractable roof structures. The selection on the structure type and modifications required to meet regional design wind speed levels, will have to take in consideration several factors, such as geographical location and terrain (topography); council regulatory building codes; insurance linked to loans; investment costs; potential payback period; and risk levels that can be managed; as well as the advice from engineers and company that supply the structure. A recent project, VG13055 – *Building Codes and Greenhouse Construction for inclusion in the National Construction Code*' and the technical guidelines to be developed after this project should advise the National Construction Code (NCC) and assist growers that are involved in the development of a new protected cropping commercial operation.

Historic information on cyclones by state can be obtained from the Bureau of Meteorology (BOM) website (http://www.bom.gov.au/cyclone/history/index.shtml). As an example for Queensland east coast, BOM reports that there is a strong relationship with eastern Australian tropical cyclone impacts and the El Niño-Southern Oscillation phenomenon, with almost twice as many impacts during La Niña than during El Niño. This information can be taken in consideration in financial and risk analyses when investments in protected cropping are planned.

The amount of heavy precipitation from any severe weather system, including tropical cyclones, has a large impact on vegetables grown outdoors. When protective structures and their covered crops are not affected, the benefits of this technology during rainy weather are greatly increased, as reduced supply from outdoor vegetable crops will command higher market prices. These unpredictable scenarios usually will shorten the payback period of a protective cropping investment.

Potential protected cropping systems tailored for warm environments

Adaptation and adoption of risk-mitigating technologies for vegetable crops in the Australian tropics could help overcome marketable yield losses caused by climate variability and extreme weather events and therefore ensure supply commitments. Climatic events affect different components of outdoor crop production. The losses incurred to crops under outdoor systems depend greatly on the intensity of the climatic event and the growth developmental stage of the crop. Crop losses can be related to mean climatic variations within time periods (e.g. suboptimal growing periods within a day, in a month, or during the year) and to extraordinary events that are more relevant than that of a mean climate parameter (e.g. flooding from intense rainfall). Recent examples of events causing serious damages on crops in 2017 include rainfall events (with strong wind and sometimes flooding) which decreased production of vegetables in the Burdekin and Bundaberg regions after Cyclone Debbie in late March, and in Bundaberg in October (http://www.abc.net.au/news/rural/2017-10-18/bundaberg-region-farmers-swamped-by-heavy-rain/9062004). For some vegetable crops, protected cropping structures can potentially address many of the above issues by providing a cost-effective control of the growing environment.

Structure designs

There are a range of potential protective structures for warm and tropical climates. Which structure design is best suited for a grower will depend on several factors which need careful consideration, such as the:

- Crop species to be grown and plant growing system;
- specific environmental and biological constraints of the location;

- desired level of environmental control;
- expected strength and durability of the structure; and
- investment budget available and broader value chain considerations.

Specific dimensions for structure width and spatial arrangement of crop rows will also need to be considered to ensure that crop management practices will be implemented in a cost-effective manner and marketable yield per square meter is maximised. The costs of the materials for the selected structures differ and structures have specific economies of scale in relation to the area to be covered. Labour and related costs for construction of structure may double the cost of materials. Growers with a small to medium business size may consider a plan to expand their protected cropping business gradually as opposed to adopting the more advanced technologies upfront. Industry awareness and knowledge of regulations associated with greenhouse construction and compliance can be obtained by accessing the Toolbox Greenhouse Construction and Safe Operation (http://www.greenhousetoolbox.com/) developed under project VG16004.

Protected cropping structures can be grouped in categories. One way focuses on broad technology categories that consider the type of structure design and also technology inputs that allow for crop environment control. These categories are defined as 'low' (e.g. walk-in poly tunnels), 'medium' (e.g. high roof passively ventilated structures) and 'high' (e.g. tall structures cladded with glass or polycarbonate and equipment to manage crop environment). From 'low' to 'high', the categories assume that investment costs increase. Therefore, the technology levels for protected cropping can be discussed using investment values per square meter of cropping area. They can also be discussed as possible periods for paying back the investment (e.g. 3; 5 and 10 years). It is essential that components included in the investment are clearly defined when using cost values to describe technology levels. It is also important to note that the descriptive categories mentioned are not definitive and that sometimes it is cost-effective to use technology components from different categories (e.g. hydroponic setup in a poly tunnel structure).

Regions in the tropics provide warm weather for growing vegetable crops and may only require protective structures that, by design, can mitigate high temperatures while acting as a rain barrier over the crop. When considering possible protective structure designs for warm environments this project focused on suitable low (e.g. poly tunnel structures that are tall) and medium-level technologies. As such, structures such as glasshouses were excluded. Such structures are usually equipped with advanced and more costly components which are required in temperate regions to effectively maintain close to optimum environmental conditions for plant growth and production. While this is not needed in warm climates, there are some components of glasshouse technology that can improve productivity and sustainability in the tropics. For example, automation and mechanisation of practices, particularly those that aim to reduce labour inputs, and reuse of drained irrigation solution in soilless culture all can be adapted for medium-level protected cropping technologies.

This project focused on four protective cropping structures that could be used to expand production in the tropics: a) walk-in, multi-bay polyethylene-covered tunnels; b) high passively ventilated greenhouses; c) retractable roof structures; and e) net houses. All these designs are used in warm environments, either to a small extent in the Australian tropics or, in warm climate locations overseas (e.g. within Mexico; South and Central America; Caribbean islands; South Eastern USA; Middle East; and regions in Africa). There are advantages and drawbacks with each design. There are also variations in design within each design category. The cost of the structures generally increases the more efficient they are in managing the plant environment and the more durable and wind-resistant they are. The four protective cropping structures are discussed below and summarised in Table 2.

High tunnels

High tunnels are light structures with steel arches covered with polyethylene film (Figures 7 and 8). In the tropics, air temperatures can reach undesirable levels when tunnels are low (<3 m) as the hot air becomes trapped under the arched dome shape of the roof creating a slow air exchange. High temperatures are associated with slow growth, low fruit set, and fruit physiological disorders. For warm environments, tunnel structures therefore need to be high, with vertical poles along their sides at least 2.5 m in height, and with roof arches reaching a height of at least 3.5 m at the centre of the arch. Structure height is especially important if the intention is to grow high trellised crops.

High tunnels are generally comprised of a series of connected structures, i.e. multispan arrangements. To improve ventilation, it is possible to partially retract the film along the length of the tunnel but this has to be done manually. This allows some air exchange along the connected tunnels. However, the additional labour required for this operation tends to be considerable. Tunnels can be fitted with large rain gutters to remove water from crops. Without gutters, a less desirable option is to make ground trenches to remove the water away from the cropping area. Most tunnel structures are not designed to support a trellised crop from the tunnel frame. Tall crops will require a separate trellis system, with wires and poles anchored into the ground. Normally, tunnels are not equipped with insect exclusion screens and doors. These accessories can be installed. In the tropics, the management of pests is more challenging without the use of insect exclusion screens. However, insect screens restrict air exchange.

The frame of tunnels is made of light steel, therefore only when wind speeds are low (<80 km/h), tunnels can resist deformation caused by wind. When cyclonic winds are forecasted to impact on large areas covered with tunnels, it may not be feasible to rapidly dismantle the structure because regional labour force, including seasonal backpackers, may not be available. This is an important consideration when thinking about setting up large areas with tunnels.

In the Bundaberg and Atherton Tablelands regions of Queensland, high tunnels are currently used in approximately 170 ha of blueberry crops. In these berry crops, as would be the case with vegetables, the main purpose of the structure is to provide some crop protection from rainfall, wind and high solar radiation.

Several vegetable crops (capsicums, melons, eggplants, and cucumbers) have been evaluated by Queensland DAF using soilless culture under a simple high tunnel structure since 2013. The particular structure tested in the Burdekin was covered with a commercial grade of woven UV stabilised polythene "fabric" (polyweave film). The polyweave film is durable (6-7 years versus 3 years for polyethylene film) and the whitish-clear colour option creates diffused light and shading, which have proved to benefit crops such as capsicum in the dry tropics. Crops such as specialty melons may perform better under clear films which allow higher solar radiation levels over the canopies.

Tunnels can be set up as semi-permanent structures as they can be relocated with relative ease. Some designs have an auger at the bottom of the steel posts and can be anchored directly into the ground without the need for concrete. This pole installation feature may be useful for soil-grown crops because at some point in time, relocation may be required as a strategy to manage soil borne diseases.

Tunnels have the lowest cost compared to the other structures discussed in this report. Tunnels are sometimes considered an entry level option for growers who aim to learn about protected cropping technology with very low investment costs. It may also be an option for growers intending to have a small area of covered crops or for growers who would like to take a step-by-step approach to adoption of different levels of protected cropping technology.

Local government restrictions may not allow the placement of structures that do not meet wind speed designs for a particular location and cyclonic region. Moreover, growers who plan to setup larger areas with tunnels and rely on investment loans may be required to have these structures insured. Insurance may be difficult to obtain when structures do not meet building requirements for the region.

Figure 7. Examples of high tunnels as light low cost structures which are generally open or can be equipped with insect exclusion screens on the front and sides of the multispan arrangement. (Image source: <http://www.tierrafertil.com.mx> and <http://www.haygrove.com/au>).

Figure 8. Tunnels where capsicums are grown supported with low stakes in soil (left) and where capsicums are grown in soilless culture, reaching to heights up to 2.5 m when plants are supported by poles and twine from both sides of the canopy (right). Whitish polyweave was used to cover this tunnel in the tropics (bottom). (Image source: DAF and <http://www.haygrove.com/au>)

High passively ventilated greenhouses

Compared to tunnels, high greenhouses covered with a polyethylene or polyweave film are much larger and comprised of stronger steel, with bays that typically span 9.6 m and are at least 4.5 m in height (floor to the gutter). The roof is curved but arches are offset to create a roof vent. These vertical openings in the roof vent have areas that are usually in the range of 15% to 25% of the total roof area, and they allow the escape of warm air through passive ventilation (Figure 9). The extent of escape of hot air greatly depends on wind speed and wind direction. Coastal regions may have prevalent winds that increase the air exchange rate in these structures. Locating structures at higher altitudes in the tropics may also provide benefits for cooling. There are variations in the design of the roof vents which can be uni- or bi-directional. Uni-directional roof vents give the roof of a multispan greenhouse a “saw tooth” pattern. The higher peak (>6.5 m) and presence of roof vents creates improved ventilation for trellised crops.

As with the tunnels, the roof covering is fixed. To reduce inside temperatures, crops can be shaded by adding a screen that can horizontally move (preferable) or is fixed (not desirable) inside the greenhouse. Sometimes a low cost option for shading is the spray of whitewash paint over the roof cladding (which later needs to be removed). In the tropics, fogging systems installed inside greenhouses and over the crop canopies can assist in two ways: by increasing air humidity, something that may be needed during dry seasons, and by lowering leaf temperatures. When managed properly, fogging leads to improvements in crop growth and fruit, and light levels are not affected.

High passively ventilated greenhouses are a common structure used in desert areas and tropical regions around the world. The steel frames of these structures are stronger than in high tunnels and provide greater protection against strong winds and better support for trellised crops hung from the structure. The structures are equipped with rain gutters which may need to be larger in regions with high precipitation. Polyethylene films and screens still need to be manually removed when cyclonic winds are forecast, something that may be unfeasible in large protected cropping areas. In warm regions, the decision whether to include or not the insect exclusion screens is a dilemma as one needs to balance the benefits of increased ventilation with prevention of incoming insect pests. While these structures are high and allow for trellising crops upright, temperatures can be excessively high during late spring and summer.

