FINAL REPORT

Strengthening northern Australia's horticultural sector through assessing protected cropping value chain linkages and pathways for adoption

A.3.1819067

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Research for **sustainable** and **inclusive** development in **northern Australia**













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- originality
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conformity with the principles of the Australian Code for the Responsible Conduct of Research (NHMRC 2018), and provided constructive feedback which was considered and addressed by the author(s).

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Peer Review Statement

Representatives of project participants read this report, made comments, and accepted the information presented in this report.

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Acronyms

CGA	Carnarvon Growers Association
CRCNA	CRC for Developing Northern Australia
DPI	Queensland's Department of Primary Industries. Known as the Department of Agriculture and Fisheries (DAF) until November 2024.
DPIRD	Department of Primary Industries and Rural Development, Western Australia
NT Farmers	Northern Territory Farmers Association
PC	protected cropping
POTL	Port of Townsville
RD&E	Research, Development and Extension
TIQ	Trade and Investment Queensland

Project Participants

Department of Primary Industries (DPI), Queensland

Department of Primary Industries and Regional Development (DPIRD), Western Australia

Carnarvon Growers' Association Inc (CGA)

Northern Territory Farmers' Association (NT Farmers)

BTM Hort Pty Ltd (representation for Cravo Australia Pty Ltd)

Port of Townsville Ltd

Pirrone Brothers Produce (now trading as Pirrone Brothers)

Project Collaborators

The success of the project activities was greatly enhanced by the invaluable collaboration and active involvement of numerous businesses and groups. Their willingness to share knowledge and, in some cases, participate in crop evaluations at their properties or the research facilities in Ayr and Carnarvon, was instrumental in advancing our understanding and development of protected cropping systems. We sincerely thank all participants for their dedication, insights, and significant contributions to this initiative.

Fresh Yellow, *banana and vegetable producer, South Johnstone, QLD*

Lands Family Farms, *vegetable and fruit producer, Gumlu, QLD*

Rocky Ponds Produce, *vegetable producer, Gumlu, QLD*

Vee Jays – Kalfresh, *vegetable producer, Bowen, QLD*

Pirrone Brothers*, vegetable producer, Ayr, QLD*

Rob Kuzmicich, *vegetable producer, Carnarvon, WA*

Sun City Produce*, vegetable producer, Geraldton, WA*

Thang Vo*, vegetable producer, Carnarvon, WA*

VF+ *fresh produce supplier*

Fresh Partners *marketing solutions*

Trade and Investment Qld (TIQ), *Queensland Government's dedicated global business agency*

Rijk Zwaan, *a vegetable and fruit seed company*

Lefroy Valley, *a vegetable and fruit seed company*

Executive Summary

Horticulture farming in Northern Australia, primarily conducted outdoors near and north of the Tropic of Capricorn, faces significant challenges due to extreme climate conditions. By 2023, protective structures—such as poly-tunnels, screens, and shade houses—covered 689 hectares, representing 4.9% of Australia's protected cropping area. This CRC for Developing Northern Australia project explored how protected cropping technologies mitigate climate risks while enhancing access to domestic and export markets.

Collaborations with industry stakeholders and Research Development and Extension (RD&E) organisations across Northern Queensland, the Northern Territory, and Western Australia identified key investment opportunities to scale protected cropping systems.

Research demonstrated the ability of these systems to manage extreme weather, pest pressures, and yield inconsistencies for high-value crops. However, challenges such as high capital and operational costs and intensive management persist. Proof-of-concept production systems and capacity-building initiatives play a crucial role in de-risking adoption and ensuring continuity.

Industry-focused evaluations at crop and technology demonstration sites in Ayr, Queensland, and Carnarvon, Western Australia, featuring retractable roof structures and on-farm trials, showcased year-round production capabilities and notable yields. Further opportunities were identified for crops such as ginger, turmeric, specialty cucurbits and dragon fruit, as well as advancements in structural resilience to strong winds.

Project activities focused on raising awareness, fostering industry networks, and showcasing innovative structure designs, crops, and technologies. Demonstration sites in Ayr (QLD) and Carnarvon (WA) provided growers and researchers with collaborative opportunities.

Key outputs—such as grower case studies, crop trials, and a video on specialty melon production for export—are helping inform investment planning. Stakeholder engagement has been central to the project, extending to industry events, education initiatives, and contributions to the Australian Protected Cropping Strategy 2021–2030.