A structure with these characteristics has been operating commercially in the dry tropics region since 2002, and crops such as cucumbers and tomatoes have been grown successfully to supply local and southern markets. More recently, in the Burdekin region, evaluations of capsicum, melon and eggplant production have been conducted under this type of structure with yields and fruit quality outcomes that are comparable to those obtained in tropical environments overseas (see Table 3).

Figure 9. Examples of high passively ventilated greenhouses with roof vents used in the tropics (Image source: DAF).

Retractable roof structures

Retractable roof structures are tall structures with gutters at heights of >4m. The key characteristics of this design is that the roof cladding can be retracted. This makes them very efficient in letting hot air escape from the crop environment (Figure 10). This design is an advantage in the tropics, as the roof can also close completely in minutes to protect crops from rain. The crop can be exposed to full sun under good weather conditions, or can be shaded with retractable screens. The cladding is usually comprised of a strong polywave film, which can be clear and whitish. Retraction is relatively quick and stepwise, and can be automated and linked to weather conditions and climate parameters inside the greenhouse. The level of retraction modifies temperature, air humidity and radiation levels and it is used to mitigate plant stress during periods in the day when radiation and temperature are high. During noon and afternoon hours or during summer periods, it is easier to remove heat from the crop in these structures compared to passively ventilated greenhouses.

These structures have high lateral sides covered with insect exclusion screens. These screens help reduce the effect of wind on crops, even when the roof is retracted. There is also the possibility of having a fixed or retractable insect exclusion screen below the impermeable film. When this screen is extended, it can be used to exclude insect pests. When insect pollination is required, the screen can be retracted for periods to allow the entrance of bees. The frame of the structure can support trellised crops. There are several retractable roof design models. In regions where rainfall is expected to occur, sloped roofs should be considered. Otherwise, there are designs with flat roofs.

These structures have not yet been evaluated for vegetable production in the northern Australian tropics. In Bundaberg, Queensland, successful vegetable crops have been obtained in a 4-ha structure built in 2015. Recently, such structures have been built in temperate and subtropical regions for production of tomatoes, capsicums and leafy crops (as well as for protection from rain in cherry trees in Tasmania). Examples of good crop performance and crops harvested for long periods (cucumbers, eggplants and tomatoes planted in August 2016 and with some crops still being harvested in May 2017) were observed in Culiacan, Mexico, during the study tour.

In circumstances where a severe cyclonic event is forecasted to pass near the structure, the roof film and net can be completely retracted and secured to protect these materials and the frame structure. This operation can be done fairly rapidly (<5 min) with minimum labour when compared to the removal of films in passively ventilated greenhouses and in tunnels.

Figure 10. Examples of retractable roof structures with peaked roofs. There are also models with flat roofs used in overseas regions where rainfall is low. A commercial retractable roof structure in Bundaberg was setup in 2015. Four extreme weather events (storms with intense wind and rainfall) between 2015 and 2017 demonstrated the level of protection that these structures can provide to vegetable crops (tomatoes and capsicums). On sunny days, the roof can be opened totally or partially to modify solar radiation, soil and crop temperatures, and air relative humidity. Similar structures have been operating in warm climates such as Florida, USA, Mexico, South Africa and Turkey (Image source: (Images source: DAF and <https:/www.cravo.com>).

Net houses

Net houses are also known as screen houses or shade houses. The frame of these structures is made of poles (wood or steel), steel cables and wire. An insect exclusion netting covers the roof and sides of the structure. The side nets are lifted when using machinery for soil preparation. Cultivation under nets is done similarly to the way it is done in field crops but higher trellis systems (either stakes or high wire and strings for support of plant canopies) are used to prolong the harvesting season.

The main purpose of this protective structure is to provide shade to crops and exclude insect pests that damage or transmit plant viruses to crops. It is not designed to protect crops against rain water. As such, these structures tend to be used in desert areas or where dry seasons are long.

Net houses are used in Middle Eastern countries, Mexico and Spain. They are used extensively in the Culiacan region, in north-west Mexico (Figure 11). Crop management under net houses varies from an extensive array of practices (similar to field production) to ones that are similar to what it is practiced in greenhouses. Crops such as capsicums, eggplants, cucumbers, and tomatoes are grown in soil, on mulched beds, and use drip irrigation. The partial shading protects crops from high solar radiation and wind, leading to greater marketable yields, with fewer occurrences of fruit disorders such as blossom-end rot and sunburn, compared to when they are grown outdoors. In Mexico it is common to see prevention strategies to minimise pest and disease entering the net houses. The entrances to the structures are equipped with foot sanitation baths (to prevent bringing soil pathogens inside) and hand sanitation stations (also for food safety issues), and can have double or even triple doors that follow a zig-zag path (to minimise outdoor wind from blowing into the structure). It is also common to see all entrance walls covered with yellow and blue sticky film in order to trap any incoming aphids, whiteflies and thrips.

Net houses have been used to some extent in Carnarvon, WA (Figure 11). Capsicums under these structures commonly yield approximately 7 kg/m^2 but yields can be lower (3 kg/m^2) or higher (up to 10 kg/m^2) depending on crop length, environmental conditions and disease pressure (Neil Lantzke, Western Horticultural Consulting, personal communication). In Culiacan, Mexico, the structures are partially dismantled at the end of May, when the hurricane season commences. Net houses in Carnarvon face a similar challenge with cyclones affecting the region and damaging the structures.

There is potential for net houses to be evaluated in other dry areas in the tropics, such as in areas inland from the coast if water is available, and where dry seasons are long. The insect exclusion component, together with a pest prevention plan, would be key components of an integrated pest management (IPM) plan to manage key pests and viruses in vegetable crops.

Figure 11. Capsicums grown under net house structures in Culiacan, Mexico (left) and in Carnarvon, WA (right image sourced from Department of Primary Industries and Regional Development, WA).

Table 2. Summary of characteristics of the four selected protective structures that could be used for vegetable production in the tropics.

		Net houses	Tunnels	Greenhouses	Retractable roof
Improved crop environment		→	→	→	→
Typical use in warm environments		Desert areas or regions with long dry seasons and for dry season production only. Production will be challenging during hot wet summers.	Dry seasons with variable rainfall. May have limited use if frequent strong winds affect the location. Production is more challenging during hot summers.	Dry season with variable rain. Production may be more challenging during hot and humid summers.	Year round production in regions with dry seasons, variable rain, or with frequent rain. Several models to address specific typical environmental conditions.
Crop protection	**Rain**	No. Salts can be leached with rain.	Yes, but ground drainage is required when rain gutters are absent. Lateral curtains absent.	Yes. Roof film fixed, open sky over crop is not an option. May have side rollup curtains for lateral rain and wind protection.	Yes, open sky over crop is possible. In soil culture, salts can be leached with rain. May have side rollup curtains for protection from lateral rain and wind.
	Solar radiation	Partial shading control. May have whitewash shading or fixed shade screens on top of netting.	Partial shading control. Manual operation. Whitewash shading or fixed screens.	Whitewash shading or fixed shading screens. May have movable shading screens with mechanical and automated operation.	Can have retractable shading screen with mechanised and automated operation.
	Wind	Good protection but provided by screens only. May require a	Tunnel sides usually open. May require a wind break.	Good. Side curtains can be closed.	Very good. All around netting also acts as wind barrier when roof is retracted.

		Net houses	Tunnels	Greenhouses	Retractable roof
		wind break.			Side curtains can be closed.
	Heat *(cooling advantage)*	All screens clad the frame. Passive ventilation. Shading increases humidity (may be good or bad) and reduces light over crop.	Improved when tunnels are high. Shading increases humidity. Climate automation not available.	Passively ventilated through roof vent and sidewalls. Curtains on side walls and roof vent can be automated on climate parameters. Movable shades can moderately assist with cooling. Fogging may be added.	Passively ventilated with roof opening at many different retraction levels. Roof retraction and sidewalls are automated by climate parameters. Humidity can be managed with roof retraction and retractable shading screen. Fogging may be added.
	Cool nights	Little or no protection	Little protection as all sides are opened	Reduced heat loss when roof vent and side curtains are closed	Reduced heat loss when roof and side curtains are closed
	Insect pests	Fixed screens on roof vent and sidewalls assist with pest exclusion	Screens normally absent. Open areas between spans and all-around sides can be covered with screens or bird nets.	Exclusion screens on roof vent and sidewalls. Screened roof vents reduce air exchange.	Screens on sidewalls and fixed or retractable screens below retractable roof assist with pest exclusion. Roof screens can be opened temporarily to allow bees inside (for crops that require insect pollination).
Structure					
	Strength *(Check with manufacturer and specific models. For wind regions see descriptions in the Australian Standards (AS/NZS*	Light galvanised steel materials or wood poles. May resist up to 80 km/h winds. Screens have to be pulled out manually when cyclonic winds are	Light galvanised steel materials. May resist up to 60-80 km/h winds. Cladding has to be pulled out manually when cyclonic winds are forecasted.	Strong and durable galvanised steel materials. May resist up to 140-170 km/h winds. Cladding may have to be pulled out manually when cyclonic winds are forecasted.	Strong and durable galvanised steel materials. Various models. May resist up to approximately 180 km/h winds when closed and even higher wind speeds (200 km/h) when roof and side

	Net houses	Tunnels	Greenhouses	Retractable roof
1170:2:2002)	forecasted. A step-up in technology are specific models of tall net houses with fixed or retractable flat roofs, which are stronger and can resist wind speeds up to 110-120 km/h.			cladding is retracted.
Crop support	Normally not linked to structure frame but is in some cases.	The light frames are not designed to support crops. A separate plant support needs to be anchored into the ground.	The stronger frames are designed to support crops. With some trellis systems, poles may be required to support crops such as capsicums and eggplants.	The stronger frames are designed to support crops. With some trellis systems, poles may be required to support crops such as capsicums and eggplants.
Removal of covering materials	No. Needs to be done manually.	No. Needs to be done manually.	No. Needs to be done manually.	Yes and can be done rapidly. Allows taking better decisions based on weather forecasts. Retracted cladding may need to be tied to frame.
Relocation	Relatively easy. May be required if soil health problems cannot be remediated.	Relatively easy if footings have the auger design and are not in concrete. May be required if soil health problems cannot be remediated.	Not easy. In soil culture grown crops, a soil health plan needs to be put in place (e.g. including practices such as soil salts lixiviation; crop rotation; cover crops; grafting; organic amendments to soil; and solarisation)	Not easy. In soil culture grown crops, a soil health plan needs to be put in place (e.g. including practices such as soil salts lixiviation; crop rotation; cover crops; grafting; organic amendments to soil; and solarisation)
Expected life	8 to 10 years (maintenance required with wood poles and if wind causes minor damage). Expected replacement of screens is every 6-10 years depending on quality.	8 to 10 years (maintenance required if wind caused minor damage). Expected replacement of roof cladding is every 3-4 years (polyethylene film). Some tunnels can be cladded with polyweave film (8-year life)	+15 to 20 years (maintenance required, especially on movable components). Expected replacement of roof cladding is every 3-4 years (polyethylene film) or 8 years (polyweave film)	+20 years (maintenance required, especially on movable components). Expected replacement of roof cladding is every 3-4 years (polyethylene film) or 8 years (polyweave film)

	Net houses	Tunnels	Greenhouses	Retractable roof
Cost of materials *Economies of scale will apply on material costs. Construction costs are variable. As an approximation, they can be estimated to be 70% to 100% of the cost of materials.*	\$5-\$10 per m^2 of covered ground area.	\$13-\$20 per m^2 of covered ground area.	\$30-\$50 per m^2 of covered ground area.	\$40-\$70 per m^2 of covered ground area.
Availability in Australia	Yes	Yes	Yes	Yes

Key agronomic practices

Specific inputs and management practices used in protected cropping technologies in warm climates can be tailored to increase yields and minimise the risk of crop losses. There has been limited exploration of opportunities for extending suitable protected cropping technologies in warmer regions of the tropics, such as the north eastern coastal strip regions of Queensland. Traditionally farming only outdoors, vegetable growers in these regions and linked value-chain stakeholders, require more information on the benefits and challenges of a production system that is new to them and the region.

Protected cropping using glasshouses (usually used in temperate regions), with active heating and cooling, are more capital intensive than field cropping and most farmers may be unable to make such an investment. Low and medium cost protected cropping usually entails a shorter investment payback period and lower operating costs compared to high-end technologies aimed at achieving a 'near-to-optimum' plant environment in order to obtain maximum yields.

Components and inputs required for protected cropping production in warm environments are available in Australia. Most would be similar to those used in the protected cropping industry established in temperate regions and can be sourced through the main industry suppliers. Key agronomic practices that relate to production when using low and medium cost technologies are discussed below.

Heating

Provision of additional heating through the burning of fuel is one component that is not necessary in almost all protected cropping scenarios in the tropics. This significantly reduces investment and operating costs. Depending on location, having lateral rollup curtains in larger structures will enable the structure to be closed during cool nights in June and July to increase inside air temperatures 1 to 2°C above outside air temperatures.

Cooling and shading

Cooling systems may be required even in taller structure designs. Additional ventilation assisted by the use of electric fans would be beneficial during warm and humid periods in the year. The increased costs from adding and operating fans will have to be compared with the production benefits they provide in each location. Automated shading systems would also be beneficial in high passively ventilated greenhouses. In tunnels, shading can be created by spraying the roof with whitewash paint products in the spring season or by using whitish polywave films. The whitish polywave films create diffuse light and can be used in retractable roof structures and greenhouses. Fogging systems act by cooling the crop canopy through evaporation of a fine mist applied to crop canopies. When operated properly, fogging provides cooling to the crop canopies, particularly during dry conditions. Shading and fogging systems will be important components when growers plan to either maintain or establish crops in the summer. Fogging may not be effective in the wet tropics or during periods of high humidity.

Among structures of medium-level technologies, retractable roof designs are the most innovative systems for protected cropping in warm climates. Currently, there are no examples of vegetable crops grown under these systems in the Australian tropics but they are expected to perform very well. These structures have been improved from earlier designs used overseas for more than 20 years (e.g. now can be equipped with insect exclusion screen below the retractable roof). Retractable roof structures are a recent technology option for growers in Australia. The retraction of the roof is operated by a controller that uses inputs and records of climate parameters. The grower, with assistance from the manufacturer, will still need to make adjustments in the controller inputs so that the roof operation performs in line with different cropping scenarios and local environmental conditions.

Root media, irrigation and fertilisation

A main factor that will differentiate the way crops are watered and fertilised relates to how the plants will be grown: in soil or in soilless media. There are commercial enterprises using these two culture systems in the tropics. Soil culture will require attention to practices that sustain a healthy soil in order to minimise problems in crops (e.g. due to soil borne diseases and plant parasitic nematodes). Well thought-through, integrated soil management programs need to be implemented and monitored (e.g. including practices such as addition of compost; rotating crop species; lixiviating soil salts; crop hygiene practices; use of cover crops; grafting onto rootstocks with resistance to diseases; and potential use of solarisation). In soil culture, it will be important that water and nutrient supply are managed to avoid unacceptable amounts of nutrients lixiviated below the root zone as they will have negative impacts in underground water. Monitoring nutrients in soil and fine tuning fertigation practices to different soil types will assist with the development of environmentally sustainable systems. This is an area where R&D and capacity building is needed to support the industry if there is an extensive adoption of soil culture systems.

Soilless culture allows for better control of crop growth and yields are greater and more consistent, with improved fruit quality outcomes. Nowadays it is becoming the system to adopt in new protected cropping investments, as in most cases it is required to grow the same crop species under the structure year after year. However, this system requires a level of knowledge that new growers or growers used to grow field crops may not have. The initial investment in soilless culture is high. Sometimes production during the first years can be started with soil culture, and as experience is gained with other cropping practices (e.g. pruning and trellising and pest and disease management) changes can be made to set up (sometimes initially in a smaller area) a soilless culture system. These decisions will depend on the grower’s experience and size of the protected cropping area.

The equipment to deliver water and nutrients to the crops will be similar to those currently used by the protected cropping industry. Fertigation of plants growing in warm environments is slightly different than in temperate climates. In the tropics the nutrient solution will have lower concentration of nutrients and the delivery to plants will have to be more frequent. Modern fertigation controllers allow for changing the concentration of the nutrient solution based on climate parameters.

For soilless culture, there are several options for type of media and size and shape of plant containers. Because plants in the tropics will require frequent irrigation, it will be important to select media with physical characteristics that will allow a good balance between water holding capacity and drainage. There are commercial media for soilless culture but there are also media that can be obtained in the regions themselves (usually a by-product of a regional industry) that may be cost effective and very suitable for production.

Nowadays, the vegetable industry is aware of the environmental impacts caused by nutrients and pesticides leaving the farm. Therefore, soilless culture with open drainage systems should not discard the nutrient solution that drain from the plant containers out into the environment. If open systems are used, the drainage should be collected and used to fertigate field crops. A better option would be a closed (recirculating) system, where the drained nutrient solution is collected and then sanitised before nutrient levels are corrected to be delivered again to plants.

Crop canopy management

In long season crops, pruning and vertical support of the plant is critical, as it will allow higher plant population densities and prolong the harvesting period. These practices have to be done efficiently (see comments below on mechanisation under the 'Labour' subheading) if not, the additional yield benefits may not cover the costs of the labour involved. In some production scenarios, such as in large protected cropping areas, the simplification of pruning and trellising practices can lead to crops that resemble practices used in field crops. However, these will lead to lower yields because plants will be smaller and the harvest season will be shorter. In some cases (e.g. large enterprises) this may be cost effective, especially if there are labour constraints (e.g. lack of a permanent workforce) and training of temporary unskilled workers is too costly or may not be feasible. Evaluations and demonstrations have been carried out by DAF in north Queensland to show that in crops such as capsicum and eggplants, simple plant trellising practices with minimum pruning can lead to good fruit yield and fruit quality with reduced use of labour (e.g. "Spanish" trellis system versus the "V" system) (Figure 12).

Genetic materials

Cultivar evaluations are usually conducted in commercial protective structures and the information about performance is often kept by the grower or may be available from seed companies. Overseas, and in places where the protected cropping industry has expanded, seed companies organise trials for growers to visit. Cultivar evaluations in the tropics should include genetic materials that are known to perform overseas under similar warm environmental conditions. This also includes the testing of rootstock materials which is now a common practice in the protected cropping industry overseas (in soil and soilless culture systems). Seed companies have been supporting the small R&D work in the Australian tropics, knowing that the industry may expand in the future.

Pests and diseases

Pest and disease management for the tropics should be focused on the use of biological control agents and soft chemicals. The use of insect exclusion screens, regular crop monitoring, implementation of crop hygiene practices and preventive management practices will solve a large number of pest and disease problems (and therefore reduce the use of pesticides). The key pests that have been observed under structures in north Queensland are: whiteflies, aphids, thrips, and mites (broad mites and spider mites and to a lesser extent russet mites). Grubs are usually present when insect exclusion screens are not used. The main disease that has been noticed in the dry tropics has been the powdery mildew of Solanaceae crops (*Leveillula taurica*). Many biological control agents that perform in cooler environments may not be effective in warm environments. Evaluations of releases of predatory mites and parasitoids and the use of banker plant systems have been promising.

Labour

Mechanisation of practices under the structures will help support the expansion of protected cropping systems. Beyond the use of robotic technology, there are simpler technological applications which can reduce fatigue in workers or assist in operations that would be otherwise carried out entirely using human labour. Some of this technology may need to be either imported or developed in Australia. Some of these technologies that are used in the glasshouse industry can be modified for medium technology levels of protected cropping. For example, pipe rails used for heating in temperate regions are also used for guiding different equipment in glasshouses (e.g. harvesting trollies, platforms with lifts, sprayers, etc.). In the tropics, heating pipes are not necessary but cost-effective systems need to be designed for moving or the functioning of equipment and to reduce labour costs. Considerations of how some practices can be mechanised to reduce labour costs will be critical. During the study tour in north-west Mexico, growers visiting the protected cropping industry in that region remarked: “How can you replicate these crops in a domestic scenario, considering that our labour cost per hour in Australia equals to the labour costs in a day in Mexico?”

Potential vegetable crop species and indicative yields under protective structures

Consideration was given to vegetable and fruit crop species that are grown to harvest their fruits; that have plants that can be supported upright to produce during a long harvesting period; and that benefit from being grown in warm and dry environments. In the tropics of Australia there are examples of such crops. Cucumber, capsicum, eggplant, specialty melons, and tomato have been grown successfully in commercial protective cropping enterprises or as part of DAF’s research evaluations and demonstration plots under commercial structures. These vegetable and fruit crop species are currently grown in the tropics outdoors during the ‘normally’ dry seasons. Some key aspects to consider when deciding on which crop to grow under protective structures are:

- Market opportunities for the crop and sufficient value chain information to target either domestic (local or distant markets) or export markets,
- the increase in yield and improvements in fruit quality that can result from using cost-effective protected cropping systems in comparison to outdoor production,
- the availability of cultivars that perform well under warm environments, and
- the knowledge on specific agronomy practices that is required to successfully produce differentiated commodities.

Values of marketable yields of crops grown under protective structures in warm environments are presented in Table 3 for selected crops. The production values are indicative, as there are many factors that can lead to variations in yield (e.g. cultivar, cropping period, and agronomical practices).

Table 3. Examples of marketable yields that have been achieved in vegetable crops grown under selected protected cropping in warm environments.

	Indicative yield for protective structure[a] and growing system				
	Net house	High tunnel		Passively ventilated greenhouse	
Crop	Soil (kg/m^2)	Soil (kg/m^2)	Soilless (kg/m^2)	Soil (kg/m^2)	Soilless (kg/m^2)
Cucumber	5-8	6-10	8-15	8-13	15-25
Capsicum	3-9	5-8	6-18	8-13	9-20
Eggplant	4-7	5-7	6-10	5-8	10-15
Melon	3-6	5-8	7-9	7-10	8-11

[a]Retractable roof structures: Yields in these structures can be estimated to be slightly greater than in the passively ventilated greenhouses and have lower yield variability as a result of an improved management of the crop environment. Some values from trials in soil were reported in Mexico for capsicums (10-13 kg/m^2) and cucumbers in soil (8-16 kg/m^2).

Estimates on yields and on production and value for areas of production

According to Protected Cropping Australia (PCA, 2016), and based on an RIRDC report (RIRDC, 2012), the Australian protected cropping industry had an estimated value of $1.8billion at the farm-gate per annum in 2009, which accounted for approximately 20% of the total gross value of production of vegetables and cut flowers combined. In recent years, the expansion of the area covered with protective structures in Australia has been in the range of 4 to 6% per annum (PCA, 2016). While this investment and expansion of protected cropping production systems has been significant, most of the growth has been concentrated in temperate regions of Australia. Recent estimates indicate that the total area of greenhouse-grown vegetables in Australia is 1,341 ha, of which 500 ha (37%) are in New South Wales and 580 ha (43%) are in South Australia (Smith, 2016). Smith (2016) estimated 30 ha (2%) of greenhouse-grown vegetables in Queensland but the current area dedicated to vegetables may be close to 40 ha when adding the recent setup of high tunnels and retractable roof greenhouses. The segment of the industry dedicated to producing vegetables using protected cropping technologies near and north of the Tropic of Capricorn is scattered and relatively small. A rough estimate of this total area including tunnels, greenhouses and net houses with vegetable production is estimated at approximately 80 ha.