Future adoption efforts must address economic, environmental, and social challenges alongside market demands. Continued investment in capacity building, demonstration sites, and industry collaboration is essential for advancing protected cropping systems and strengthening agriculture in Northern Australia.

Extended Summary

Horticulture Farming and Protected Cropping in Northern Australia: Horticulture farming near and north of the Tropic of Capricorn in Australia is conducted almost exclusively outdoors. By 2023, protective structures such as poly-tunnels, screens, and shade houses covered 689 hectares, supporting berry, vegetable, and tropical fruit production—4.9% of Australia's total protected cropping area.

Project Highlights and Opportunities: This project underscores the potential for growers in the Australian tropics to benefit from protected cropping technologies that mitigate risks associated with climate variability and enhance access to domestic and export markets. It brought together industry stakeholders and government research, development, and extension (RD&E) organisations across Northern Queensland, Northern Territory, and Western Australia to identify investment opportunities for scaling up commercial protected cropping.

Research and Findings: Research activities across northern Australia suggested that for some high-value commodities, protective cropping technologies are a cost-effective way for growers to mitigate the effects of extreme temperature, rainfall, changes in humidity, wind, solar radiation, and pest and disease pressures, which can negatively impact yield, quality, and consistency of supply. Most protected cropping systems are intensive in terms of management requirements and have high capital and operating costs. Increasing capacity building and generating proof-of-concept for production systems are critical to de-risk investments and support business continuity.

Project Activities and Outputs: Throughout the project, research focused on increasing awareness of suitable protected cropping systems for growers in northern Australia, networking and sharing information, and testing structure designs, crops, and technologies to demonstrate production systems. To complement on-farm research, DPI at Ayr, QLD, and DPIRD in Carnarvon, WA, set up innovative protected cropping infrastructure and RD&E demonstration sites where staff and industry stakeholders collaborated. Evaluations under retractable roof structures and on-farm trials, demonstrated year-round production capabilities and notable yields: capsicums (15 kg/m^2), eggplants (18 kg/m^2), cucumbers (10 to 20 kg/m^2, in short and long crops, respectively), zucchini (15 kg/m^2), beans (6 kg/m^2), and specialty melons (3 fruits/m^2 at 16 °Brix). Further opportunities were identified for crops such as ginger, turmeric, and dragon fruit, as well as advancements in structural resilience to strong winds. The project also produced grower case studies and a video showcasing specialty melon production as an example of a potential new crop for warm climates and export markets.

Knowledge Sharing and Stakeholder Engagement: Project findings were shared at industry events and conferences, as well as with university programs and regional high schools. Stakeholder consultations reinforced the need to support fit-for-purpose production systems for tropical climates, aligning with the Australian Protected Cropping Strategy 2021–2030.

Future Directions: The adoption of protected cropping systems in Northern Australia must address economic, environmental, and social challenges while considering market needs and resource availability. Continued investment in capacity-building programs and technology demonstration sites will help producers adopt these systems and ensure business continuity. The collaborative network established through this project provides a foundation for expanding protected cropping to strengthen Northern Australia’s agricultural industry.

Definitions and selected concepts

Northern Australia region. The Australian Government defines Northern Australia as all of the Northern Territory and those parts of Queensland and Western Australia that intersect with the Tropic of Capricorn, as well as the Indian Ocean Territories of Christmas, Cocos, and Keeling Islands (Figure 1). The Tropic of Capricorn (latitude 23°26’13.3” south of the equator) serves as the dividing line between the Southern Temperate Zone to the south and the Tropics to the north. In Australia, this imaginary line crosses Queensland, Northern Territory, and Western Australia.
For discussions in this report, regions close to and north of the Tropic of Capricorn were also considered for expanding the use of protected cropping.