The selected vegetables in Table 3 are examples of crops currently grown in Australia that in regions with warm environments could benefit from protected cropping technologies. Calculations were performed to provide approximate estimates of yields and production value per unit of area for crops grown under cover in a year (Table 4). Estimates for volumes of production (Table 5) and values of production (Table 6) were also calculated for crops established using protected cropping technologies in several hypothetical areas (i.e. from 1 to 100 ha as examples).

For the approximate 80 ha of protected cropping estimated to operate in the tropics in 2016-17 and assuming a gross return in the order of $90/m^2 (based on values presented in Table 5), the value of protected cropping production of vegetables in the tropics could be valued at approximately $72 million.

Table 4. Estimated yields for selected vegetable and fruit crops grown under protected cropping systems and estimated gross value for selected market prices assumed for greenhouse-grown produce.

Crop	Estimated yield (kg/plant)	Estimated yield[a] (kg/m^2)	Crops/year same area[b]	Example price[c] ($/kg)	Estimated gross value[d] ($\$/m^2$)
Capsicum	4.3	13	1.5	7.00	136.50
Cucumber	4.0	12	3.0	3.00	108.00
Eggplant	4.0	12	1.0	4.00	48.00
Melon[e]	3.0	9	3.0	4.00	108.00

[a] Selected yields obtained with high quality produce from production systems in soil (capsicum, cucumber, eggplant) and soilless (specialty melons).
[b] Number of crops assumed to be grown in the same area in a year.
[c] Example of price values reported for high quality produce sourced from produce wholesalers and growers.
[d] Estimated gross value ($\$/m^2$) = Estimated yield per crop (kg/m^2) x Crops/year x Example price ($/kg)
[e] Specialty melon (e.g. fruit types Galia, Charentais, or Canary).

Table 5. Estimated production volumes that could potentially result from adopting protected cropping in selected vegetable and fruit crops assuming yields listed in Table 5.

Crop	Estimated annual volumes (t x1000) from hypothetical levels of protected cropping adoption (ha)					
	1 ha	**5 ha**	**10 ha**	**20 ha**	**50 ha**	**100 ha**
Capsicum	0.13[a]	0.65	1.30	2.60	6.50	13.00
Cucumber	0.12	0.60	1.20	2.40	6.00	12.00
Eggplant	0.12	0.60	1.20	2.40	6.00	12.00
Melon	0.09	0.45	0.90	1.80	4.50	9.00

[a] Estimated annual production volume (t x1000) = Estimated yield per crop (kg/m^2) x Crops/year x Area of adoption with protected cropping (ha). Examples for adoption from 1 to 100 ha.

Table 6. Estimated gross values that could potentially result from adopting protected cropping in selected vegetable and fruit crops assuming yields and prices presented in Table 4 and production estimated in Table 5.

Crop	Estimated value of production ($m) from hypothetical levels of protected cropping adoption (ha)					
	1 ha	**5 ha**	**10 ha**	**20 ha**	**50 ha**	**100 ha**
Capsicum	1.6[a]	7.9	15.8	31.5	78.8	157.5
Cucumber	1.2	5.9	11.7	23.4	58.5	117.0
Eggplant	0.5	2.4	4.8	9.6	24.0	48.0
Melon	1.1	5.4	10.8	21.6	54.0	108.0

[a] Estimated value of production ($m) = Area adopting protected cropping (ha) x Volume of produce estimated in Table 5 (t x1000/1-100ha) x Estimated price for produce presented in Table 5 ($/kg x1000). Examples for adoption from 1 to 100 ha.

Commodities grown from field crops and from protected crops are generally different. It is important to note that protected cropping systems would most likely be used to grow specific fruit types and cultivars. This produce will be different from the same vegetable species grown outdoors. To relate the previous estimated values for the selected four crops in Tables 5 and 6 to total production of these crops in Australia, a table with production and value statistics from the 2014/15 Australian Horticulture Statistics Handbook (Hort Innovation, 2016a; Hort Innovation 2016b) is presented in Table 7. The origin of the data and methodology for reporting the statistics are described in the Australian Horticulture Statistics Handbook. With the exception of cucumber (largely produced in greenhouses), crops such as capsicums and melons are by large produced in the field. In the recent years there has been an increase in production of eggplants in greenhouses therefore values in these statistics may contain field and greenhouse production.

Because data for area and production and value of production were compiled from different information sources, the estimation of average yield per m^2 (calculated as production divided by area) and value of production per m^2 (calculated as value of production divided by area) for the selected crops are indicative and presented only for the purpose of an approximate comparison between outcomes in field production systems and potential outcomes when using protected cropping.

Table 7. Production of selected vegetable and fruit crops grown in Australia (2014/15) and estimated average yields and value per unit area. Data extracted from the Australian Horticulture Statistics Handbooks 2014/15 (Hort Innovation Australia, 2016a; 2016b).

Crop	Total Production Australia 2014-15 Gross value ($m)	Volume (t x1000)	Area (ha)	Average yield[a] (kg/m^2) (= 10 t/ha)	Gross value per unit area[b] ($/$m^2$)	Major production areas
Capsicum	144.7	69.0	1950	3.5	7.42	Bowen, Burdekin, Bundaberg (QLD); Carnarvon (WA)
Cucumber	183.5	79.8	800[c]	10.0[d]	22.94	Bowen, Bundaberg (QLD); Riverland (SA)
Eggplant	16.2	8.1	780[e]	1.0	2.08	Bowen, Burdekin, Bundaberg (QLD); Sydney region (NSW); Goulburn valley (VIC)
Melon[f]	69.5	51.6	3500[g]	1.5	1.99	Bowen, Burdekin, Bundaberg (QLD); Darwin (NT); Cowra, Riverina (NSW); Sunraysia (VIC); Riverina (SA); South Perth (WA)

[a] Gross estimation obtained from dividing volume of production and cropped area (note comments regarding yields calculated using data from different sources).

[b] Gross estimation obtained from dividing value of production and cropped area (note comments regarding values calculated using data from different sources).

[c,e,g] Estimated from production and previous years' reports on area.

[d] Yield derived from production that is mostly continental and Lebanese cucumbers grown undercover (93% of total production volume). An indicative yield for slicers in the field can be 3 kg/m^2.

[f] Muskmelons.

The investments and increase in production will have to be guided by current and new marketing opportunities and supply chains. Enterprises with large production areas may find opportunities in domestic markets and complement supply from other temperate climate regions. There may be potential to target export markets, particularly focusing on high value vegetable commodities demanded in Asian countries with market access arrangements. High quality produce grown with sustainable practices such as biological control practices may be attractive to buyers in Hong Kong, Japan, and Singapore. Small protected cropping investments in the tropics may find opportunities supplying the domestic market as well as regional markets.

Protected cropping investments in regions that have outdoor vegetable production already benefit from the closeness to road infrastructure, ports and airports. Airports such as the ones in Cairns, Perth, Darwin and Brisbane can send fresh produce to overseas markets. When close to an airport, fresh produce can be packed and airfreighted to Asian markets within 48 to 60 hours from harvest.

Produce sent by sea on refrigerated containers can be in Asian markets within 12 to 20 days from harvest. Produce would need to be transported to ports in Brisbane and Perth for connections with overseas by refrigerated cargo. On the east coast, the Port of Townsville recently commenced to open opportunities for sending fresh refrigerated produce to Asian countries (Port of Townsville, personal communication). If soilless culture is planned for production, the structure could be placed next to an export centre.

Drivers and barriers to adoption

Drivers and barriers to adoption (or consideration) of protected cropping systems were mentioned during discussions with growers, value chain members and other industry stakeholders. These are summarised in Table 8.

Table 8. Drivers and barriers to adoption of protected cropping systems.

Drivers to adopt or consider adoption of protected cropping technologies	**Barriers to adopt or consider adoption of protected cropping technologies**
• Reduction in risks of yield losses from climate variability • More efficient planning for the production and increase in assurance of supply (volume and quality supply) • Increased demand on consistent quality • Possibility to access niche markets with specialty commodities that are difficult to grow outdoors • Potential to access export markets with specific commodities demanded by overseas buyers • Management practices and technologies that enable greater control of crop growth and production • Technologies that can better integrate biological control practices and improve management of pest and diseases with less chemical inputs • Methods to extend the production season and reduce risks of losses in early and late periods of the season • Technologies that complement existing field production in the farm during periods when outdoor production is challenging • Technologies that complement supply from southern regions with lower costs and energy inputs • An early start learning the production systems with the anticipation that it will become more standard in the years to come in warm environments • Exposure to experiences overseas where the technology is widely used in warm regions • Personal experiences or observations of the benefits of using protected cropping	• Limited understanding of protected cropping technologies and the range of technologies that can be used to address production constraints in warm environments • High capital investment • Risks associated with cyclonic weather events • Being a (relatively) new production system with few examples in the region (uncertainty that it is feasible) • Insufficient evaluations and commercial examples to determine if it is feasible • Limited understanding that it is a system of production, not just the placement of a structure over a field crop • Not enough regional knowledge to support expansion with extension activities • Absence of operators with skills in intensive production systems • Irregular or seasonal labour availability and with variable skill level • High cost and time initially involved associated with a high learning curve • Risk of failure if support is not available • Closed industry that makes it difficult to access regional information and to share experiences • Lack of familiarity with potential opportunities to visit regions with similar environments where the technology is used

The discussions with growers and industry stakeholders revealed additional challenges, opportunities and questions associated with the potential of expanding protected cropping in a region that has a very small and scattered protected cropping industry:

In relation to yield uncertainty and impact from weather events,

- “*Every morning I worry about what the weather will do to my crops, knowing that I have few to no tools to avoid production losses in my field-grown crops*” (vegetable grower in the tropics)
- “*It would reduce a lot of the uncertainties in this business if I could know that there is a way to ensure that I can plant on a certain day and then deliver a contracted volume*” (vegetable grower in the tropics)
- *“It is raining outside and we are working on the crop!”* (vegetable grower evaluating a small area with protected cropping in the tropics)

In relation to adopting protected cropping as a new technology,

- “*Why would you use a greenhouse in the tropics?*” (vegetable grower using protected cropping in a temperate climate)
- “*I agree that this is the production system [referring to protected cropping] that will be used in years to come but this will require a big change in doing things and a large investment at my age…*” (vegetable grower in the tropics)
- *“This technology would be attractive to young growers”* (vegetable grower visiting a demonstration trial)
- “*We don’t need glasshouses in the tropics!*” (vegetable grower in the tropics)
- “*Who will teach me how to produce under this system?*” (vegetable growers visiting a demonstration trial)
- “*It looks promising [referring to protected cropping], but I don’t want to be the first one taking the risks on a new production system*” (field vegetable grower in the tropics)
- “*Who is going to adopt this technology in the region?*” (vegetable grower visiting a demonstration trial)
- “*What will happen to field farmers if more growers move into protected cropping?*” (vegetable grower visiting a demonstration trial)

In relation to observations when visiting in demonstration sites or managing commercial sites,