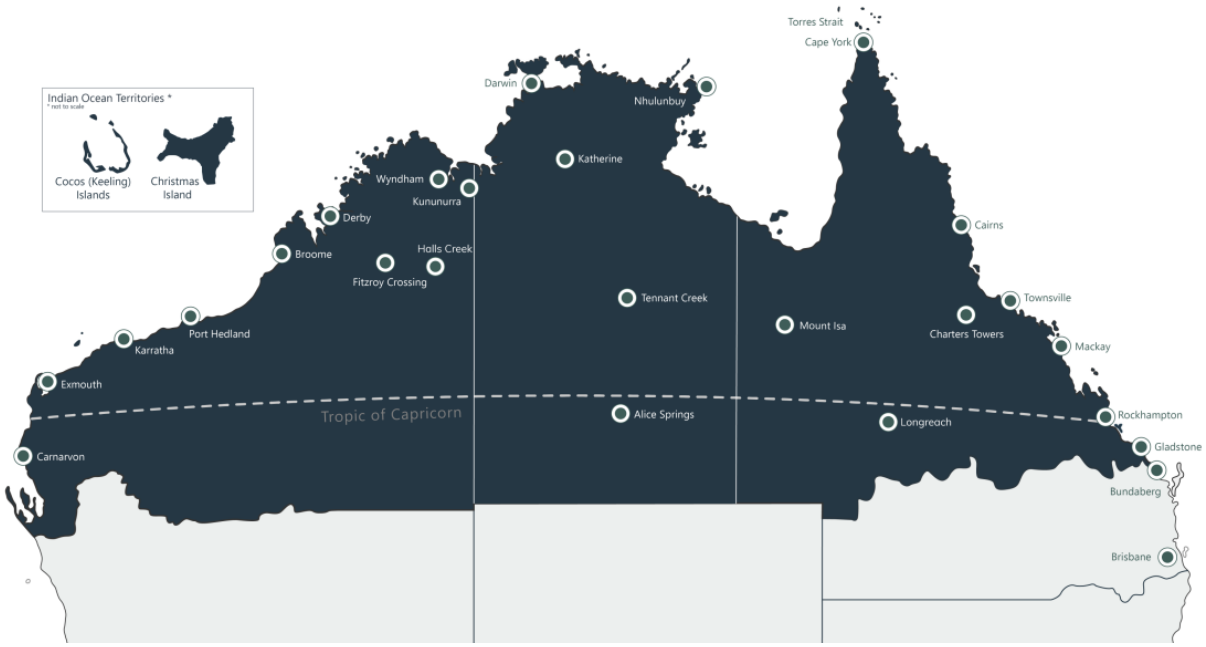


Figure 1: Northern Australia region in dark blue shading.

Protected cropping. This report uses the protected cropping (PC) definition from the Australian Protected Cropping Strategy 2021-2030 (Hort Innovation Australia, 2021). Protected cropping involves the production of crops within, under, or sheltered by structures to provide modified growing conditions. The aim of PC is to maximise crop production and quality, extend or target supply periods, and provide protection from pests, diseases, and adverse weather.
Examples of PC structures include plant factory rooms, glasshouses, passive ventilated greenhouses, retractable roof structures, poly-tunnels, screen and shade houses, netting, row covers, and floating crop covers. Some of these structures are permanent or temporary and can be placed over the crop and at the production site.

Protected cropping systems. 'Protected cropping systems' refers to whole-of-enterprise PC solutions, encompassing both PC structures and related agricultural technologies. This term reflects the fact that PC systems are much more than just the structures that cover the crops; they also include all the tools and technologies used within the cropping system to optimise plant growth and increase productivity. These tools and technologies are critical elements of the system and need to be selected, adapted, and/or developed for specific use in covered cropping. In the context of this report, PC systems can be used across a range of horticultural crops, particularly within the vegetable, berry, nursery, and tree-fruit industries.

Improving crop environment. An optimum crop environment is essential for achieving high yields, but it can be costly to maintain. Although technologies exist to create ideal environments for crops, the level of environmental control and selection of particular structures and associated technologies will depend on various factors. The tropics in Australia experience long periods each year that are close to ideal for growing many horticultural crops. However, there are daily and seasonal changes in environmental conditions that can be suboptimal for plant growth and production. Additionally, extreme events like cyclones can damage infrastructure and crops. Understanding available protected cropping technologies and conducting cost-benefit analyses for business plans will help identify which technology packages and agronomy practices are fit-for-purpose.

Designing a protected cropping system. Protected cropping systems are complex and diverse, but they commonly involve high investment and operating costs per unit of cropped area. The entire production system should be designed to address market-driven business objectives, taking into consideration available resources and constraints, economic and environmental sustainability, and the grower's knowledge and skills, among other factors.

Soil and soilless plant growing systems. Soil and soilless refer to the type of substrate supporting plant roots. In protected cropping, crop roots can grow in soil, as in field-grown crops, or in soilless systems where organic or inorganic media is placed in plant containers. Hydroponics is a type of soilless system where the only media is a nutrient solution. In all cases where the media does not provide all the required nutrients to plants, nutrients are added in a solution delivered with irrigation, a practice known as fertigation.

Open and closed fertigation systems. When irrigating crops grown in containers, drainage is necessary to limit the accumulation of salts in the root substrate. Open and closed fertigation systems refer to how this drainage of water and nutrients is managed in soilless systems. In **closed fertigation systems**, the drained solution is reused to fertigate the crop under the protective structure. The drained solution is treated for potential pathogens, adjusted in nutrient concentration and acidity, and then reused. However, there are limitations on how long closed systems can operate effectively before a new solution needs to be prepared to maintain specific nutrient concentrations. In **open fertigation systems**, the drained solution is either disposed of (not recommended) or captured and used to irrigate other outdoor crops.

About this report

Introduction and project aim: The report begins by highlighting the opportunity to extend the use of protected cropping (PC) in horticulture in the Australian tropics, stating the overall objective of project A.1819067 – *Strengthening Northern Australia's horticultural sector through assessing protected cropping value chain linkages and pathways for adoption*.

Key environmental challenges: An outline of key environmental challenges to be addressed with PC is provided, along with remarks on key factors affecting the dynamics of PC adoption.

Extent of PC use: The report includes an update on the extent of PC use in the Australian tropics, mentioning commonly used PC structure designs and the services they provide to crops.

Priorities and drivers: Identified priorities to support adoption from the Australian PC strategy are mentioned, followed by key drivers and barriers to adoption reported by industry, and potential activities to increase PC adoption.

Summary of activities: The report summarises activities carried out by project participants to assist with PC adoption in QLD, WA, and NT. This includes communication materials and information shared with stakeholders. The selected activities are expected to contribute to PC expansion in the mid and long term, recognising that technology adoption is a slow and dynamic process.

Recommendations: The report ends with key recommendations to further strengthen the adoption of fit-for-purpose production systems in the tropics and help farmers with business continuity.

Introduction

Farming in the Australian tropics, near and north of the Tropic of Capricorn, is primarily conducted outdoors. Horticultural crops such as fruit trees, bananas, vine fruits, blueberries, and vegetables are grown in specific locations, including northern Queensland (eastern coastal strip regions), northern Western Australia (central west region), and the Northern Territory (centre north region). These areas experience warm climates with distinct wet and dry periods, enabling off-season produce supply to southern urban areas. This supports domestic market demands during colder months and expands business opportunities. Northern producers are also well-positioned to meet the increasing overseas demand for high-quality fresh horticultural products.

However, extreme and variable climate conditions pose significant challenges, impacting yield and quality consistency, particularly for vegetables, melons, blueberries, and tropical fruit orchards utilising outdoor production systems. Labour shortages, rising production costs, and fluctuating produce prices further affect the sector. To address these issues, efforts are focused on mechanisation, technology adoption, and ensuring a reliable supply for long-term agreements.

Protected cropping (PC) systems, initially developed in temperate and subtropical regions during the 1960s and gradually adopted in tropical areas since the 1990s, offer a promising solution to mitigate the effects of climate variability (Figure 2). Evidence from tropical regions worldwide and demonstration plots in northern Australia highlights that PC technologies can cost-effectively reduce risks associated with extreme temperatures, rainfall, humidity, wind, solar radiation, and pests. These technologies have been shown to improve yield, quality, and consistency of supply (Table 1). PC systems are particularly beneficial for growers producing high-value horticultural crops, helping them address current and future market challenges and opportunities.

The use of PC in the Australian tropics remains limited and geographically scattered, with examples in a few locations in the dry and wet tropics of northern Queensland, around Darwin in the Northern Territory, and in Carnarvon in northern Western Australia. In 2023, northern Australia accounted for only 689 hectares (4.9%) of the estimated total of 13,932 hectares of PC usage across Australia (Table 2) (Applied Agric. Remote Sensing Centre, 2022). In the tropics, a variety of relatively simple PC structures—such as passively ventilated greenhouses, high polytunnels, and screen/shade houses—are used in combination with crops grown in soil or plant containers with soilless media. For high-value vegetables, blueberries, and some intensive orchards (e.g., tropical tree fruit and grapes), PC systems demonstrate clear benefits, including targeted or prolonged supply periods, increased yields per unit of cropped area, improved water and nutrient use efficiency, and enhanced product quality. These outcomes result from crop protection against rain, wind, and solar radiation, as well as the specific and intensive agronomy practices employed under the structures (e.g., suitable plant genetics, frequent fertigation, and plant canopy management). When managed correctly, PC systems can also improve pest and disease control, further increasing productivity compared to crops grown outdoors.