- “*We have high transportation costs to faraway markets but we do not need to burn fuel for heating*” (vegetable grower evaluating a small area with protected cropping in the tropics)
- “*You can almost put a name to each plant*” (vegetable growers commenting on the labour inputs per m^2 in comparison to outdoor crops)
- “*You can count almost the same number of capsicums in every plant and there is no fruit to throw away*” (vegetable grower visiting a demonstration trial)
- “*You could export these melons*” (vegetable grower and marketing agent visiting a demonstration trial)
- “*I can achieve an almost year-round production*” (vegetable grower evaluating a small area with protected cropping in the tropics)

- "*I can manage a smaller area with higher productivity per m^2*" (vegetable grower evaluating a small area with protected cropping in the tropics)
- "*Why is nobody else growing crops using these production systems?*" (vegetable grower evaluating a small area with protected cropping in the tropics)
- "*If you can grow a crop with this good quality under this low-cost structure, imagine what would be possible in a taller structure with improved environmental control*" (greenhouse manufacturer)
- "*I never thought that a capsicum could grow to a height of 2.5-m*" (vegetable grower visiting a demonstration trial in the tropics)
- "*How would you grow those crops in one hectare?*" (vegetable grower visiting a demonstration trial)
- "*I will try some of these practices to improve production in my field crops*" (grower extending knowledge from a greenhouse crop to field crops)
- *"With the release of parasitoids [biological control] I do not need to spray for aphids"* (vegetable grower evaluating a small area with protected cropping in the tropics)
- *"Marketing is fundamental as you do not want to sell the differentiated product at the price of a field-grown vegetable"* (vegetable grower evaluating a small area with protected cropping in the tropics)
- "*I would like to improve some practices but it is inefficient to train unskilled staff every year*" (vegetable grower commenting when discussing plant pruning methods")
- "*It is the same plant as in the field but indoors the quality is better and the price is higher*" (vegetable grower evaluating a small area with protected cropping in the tropics)

In relation to information that is required and having a good understanding of technologies suited for warm environments,

- *"What structure should I use?"* (vegetable grower visiting a demonstration trial)
- "*Where do I get cultivars that would perform well in these warm environments?*" (vegetable grower evaluating a small area with protected cropping in the tropics)
- "*How do you prune and trellis those crops?*" (vegetable grower in the tropics)
- "*How can you reduce labour inputs?*" (vegetable grower using protected cropping)
- "*How do you water and fertilise these crops?*" (vegetable grower visiting a demonstration trial)
- "*Which other soilless media can be used?*" (vegetable grower using protected cropping)

Early demonstrations in the Dry Tropics, Queensland

Feasibility and economic viability studies for a variety of crops and production systems within protected cropping, as well as tailored recommendations for successfully producing in tropical environments, are still required. Some work in this area has been initiated by the Queensland Department of Agriculture and Fisheries (DAF). Over the past 8 years, DAF has been providing advice to current and prospective protective cropping growers in the Dry Tropics, Tablelands, and Bundaberg region. This has been in response to growing interest in protective cropping among farmers. Funded by the Australian Centre for International Agriculture Research (ACIAR), and with project activities in the Pacific Islands and in Queensland, a small ‘proof of concept’ project was led by DAF to provide preliminary information to regional vegetable growers about the benefits and challenges of using high tunnels and passively ventilated greenhouses technologies. Under this project, preliminary trials and small semi-commercial demonstration plots were established in Ayr and Giru and have been running since 2013. Although structures used by commercial farmers are expected to be larger and have improved designs, the results obtained from this small proof of concept project have been very encouraging for vegetable industry stakeholders in north Queensland. For example, in comparison to open field production systems, marketable yields of coloured capsicums grown with soilless culture under the poly tunnel were up to 6 times greater (18 kg/m^2) when grown following specific canopy pruning and trellis systems (Table 9). High fruit yield and quality were also obtained with cucumbers, melons, tomatoes, beans, eggplants, and ginger, some crops grown in soil and others in soilless systems (Figures 12 to 16). Inquiries and production recommendations have been given to prospective and existing protective cropping growers from Far North Qld to Bundaberg, as well as to growers from other regions of Australia and input suppliers (e.g. greenhouse manufacturers, seed companies, and fresh produce distributors).

Figure 12. Capsicum trials in soil and soilless culture in a poly tunnel and greenhouse in the dry tropics (Image source: DAF).

Table 9. Capsicum yields in high poly tunnel in north Queensland and comparison with the yield of a capsicum crop grown in the field (Jovicich and Wiggenhauser, 2014). Under the tunnel, transplanting was early June and 25 harvests were conducted from September 2014 to March 2015.

Cultivar	Marketable yield kg/m^2	no/m^2
Tunnel Giru		
430-0	14.5	90
Atalante	17.7	136
Bellisa	17.2	243
Bronson	20.1	334
Clair	10.9	53
Red Jet	11.1	68
Volante	14.4	89
Warlock (field cultivar)	7.2	40
Field Bowen		
Warlock	2.9	9

Figure 13. Example of fruit set, early yield and quality of capsicums achieved in soilless culture in north Queensland using protected cropping and specific agronomic management practices (Image source: DAF).

Figure 14. Specialty melons grown upright under protected cropping in the tropics (Jovicich and Wiggenhauser, 2015) (Image source: DAF).

Figure 15. Examples of the quality of specialty melons that can be grown in soil and soilless culture in north Queensland using protected cropping and specific agronomic management practices (Image source: DAF).

Figure 16. Specialty melons grown in north Queensland during a 'dry' season but when several rainfall events affected field crops. Left: melons harvested under a protected structure. Right: melons grown in the field and where quality was reduced, particularly affecting the area where the fruit lays on the ground (Image source: DAF).

Preliminary economic analysis for hypothetical protected cropping enterprises in the tropics: *Selected capsicum cropping scenarios*

An economic analysis was undertaken to explore the economic viability of protected cropping in the Dry Tropics region of north Queensland. This region was used as an example in the Australian tropics. Capsicum (blocky type fruits) was used as a model crop. Operating profit, return to capital and an assessment of yield and price risk are presented for a selection of possible production systems and greenhouse structures. Economic data for production in field-grown crops is provided for comparison.

Because the area with commercial protected cropping is small in north Queensland, the analysis was carried out using information gathered from recent local trials and semi-commercial plots (2013-2016). Where data was lacking, assumptions informed by overseas research and commercial protected cropping conducted under warm environment were included. Confidentiality was maintained in order to not reveal economic business information from commercial operations. The analyses for the selected crop scenarios reflect the limited extent of adoption as well as the limited research work conducted in the Australian tropics. Therefore results should be regarded as preliminary.

Selected protected cropping scenarios

Protected cropping production systems and structures were selected for analysis on the basis that there was either data available from trial work undertaken recently in north Queensland, or there was research undertaken in comparable climate zones to north Queensland. The key characteristics in the selected production systems modelled in this analysis were the main design characteristics of the protected structure and the growing system associated with the root media in which plants grow: soil or soilless culture (Figures 17 and 18).

Production was assumed to be conducted in three types of structures. One structure design was a walk-in multi-span polyethylene-covered tunnel with open lateral sides. Poles along the sides were 2.5-m high and roof arches reached to a height of 3.5-m at the centre of the tunnel. The second structure design was a multi-span high passively ventilated greenhouse with a “saw tooth” roof design (4 m to the gutter and roof peak at 5 m) covered with a polyweave film. This greenhouse design had insect exclusion screens that covered the all-around sidewalls and roof vents. The third structure design was a multi-span retractable roof structure with peaked-roof on every span (4.3 m to the gutter and roof peak at 6 m).

Under the selected structures, plants were considered to be grown in either the native soil under the greenhouse (soil culture), or in containers filled with a medium (soilless culture). In both cases crops were irrigated with a nutrient solution. The fertigation method and scheduling suited to each culture type. The methods used to vertically support plants and minimal pruning practices were assumed to be the same in all enterprise scenarios. It is important to note that even with the assumptions considered here, there is a range of options for inputs to be used within these production scenarios, which will lead to different costs of production and economic outcomes. The protective structure designs and growing system modelled in this analysis are summarised in Table 10.

Figure 17. Images of protective structure designs included in the analysis: high poly tunnel, high passive ventilated greenhouse and retractable roof structure (Image source: Left <http://www.tierrafertil.com.mx>; centre & right: DAF).

Figure 18. Soilless and soil production of capsicum evaluated in north Queensland (Image source: DAF).

Table 10. Summary of enterprise scenarios (A, B, C, D, and E) for capsicum production.

	Protective structure type		
Plant growing system	High roof poly tunnel	High roof passively ventilated greenhouse	Retractable roof
Protected cropping with soilless culture (39-weeks crop)	A		D*
Protected cropping with soil-grown plants (18-weeks crop)		B	
Protected cropping with soil-grown plants (39-weeks crop)		C*	E*
Field-grown (18-weeks crop)			

**Enterprises C, D and E assume capsicum production systems and protective structure types that are untested in north Queensland.*

The data used in the field-grown scenario was sourced from Queensland Department of Agriculture (DAF) industry experts according to local standard practice for field-grown capsicum production (Tom Mullins; senior financial advisor; Bowen Research Station). Data used in the analysis for scenarios A and B was sourced from trial work conducted by DAF in north Queensland (Table 10). Enterprise types C, D and E have not been tested in north Queensland. Consequently, additional caution must be applied when interpreting findings with regard to scenarios C, D and E.

Crop Cycle

Crop production cycles modelled in this analysis reflect recent evaluations in north Queensland. A 39-week crop production cycle with planting in late February was modelled for both soilless (scenarios A and D) and soil-grown scenarios (C and E) of protected cropping production systems. An 18-week crop production cycle transplanted in early August, which reflected an evaluation in north Queensland, was also modelled for the soil-grown passive ventilated structure (scenario B). For the field-grown crop, an 18-week production cycle was modelled, to reflect one of the standard industry practices (Table 11).

Mature ripened fruit (red) were picked during the harvesting periods. In all 39-week cropping periods, harvesting commenced in June, approximately 100 days after transplanting, and continued until December (the total number of estimated harvests was 25). Harvesting under the passive ventilated structure in the soil-grown 18-week crop commenced in October and continued until December (the total number of harvests was 10). Harvesting in the field-grown crop was undertaken twice, with first fruit pick 100 days after transplanting. Harvesting periods in the field can vary in length in the dry tropics region. Depending on market prices, environmental conditions, and pest and disease pressure, the total number of harvests can sometimes be increased to 3 or 4; however, this is not common where supply is derived from sequential planting throughout the growing season.

Table 11. Area under production, plant arrangement and crop duration used in the analysis.

		Field	**Protective structure scenarios**		
	Units		*Scenarios A and D* Soilless	*Scenario B* Soil	*Scenarios C and E* Soil
Crop duration	weeks	18	39	18	39
Total area	m^2	200,000	10,000	10,000	10,000
Distance between beds	m	1.30	1.45	1.60	1.60
Within-row spacing	m	0.4	0.25	0.25	0.25
Number of plants	plants/ha	32,050	27,600	32,000	32,000
Plant density	plants/m^2	3.2	2.8	3.2	3.2

Production system

A capsicum production cycle grown in one hectare was assumed for all protected cropping enterprises. In soilless culture, plants were grown in 12-L pots with media and irrigated with a complete nutrient solution using an automated fertigation system. In soil and soilless cultures, capsicum plants were grown with minimum pruning of shoots and a removal of first 3-5 flowers.

They were trellised vertically, supported by up to 17 levels of horizontal string pairs following practices used in the “Spanish” trellis system (Jovicich et al. 2005). The field crops had plants that were not supported vertically. A typical production cycle for twenty hectares of capsicum was assumed for the field production system. Results are presented on a per hectare basis. Plant arrangements for greenhouse structures and field-grown crop are presented in Table 11.

Marketable yields

Estimated marketable yields used in the analysis are presented in Table 12. Fruit yields in kg/m^2 for scenarios A and B were sourced from cultivar evaluations undertaken by DAF. Average monthly yield in kg/m^2 represents the average marketable yield of a group of cultivars tested and replicates for each one year trial. Fruit yield for scenarios C, D and E are informed by ranges reported by Jovicich et al. (2005) or by producers in warm regions overseas, and were confirmed by expert opinion. Crops under a 4-ha retractable roof structure have been grown in Bundaberg in the past 1.5 years; however capsicums there were grown by managing canopies to low heights (<1.5 m). Therefore, most of the time, crops did not produce for a long period and led to yields in a range of 4-5 kg/m^2. In the modelled scenarios D and E, it was assumed that crops would be pruned and trellised upright to heights up to 2.0 m using similar methods to scenarios A and B. This canopy management in soil production should increase yields to at least 12 kg/m^2 under retractable roof structures. Fruit yield for the field-grown enterprise reflect findings using conventional practices for growing capsicums in trials undertaken by DAF in Bowen during four years (VG09038 - Vegetable Soil Health Systems for Overcoming Limitations Causing Soil borne Disease) and yield values were confirmed by local expert opinion.

Table 12. Summary of estimated capsicum marketable yields in the selected crop production scenarios. Mean values and a range with minimum and maximum expected yields.

Protected cropping structure	Production System		Mean and range of marketable yields (kg/m^2)
High roof poly tunnel	A	Soilless culture (39 week)	**12.5** *(6 - 21)*
High roof passively ventilated greenhouse	B	Soil grown (18 week)	**6.5** *(3 - 11)*
High roof passively ventilated greenhouse	C	Soil grown (39 week)	**8** *(7 -14)*
Retractable roof	D	Soilless culture (39 week)	**13** *(10 - 25)*
Retractable roof	E	Soil grown (39 week)	**9.5** *(8 -15)*
Field (18 week)			**2.7** *(0.8 - 3)*

Prices

Capsicum prices were estimated from historical price records for red fruit packed in 5-kg cartons, at the Brisbane wholesale market (greenhouse fruit are primarily packaged in 5-kg cartons). Monthly prices in $/kg were obtained from the average of high, low and average prices for 2010 and from 2012 to 2015 (5 years). Capsicum prices for field grown fruit were estimated from historical price records for 8-kg red capsicum cartons at the Brisbane wholesale markets from 1997 to 2015.

Enterprise budget

Methodology described by Makeham & Malcolm (1994) was used to develop a budget for each enterprise scenario. Operating return was calculated by subtracting total costs (fixed plus variable costs) from gross revenue. Taxes, finance costs and the purchase price of land were not included in the analysis.

Costs were divided into fixed costs and variable costs. Fixed costs included management labour and items that do not change directly with production. Annual depreciation was calculated using the straight-line method and assuming a zero salvage value (Makeham & Malcolm 1994). Capital items original cost, useful life and fixed costs were estimated according to expert advice.

Variable costs included pre-harvest costs (growing costs), harvesting, packing and marketing. Input quantities were estimated from both field trial records and expert opinion. Prices were obtained by contacting local suppliers. Casual labour was valued at $24.23/h (award wage plus superannuation). Pesticide application and crop monitoring was costed at local contract rates. Freight cost was per pallet from the Burdekin region to the Brisbane wholesale market. Commission was estimated to be 15% of gross revenue.

The enterprise budget was used to estimate annual operating return. Operating return was calculated by subtracting total costs (fixed plus variable costs) from gross revenue.

Investment analysis

Investment costs included in the analysis were site preparation costs, greenhouse structure and construction, ancillary buildings (head house and packing shed), irrigation equipment, trellis accessories, farm vehicles, tractors, machinery and other durables (Table 13). Investment costs were estimated according to market prices and expert opinion. The prices of structures (frame and cladding materials) were estimated as follow: poly tunnel (\$12.50/m^2); greenhouse (\$30.00/m^2) and retractable roof (\$43.5/m^2). The purchase price of land was not included in the analysis. Return on capital was calculated as operating return divided by total investment cost.

Table 13. Estimated cost of investment in selected protected cropping scenarios for capsicum production.

	Field	High roof poly tunnel	High roof passively ventilated greenhouse	Retractable roof structure	
	Soil	**Soilless** (A)	**Soil** (B and C)	**Soilless** (D)	**Soil** (E)
	($/20ha)	($/ha)	($/ha)	($/ha)	($/ha)
Total investment	**$488,950**	**$737,860**	**$1,111,110**	**$1,187,860**	**$1,211,110**
Greenhouse structure, film and screen materials, construction costs and site preparation		$315,800	$654,500	$765,800	$754,500
Head house structures	$20,000	$20,000	$20,000	$20,000	$20,000
Packing facilities and equipment	$172,500	$172,500	$172,500	$172,500	$172,500
Irrigation equipment	$59,950	$91,080	$59,950	$91,080	$59,950
Trellis accessories		$15,660	$15,660	$15,660	$15,660
Farm vehicles	$40,000	$40,000	$40,000	$40,000	$40,000
Tractors and machinery	$143,000		$85,000		$85,000
Harvesting equipment and other durables	$53,500	$82,820	$63,500	$82,820	$63,500

Risk Analysis

A Monte Carlo simulation based on the framework presented in Richardson et al. (2000) was used to incorporate yield and price risk into the enterprise budget for scenarios A and B. Scenarios A and B were selected for sensitivity analysis on the basis that data for these scenarios was available from trial work. Trial yield data and historical Brisbane wholesale market prices were used to simulate the stochastic variables. Summary statistics for the stochastic variables used in the risk analysis are presented in Table 14.

Table 14. Summary statistics for stochastic variables.

Variable	Unit	Mean	Standard Deviation	Minimum	Maximum
Yield – Field					
Mean Total	kg/m^2	2.67	0.54	0.84	3.28
Yield – Tunnel-soilless (39-weeks): Scenario A					
June	kg/m^2	0.27	0.35	0.00	0.81
July	kg/m^2	2.95	0.57	1.80	4.07
Aug	kg/m^2	1.47	0.86	0.07	2.90
Sep	kg/m^2	1.74	0.66	0.80	3.04
Oct	kg/m^2	3.27	0.86	1.85	4.91
Nov	kg/m^2	2.42	0.71	1.30	3.73
Dec	kg/m^2	0.46	0.44	0.00	1.71
Mean Total	kg/m^2	12.59			
Yield – Greenhouse-soil (18-weeks): Scenario B					
June	kg/m^2				
July	kg/m^2				
Aug	kg/m^2				
Sep	kg/m^2				
Oct	kg/m^2	0.79	0.66	0.00	2.05
Nov	kg/m^2	2.82	0.84	1.05	4.00
Dec	kg/m^2	2.94	0.82	2.03	5.08
Mean total	kg/m^2	6.55			
Price – Field					
Average	$/kg	2.08	0.52	1.45	3.01
Price – Tunnel and Greenhouse (39-weeks): Scenarios A and B					
June	$/kg	4.00	0.00	4.00	4.00
July	$/kg	4.40	0.00	4.40	4.40
Aug	$/kg	4.80	0.00	4.80	4.80
Sep	$/kg	7.28	1.92	4.80	10.00
Oct	$/kg	7.13	1.47	5.00	10.00
Nov	$/kg	6.02	1.11	4.00	7.81
Dec	$/kg	6.45	1.27	4.00	9.00

Results

The enterprise budget is presented in Tables 15 and 16. Total yield ranged from 130,000 kg/ha in the retractable roof soilless culture enterprise (scenario D) to 26,674 kg/ha in the field grown crop. Price per kilogram was $2.08/kg for the field grown crop; $5.73/kg in scenarios A, C, D and E (protected cropping crops) and $6.53/kg in scenario B (the 18-week greenhouse crop, reflecting monthly prices averaged over time of harvest).

Gross revenue was estimated at $746,886/ha for scenario A; $415,487 for scenario B; $458,400/ha for scenario C; $744,445/ha for scenario D; $544,018/ha for scenario E and; $55,566/ha for the field-grown crop (Tables 15 and 16).

Pre-harvest costs ranged from $166,329/ha in the soilless system (scenarios A and D) to $15,684/ha in the field grown crop (Tables 15 and 16). Fertiliser, labour and other material inputs (including expenses such as the cost to operate machinery, trellising equipment, plastic mulch, pots and potting media) where the largest components of pre-harvest costs in the greenhouse systems reflecting the intensity of these production systems and high yield per hectare.

Harvesting costs reflect yield per hectare and range from $5,178/ha in the field grown system to $46,445 in the 39-week greenhouse systems (Tables 15 and 16). Per unit packing and marketing costs were slightly higher in the greenhouse systems ($0.81/unit vs. $0.68/unit in the field grown crop) reflecting smaller carton pack size (5kg versus 8kg) (and therefore greater number of cartons per kg fruit).

Fixed costs ranged from $5,563 in the field grown system to up to $158,635/ha in Scenario D (Tables 15 and 16). Depreciation of the greenhouse structure, packing shed, equipment and ancillary buildings was a large component of fixed costs for the protected cropping scenarios.

Total operating return was $2,619/ha in the field grown system, $176,755 in scenario A, $47,925 in scenario B, $71,534 in scenario C, $267,520 in scenario D and $137,631 in scenario E (Tables 15 and 16). Total investment cost (excluding land) was $2,619/ha in the field-grown crop; $737,860 in scenario A; $1,111,110 in scenario B; $1,111,110 in scenario C; $1,187,860 in scenario D, and $1,211,110 in scenario E (Table 13).

Return on capital (excluding land and calculated as operating return divided by total investment cost by 100) was 11% in the field-grown crop; 24% in scenario A; 4% in scenario B; 6% in scenario C; 23% in scenario D, and 11% in scenario E (Tables 15 and 16).

Break-even yields were calculated for various capsicum prices and ranged from $1.5/kg to $9/kg (Table 17) for all outcomes including field crop and scenarios A and B. Assuming an average price of $5/kg, the break-even yield was 0.74 kg/m^2 for the field crop; 10.35 kg/m^2 for scenario A and 7.33 kg/m^2 for scenario B. For scenario A, break-even price for a fruit yield of 12.6 kg/m^2 was $4.28/kg and for scenario B, break-even price for a fruit yield of 6.55kg/m^2 was $6.21/kg. For the field crop break-even price for yield of 2.67kg/m^2 was $1.97/kg (Table 18).

Table 15. Enterprise budget for capsicum grown under selected production systems A, B, and C.