Australia's vast areas of arable land and diverse climates have ensured a reliable domestic supply of fresh horticultural products for a relatively small population of 26.7 million. However, as identified in the Australian 2021-2030 PC Strategy (Hort Innovation Australia, 2021), expanding PC usage will require targeting new crops and markets. PC systems will play a critical role in supporting export value chains, particularly to markets in Asia. In the tropics, these systems can provide a reliable supply of fresh produce with consistent quality, and in some cases, target higher prices during winter periods. Efficient and cost-effective cold chains will be essential to minimize quality degradation during transport.

While some information about PC systems for horticultural crops in the tropics is available—based on industry use in northern Australia and limited support from RD&E groups (Hort Innovation Australia, 2018; Lantzke, 2017)—extensive knowledge can be drawn from widespread adoption in warm climates outside Australia. Over the past 15 years, RD&E programs in QLD and WA have increasingly focused on PC systems for warm climates. Industry stakeholders, including growers and input and service suppliers, have expressed the need for better understanding of how to design fit-for-purpose PC systems and manage them efficiently. Younger generations of growers are considering production systems that will mitigate supply risks and safeguard investments while ensuring business continuity.

To respond to these industry needs, innovative structure designs were established in 2020 as research and demonstration sites by DPI in Ayr, Queensland, and by DPIRD in Carnarvon, Western Australia. These sites serve to support industry adoption pathways by allowing stakeholders to assess crops and technologies, participate in training, and evaluate proof-of-concept cropping systems (Figure 3).



Figure 2: Protected cropping systems can address some of the challenges facing horticulture production in the tropics and strengthen value chains with a focus on domestic and export markets. Fit-for-purpose structures and agronomy can mitigate suboptimal crop environments such as rainfall, heat and humidity, high solar radiation, and strong wind, which are characteristic of locations in the Australian tropics. Top: South Johnstone, QLD, and bottom: Carnarvon, WA.

Table 1: Overall challenges in outdoor horticulture in the Australian tropics and the benefits of fit-for-purpose protected cropping systems.

Environmental challenges	Potential impacts on outdoor production	Benefits of protected cropping
Rainfall • Seasonal (dry tropics) • Year-round (wet tropics) • High intensity • Prolonged events (Monsoon) Solar radiation • High seasonal or year-round • Low during monsoon and overcast periods Temperature • High • Mild low (inland locations, not an issue in coastal regions) Relative humidity • High seasonal or year-round • Low seasonal or year-round Wind • Low speed (conducive to warm conditions) • High speed (conducive to crop stress conditions and damage) • Cyclonic (damage to structures and crops) Pests & diseases • Insect populations or pathogen inoculum favoured by warm conditions (damage to crops)	• Shortened production season • Loss of crops or reduced plant establishment • Reduced fruit set • Diminished produce quality • Reduced marketable yield • Short produce shelf life • Reduced water and nutrient use efficiencies • Greater impact from pests and diseases • Potentially increased use of chemicals to manage pests and diseases. • Nutrients and agrichemicals can runoff into waterways if excess water and fertilizer are applied	• Improved crop environment and plant growth • Assured planting dates and harvests • Longer production season • Increased marketable yield • Increased and more consistent produce quality, with a longer shelf life • Possibility to reduce the use of agrochemicals with integrated management approaches, including the use of biological control and active ingredients with lower toxicity. • Increased water and nutrient use efficiencies, with the possibility to recycle water and nutrients. • Stronger designs with retractable cladding allow crops to be planted relatively quickly after an event of destructive winds.

Table 2: Total area with protected cropping structures in the Australian tropics in 2023.

	Australian Tropics regions in			
	QLD	**WA**	**NT**	Total
Total protected cropping (ha) [1]	372[2]	232[3]	85[4]	689
Share of Australia's protected cropping area, 13,932 ha (%)	2.7	1.7	0.6	4.9

[1] Includes commercial structures covering over 0.2 ha, identified using the Protected Cropping Map Dashboard (Applied Agric. Remote Sensing Centre, 2022). This data combines areas with designs such as nets, polytunnels, shadehouses and glasshouses.
[2] Region near south and north the Tropic of Capricorn in QLD includes data from the Protected cropping Map Dashboard for subregions Livingstone (north of Rockhampton), Mackay, Whitsunday, Burdekin, Townsville, Hinchinbrook, Cassowary Coast, Cairns, Tablelands, Mareeba, Douglas, and Cook.
[3] Region near south and north the Tropic of Capricorn in WA includes data from the Protected cropping Map Dashboard for subregions Wyndham-East Kimberley, and Carnarvon.
[4] Regions in NT includes data from the Protected cropping Map Dashboard for subregions Unincorporated NT, Litchfield, Coomalie, and Katherine.