		Field			High roof poly tunnel		
		Soil (18-weeks)			Soilless (39-weeks) (A)		
		Quantity	Price	Total	Quantity	Price	Total
	Unit	(units)	($/unit)	($/ha)	(units)	($/unit)	($/ha)
Gross revenue	kg	26,674	$2.08	**$55,566**	125,871	$5.73	**$746,886**
Variable costs							
Fertiliser				$464			$38,383
Pesticides				$1,564			$2,444
Other material inputs				$9,026			$55,952
Energy				$77			$154
Water				$55			$109
Contract labour				$767			$8,650
Labour				$3,732			$60,637
Total preharvest costs				**$15,684**			**$166,329**
Harvesting				$5,178			$46,445
Packing and marketing	kg	26,674	$0.68	$26,523	125,871	$0.81	$214,197
Total variable costs				**$47,384**			**$426,971**
Gross margin				***$8,182***			***$319,915***
Fixed Costs							
Depreciation				$1,883			$69,560
Management labour				$2,500			$50,000
Other fixed costs				$1,180			$23,600
Total fixed costs				**$5,563**			**$143,160**
Total costs				**$52,947**			**$570,131**
Operating return				***$2,619***			***$176,755***
Return on capital				***11%***			***24%***

Table 15. *Continued*

		High roof passively ventilated					
		Soil (18-weeks) (B)			Soil (39-weeks) (C)		
		Quantity	Price	Total	Quantity	Price	Total
	Unit	(units)	($/unit)	($/ha)	(units)	($/unit)	($/ha)
Gross revenue	kg	65,464	$6.53	**$415,487**	80,000	$5.73	**$458,120**
Variable costs							
Fertiliser				$19,072			$38,145
Pesticides				$1,504			$2,444
Other material inputs				$27,184			$28,713
Energy				$96			$154
Water				$68			$109
Contract labour				$3,980			$8,650
Labour				$29,406			$47,740
Total preharvest costs				**$81,310**			**$125,954**
Harvesting				$21,540			$46,445
Packing and marketing	kg	65,464	$0.81	$115,457	80,000	$0.81	$64,933
Total variable costs				**$218,307**			**$237,331**
Gross margin				***$197,180***			***$220,789***
Fixed Costs							
Depreciation				$75,655			$75,655
Management labour				$50,000			$50,000
Other fixed costs				$23,600			$23,600
Total fixed costs				**$149,225**			**$149,255**
Total costs				**$367,562**			**$386,586**
Operating return				***$47,925***			***$71,534***
Return on capital				***4%***			***6%***

Table 16. Summary of enterprise budget outcomes for capsicum under selected production scenarios D and E. Variable costs and pre-harvest costs were considered at same values as with production under a high roof passively ventilated structure.

	Retractable Roof Structure	
	Soilless (39-weeks) (D)	Soil (39-weeks) (E)
Gross margin	***$318,289***	***$294,511***
Fixed Costs	***$158,635***	***$156,880***
Operating Return	***$267,520***	***$137,631***
Return on capital	***23%***	***11%***

Table 17. Break-even yields for a range of wholesale market prices in field-grown capsicums and in capsicums grown in protected cropping scenarios A and B.

	Break-even yield (kg/m^2)		
Wholesale price ($/kg)	**Field**	**High roof poly tunnel Soilless (39-week) (A)**	**High roof passive ventilation Soil (18-week) (B)**
$1.50	4.73	76.82	54.41
$2.00	2.60	40.07	28.38
$3.00	1.41	20.48	14.50
$4.00	0.97	13.75	9.74
$5.00	0.74	10.35	7.33
$6.00	0.60	8.30	5.88
$7.00	0.50	6.93	4.91
$8.00	0.43	5.94	4.21
$9.00	0.38	5.20	3.69

Table 18. Break-even prices for yields in field-grown capsicums crop and in capsicums grown in protected cropping scenarios A and B.

	Price ($/kg)		
Yield[a] (kg/m²)	Field	High roof poly tunnel Soilless (39-week) (A)	High roof passive ventilation Soil (18-week) (B)
2.67	$1.97		
6.55			$6.21
12.59		$4.28	

[a] Yields are averages from commercial crops and trials presented in Table 14.

The cumulative distribution function for operating return for the scenario A and scenario B are presented in Figure 19. Figure 20 shows the cumulative distribution function for operating return for the field-grown crop. For scenario A, there was a 99% probability of a positive operating return. For scenario B, there was approximately a 65% probability of a positive operating return. For the field grown crop simulation there was just over 50% probability for operating return to have positive values.

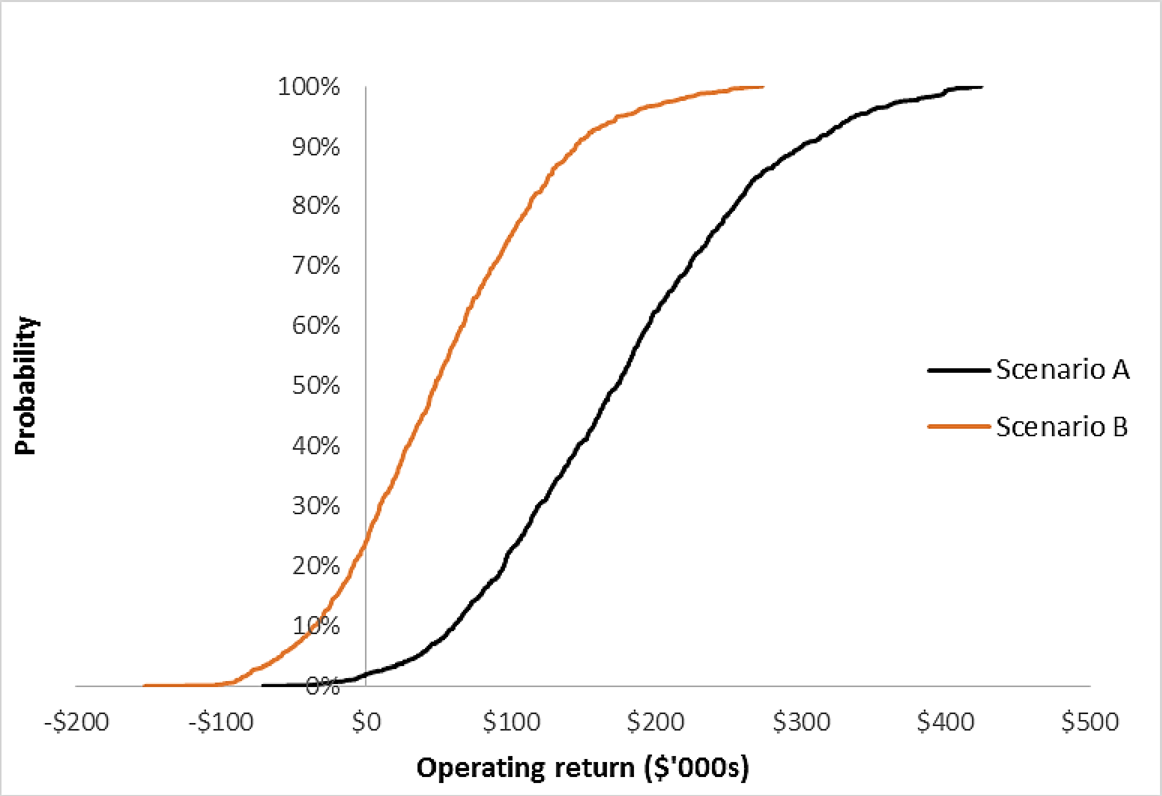


Figure 19. Cumulative distribution function for operating return for capsicums grown under protective structures. Scenario A is for a soilless culture 39-week crop under a high roof poly tunnel. Scenario B is for a 18-weeks crop grown in soil under a high roof passively ventilated greenhouse.

Figure 20. Cumulative distribution function for operating return for field-grown capsicums.

Payback periods for investments and growing capsicum production assumptions were calculated for the protected cropping scenarios. Payback period is an estimation of the time it will take to repay the initial investment cost. It is calculated by dividing the total investment by annual (non-discounted) cash flow (note depreciation is not a cash flow).

The same cautions applied to the interpretation of operating return and return on assets should be applied for the payback periods. In particular, the annual cash flow used to make the calculation is the expected average annual cash flow when the business is fully mature and operating at full efficiency. For new growers, there is likely to be a steep learning curve when starting to use a new technology such as protected cropping systems, and cash flow in the initial years may be lower due to lower yields (this element has not been modelled in these economic analyses). Ultimately, while the payback period is relative simple and easy to interpret, the relative importance of payback period will depend on each individual grower's circumstance and risk tolerance. The payback period values in Table 19 are most informative as a means of comparing each system, i.e. payback period for C is relatively longer than A - rather than making statements like 'you can repay A in 3 years').

Table 19. Break-even yields for a range of wholesale market prices in field-grown capsicums and in capsicums grown in protected cropping scenarios A and B.

	Field	High roof poly tunnel	High roof passively ventilated greenhouse		Retractable roof structure	
	Soil	Soilless	Soil (39-week)	Soil (18-week)	Soilless	Soil
		(A)	(B)	(C)	(D)	(E)
Total investment	$ 24,448	$ 737,860	$ 1,111,110	$ 1,111,110	$ 1,187,860	$ 1,211,110
Operating return	$ 2,619	$ 176,755	$ 47,925	$ 71,534	$ 267,520	$ 137,631
Depreciation	$ 1,883	$ 69,560	$ 75,655	$ 75,655	$ 85,035	$ 83,280
Annual Cash Flow	$ 4,502	$ 246,315	$ 123,580	$ 147,189	$ 352,555	$ 220,911
Payback period (years)	**5.4**	**3.0**	**9.0**	**7.5**	**3.4**	**5.5**

Discussion

Under the greenhouse structures, management practices, market prices and capsicum yields used in this analysis, preliminary results suggest that protected cropping is a viable business opportunity for growers in the tropics.

Although the returns on capital can be high with lower cost structures such as poly tunnels used with soilless culture systems, in cyclonic regions it may be unlikely that large areas of vegetables will be established with these type of structures. However high poly tunnels may be an option for growers that decide on small protected cropping investments. In the tropics, long-season capsicum crops (or two short crops in a year, which was not modelled here) would be better suited to taller structures such as passively ventilated greenhouses and retractable roof structures. The tall structures are more likely to allow for longer harvesting periods which will lead to greater yields. Soilless production will give higher yields than soil systems. In these analyses, the assumptions of using retractable roof structures with soilless production estimated a high return on capital. It would be particularly interesting to test this relatively new technology for Australia as a proof of concept in the tropics. Production in net or screen houses, which are used in desert areas or regions with little precipitation was not considered in this analyses. Carnarvon would be one of the regions described in this report where net houses are structures that benefit capsicum production, but without protecting crops from rainfall events.

The scenarios, assumptions, and outcomes in these analyses apply to capsicums. It is important to note that niche markets, capsicum fruit types, and particular costs (e.g. transport to market and agronomy practices) will change the estimates of economic outcomes. Similar analyses could be conducted for other crops such as eggplants, cucumbers and melons. These crops will have specific growing and production periods, labour inputs, yields and prices. However, they could be all grown using the structures and technologies described here. Cucumbers and melons could be grown 3 to 4 times in a year, while capsicums and eggplants could have one long or two shorter crops in a year.

Market prices used in this analysis were wholesale prices on the Brisbane market. The Brisbane market is the principal fruit and vegetable market and main distribution centre in Queensland. However, distance to market for northern producers presents a considerable freight cost disadvantage. Similar protected production systems in temperate regions will have savings in freight costs but will have additional costs for heating. The enterprises in the tropics will have to explore where prices and marketing arrangements may be favourable. For smaller volumes, there will be regional opportunities at shorter distances from production. Through business partnerships with protected cropping production in southern regions, there may be opportunities to complement supply in the domestic market. There may also be opportunities for exporting from northern ports and airports.

Market price assumptions made in this analysis could also be improved by a better understanding of the impact of quality on price. In this study, the average wholesale market price for greenhouse-grown capsicum fruit packaged in 5-kg cartons was $5.7/kg, more than double the price of field-grown fruit packaged in 27-L cartons ($2.5/kg). Studies overseas reflect the quality difference in the market prices when comparing coloured capsicums grown in the field with coloured capsicums from crops grown in greenhouses (Jovicich et al., 2005).

In the Queensland tropics, current research suggests possible crop establishment in late January to February. Protected cropping would ensure the establishment of crops, regardless of rainfall occurring during this time of the year. Higher summer temperatures can lead to the drop (abscission) of first flowers, but this would reduce labour in the early practices of flower removal. These planting times are similar to those carried out under greenhouses in warm regions in South America, where production is aimed to supply during winter months. The crops from early plantings will resemble those started with August plantings in warm regions in the northern hemisphere.

Tall structures equipped with retractable roofs and shading options should provide further advantages when managing crop environments in the tropics. This should be reflected with increased yields, improved fruit quality, and more consistent production throughout the year. Probability estimates for positive returns for soilless culture under high passively ventilated greenhouses and retractable roof structures were not calculated because larger data sets of regional capsicum yields were not available. It can be expected that because environments will improve under high passively ventilated greenhouses and retractable roof structures in comparison to high poly tunnels, marketable yields with soilless culture will be greater in the larger structures, possibly reaching yields in range of 13 to 20 kg/m^2 for long season crops. There is evidence of high yields in other crop species such as cucumber, grown commercially in soilless culture under high passively ventilated greenhouses structures in north Queensland. Research and development and more information on production under these structures in the tropics, will allow for carrying out models for probability of positive operating returns.

In the tropics there are risks of structures being damaged by severe weather conditions. Early sections in this report comment about advantages and disadvantages from using different types of structures (e.g. strength of the structures and their capability to improve the environments around the crops). There are also management practices that are implemented to save structures in the event severe weather conditions are forecast. The risks of structure damage and costs of contingency plans vary with structure designs. These factors were not included in this economic analysis and modelling of probability for operating returns. Risk of damage will be lower and management of damage prevention will be more efficient with the retractable roof structures than with passively ventilated greenhouses and high tunnels.

Economic analysis incorporating price and yield risks is significantly more informative than single point estimates which provides no perspective on upside or downside risk. Risk analysis is especially relevant when evaluating the profitability of agricultural investments due to the inherent volatility of farming enterprises. For example, prices for horticultural commodities respond readily to over- and under-supply primarily driven by weather events. The risk analysis included in this report must be considered in the context of the range of the stochastic variables (price and yield) used. Yield data from a limited number of field trials is unlikely to adequately reflect the true experience of commercial growers. Yield assumptions could be improved by variety trials in a range of structures over several seasons.

Implementing a new production system requires new skills and technical expertise and new growers are initially unlikely to achieve the higher yields within the ranges depicted in this analysis. Economic analysis incorporating more realistic assumptions about the learning experience of new growers improved by greater trial work and information from a variety of commercial enterprises would improve on the economic modelling in this study.

In the future, and for specific commodities (e.g. for capsicum, tomato, cucumber, melon, eggplant, leafy salad crops), protected vegetable production will increase the share of produce that is currently supplied mostly from field crops. Some of these changes are already evident with a range of high value vegetable commodities. Global competitiveness will also continue to drive the expansion of greenhouse technology. Consequently, the suitable environment in the tropics will enable growers to consider the economic viability of protected cropping.

The results of this study must be considered with regard to the specific assumptions and circumstances of the hypothetical enterprises under evaluation. Each greenhouse production system will have unique bio-physical and economic characteristics that influence the production system, yields and marketing. Future research investigating the heterogeneity of protected cropping enterprises would serve to confirm the findings from the stylised scenarios examined here, especially in light of the practical implications of the technology in a commercial situation.

Outcomes

The intended outcome of this project was to provide vegetable levy payers, industry stakeholders and value chain members with access to information about the feasibility and economic credentials of protected cropping in the tropics. This was achieved through the consolidation, in this report, of critical gaps in information associated with protected cropping in north Australia and its economic viability. As global competition continues to drive the expansion of protected cropping technologies, growers in the Australian tropics have an opportunity to adopt these production systems as a complimentary system to open-field cultivation. Successful adoption of protected cropping technologies that are suitable for the north Australian tropics will critically depend, in the first instance, on growers having access to reliable and context-relevant information about both technological options (e.g. structures, vegetable cultivars, management practices suitable for tropical environmental and climatic conditions) and the economic viability of protected cropping. This is necessary for growers to be able to make an evidence-based assessment about the potential and risks of adopting this technology, in line with their specific resource endowment and production constraints, as well as external factors such as markets and value chains. The report produced through this project provides the vegetable industry with some of this critical information. It will assist Hort Innovation Australia prioritise future R&D investments and support the vegetable industry and key associated stakeholders with improved decision making and increased adoption. It also contributes to Hort Innovation Australia's Strategic Investment Plan by addressing issues that relate to managing risks and enabling sustainability (e.g. climate adaptability responses), stimulating productivity and driving growth (e.g. emerging technologies and innovative cropping systems) and, building capacity (e.g. knowledge-sharing and people development).

This report represents the key repository of information on the feasibility and an example with economic credentials of protected cropping in the Australian tropics. During the project, vegetable industry representatives and value chain members were also given access to protected cropping information via presentations and one-on-one technical advice, both provided by the project leader. These are summarised below:

- A presentation on protected cropping opportunities in the tropics given to vegetable industry representatives (including protective cropping users) in Bundaberg, as part of a meeting organised by the board of management of the Queensland Department of Agriculture and Fisheries (DAF) (Bundaberg, Qld, 22 June, 2017)

- A presentation on using protected cropping with melons given to melon industry stakeholders in a meeting organised by the Australian Melon Association (Ayr, Qld, 23 August 2017).

- A presentation on using protected cropping with specialty melons given to Japanese stakeholders in a meeting in Ayr organised by Trade and Investment Queensland, Nomura Research Institute (NIR), and Japan Ministry of Agriculture (Ayr, Qld, 19 July 2017).

- Advice on production considerations when adopting protected cropping given separately to seven growers, four of whom had recently established structures in North Queensland (Atherton Tablelands, Ayr, Gumlu, Bundaberg, and Gatton, Qld, from March to October 2017).

In addition to delivering the above intended outcome, the project has enhanced awareness among growers (those who participated in project discussions) of the benefits of sharing of information and experiences. Safeguarding of acquired knowledge is something that is not atypical in the protected cropping industry. The project provided an opportunity for growers to discuss production issues and opportunities for using protected cropping technologies. The discussions raised awareness that there is no ‘copy and paste’ approach to the adoption of protected cropping technologies and management practices, and what may work for one enterprise may not necessarily work for another. Differences in aspects of the value chain, business structure, and geographical location mean that technologies and practices will need to be tailored and, as such, sharing of information and experiences does not pose a risk to a grower’s enterprise but rather is an asset.

An additional positive unintended outcome of this project has been capacity-development of growers who have recently adopted protected cropping technologies in north Australia. Although this project did not have any explicit capacity-building activities, a small group of growers were provided with opportunities to be exposed to current R&D activities on protected cropping through attendance at the following conferences and trips:

- Two growers from the Queensland tropics (Burdekin and Atherton tablelands) attended the Protected Cropping Australia (PCA) meeting in Adelaide July 9-12 2017.
- They reported that they had greatly benefited from interacting with other stakeholders of the protective cropping industry. In particular, sharing with others their early experiences growing crops in the tropics made them more aware about the benefits and challenges of using cost-effective technologies. This opportunity also made them recognise the importance, in their path to adopting protective cropping technology, of the benefits of attending industry events and interacting with and collaborating with R&D organisations.
- One grower from the Queensland tropics, a Nuffield scholar, travelled on his scholarship funds with the project leader to Mexico (30 April 2017 to 8 May 2017) where they were joined by other growers and industry stakeholders from Australia, USA, New Zealand, Israel, Canada, and Mexico and visited commercial and R&D protected cropping sites tailored for warm environments. Contacts with stakeholders in Mexico were made and the feasibility of organising a future study tour with a larger number of Australian growers is being assessed.
- One grower from the Queensland tropics travelled to the Bundaberg region in June 2017 where he met with three greenhouse producers and industry input suppliers. The discussions with growers with different size of enterprises and value chains where they operate made this grower aware of the diversity within the protected cropping industry and the benefits and challenges in each enterprise.

Evaluation and discussion

The completion of this report, which includes a gap analysis and economic assessment of protected cropping systems for vegetables in tropical growing regions, was the overarching output of this project. The report informs growers and other stakeholders of the feasibility and early economic credentials of technologies that are currently used to a very limited extent. Through this report, Horticulture Innovation Australia now has access to key information on the viability of protected cropping in north regions of Australia. The information in the report supports Hort Innovation strategic plans and goals.

Discussions with industry stakeholders were instrumental to complete the activities for this report. Previous and current R&D and collaboration with industry stakeholders using or considering the use of protected cropping also facilitated the collection of information. However, the report indicates that the feasibility studies carried out are less complete than studies done in regions where protected cropping has been a common practice for a long time and there is extensive data available. Growers using protected cropping operate in a competitive and small industry. It was fundamental for the project team to maintain a bi-directional flow of information and knowledge sharing with producers in a variety of regions, which has helped build trust and mutual benefits.

The discussions that informed the report were obtained during farm visits, presentations, current collaborative R&D work, study tour, phone and face to face conversations, and the PCA conference. The feedback received in relation to the purpose of this work was always positive.

Currently, there are growers who are considering investing in protected cropping but have limited information about which protected cropping technologies would be most appropriate and cost-effective. It is expected that information in this report will increase their awareness and provide them with some guidance. The report will assist Hort Innovation Australia prioritise future R&D investments, and Hort Innovation's contribution towards supporting industry stakeholders with improved decision making and increased adoption.

Recommendations

Successful adoption of protected cropping technologies that are suitable for the north Australian tropics will critically depend, in the first instance, on growers having access to reliable and context-relevant information about both technological options and the economic viability of protected cropping. If adoption increases in the tropics, recommendations will need to be developed concurrently with the expansion of the technology to respond to new knowledge requirements of growers and to adapt protected cropping recommendations existing in other regions in Australia.

The following are selected recommendations for additional research and capacity building activities that will support the current protected cropping industry and enable the scaling-up of adoption in the Australian tropics:

- Vegetable crop agronomy within protected cropping systems, with specific topics that require developing recommendations for:
    - Water and nutrient management that ensure economic and environmental sustainability
    - Soil production systems that sustain soil health through a combination of practices that growers could use and align with their market supply plan
    - Soilless culture systems that recycle or sustainably reuse drainage nutrient solution.
    - Integrated pest and disease management systems with a large component of practices that rely on biological control
    - Genetic materials suitable for warm environments as well as new types of commodities that could be of interest to domestic and export markets.
    - Technologies and crop management options to mitigate the effect of extremes temperatures on crops
    - Crop production practices under different protective cropping structure designs that are suitable for using in the tropics
    - Technologies that can reduce labour inputs through mechanisation and automation of operations during crop production.

- Capacity building activities that will support the current protected cropping industry and enable the scaling-up of adoption in the Australian tropics. This should target growers and related industry stakeholders.

- Development of proof of concepts through demonstrations, communication materials, and grower study tours are needed to continue to increase knowledge about opportunities, benefits and challenges of using protected cropping in warm environments through evidence-based assessments. In this process, engage the input supply industry and other vegetable industry stakeholders.

Nowadays technology can greatly assist with the collection of data in protected cropping scenarios. However, growers will have to learn how to make sense of the data and new information in order to make informed decisions. Capacity building should include how to effectively use this information to identify crop issues and potential solutions. Potential adopters of protected cropping could be regional growers with outdoor farming experience and enterprises who bring knowledge and experiences from other regions. Capacity building will need to be tailored to the specific needs of these potential adopters.

Because protected cropping is a new production system for most of the current vegetable growers in the tropics it will be important to prepare recommendations to support the early investments that have occurred and those that may follow. The support should aim at developing recommendations and providing training to address crop management issues to minimise initial risks after the investment and to make the initial learning phase more efficient.

Scientific refereed publications

None to report.

Intellectual property/commercialisation

No commercial IP generated.

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Appendices

None.