Figure 3: A retractable roof structure closes in minutes to protect a crop trial from a 200-mm summer rainfall at the DPI Ayr Research Station in QLD (left). In Carnarvon, WA, partial shading and wind protection is provided to a capsicum crop trial at the DPIRD Research Station (right).

Research aims

Objective and Scope:
The objective of project A.1819067 – *Strengthening Northern Australia's horticultural sector through assessing protected cropping value chain linkages and pathways for adoption* – was to increase awareness of PC systems in the tropics, highlight their potentials and challenges, and provide insights to expand the use of PC technologies in northern Australia.

Key Activities:
The work involved expanding RD&E networks across North Queensland, Western Australia, and the Northern Territory, demonstrating new crops and technologies to stakeholders, delivering training activities, and developing and sharing communication materials at regional and national industry events. Informal and formal interviews with stakeholders identified key priorities to support the adoption of PC technologies. Some interviews and discussions in northern Australia were conducted in parallel with the development of the Australian Protected Cropping Strategy 2021-2023 (Hort Innovation Australia, 2021).

Building on Previous Work:
The activities built on recent projects such as "Gap Analysis and Economic Assessment for Protected Cropping Vegetables in Tropical Australia" (Hort Innovation Australia, 2018) and other reviews assessing the use of PC in northern Australia (e.g., Lantzke, 2017), aligning with priority outcomes in the Australian Protected Cropping Strategy 2021-2030.

Filling Knowledge Gaps:
The project aimed to fill gaps in knowledge regarding key changes required to support PC expansion in northern Australia. This includes gaps in information about PC opportunities (technological, crop management practices, marketing, value-chain linkages), benefits (increased production, improved financial wellbeing of farmers, better-integrated value chains), and obstacles and challenges (environmental, technological, transportation, economic, and marketing). Addressing these gaps is essential to enable long-term production efficiency and scaling adoption, contributing to increased incomes, GDP, jobs, and social well-being.

Research and Extension:
Research and extension activities gathered information to fill these gaps and contribute to the development of region-specific potential pathways for PC adoption in northern Australia. The work mainly focused on regions in North Queensland and Western Australia, but also included northern areas in the Northern Territory.

Activities in this project and Research methodology

To support pathways to adoption, the project drew on secondary sources of information and direct engagement with industry stakeholders (including growers, grower associations and growers across northern Australia, and input suppliers and other value chain actors) and R&D experts.

The key methodologies used to collect and share information were:

- **Review of PC use in the Australian tropics:** Collecting data on existing technologies and practices
- **Collation of expert knowledge:** Leveraging the expertise from DPI's R&D work in North QLD and contributions from DPIRD and Growers' Associations in Carnarvon and NT.
- **Direct engagement with industry stakeholders:** This included:
    - Discussions with industry liaisons and value chain actors (e.g. input suppliers, marketing consultants and produce distributors)
    - Participatory meetings with growers and stakeholders across key locations (e.g. Burdekin; Innisfail; Atherton Tablelands; Carnarvon; Lake Bennett)
    - Semi-structured interviews with current and potential PC users, industry input suppliers, and other industry representatives.
- **Sea freight transport analysis.** Conducted by the Port of Townsville, engaging regional industry and export supply chain participants.
- **Presentations and symposia:** Facilitated at national events for horticulture and PC industries, focusing on research, development, and opportunities for PC.
- **Visits to PC demonstration sites and farms:** Allowing stakeholders to observe crop plots and engage in discussions at sites in Ayr and Carnarvon, and around Darwin.
- **Training activities:** Organised through workshops, short courses, and hands-on activities on farms to disseminate knowledge and practical skills.
- **Regular feedback:** Obtained from industry participants after each activity to ensure continuous improvement and relevance.
- **Linkages with other projects:** Creating synergies with other funded projects that support the adoption of new technologies, including PC systems.
- **Production of communication materials:**
    - **Video Content:** Instructional videos and recorded presentations to visually demonstrate techniques and share insights from experts.
    - **Case Studies:** Real-life examples of PC adoption to inspire and guide other growers.
    - **Web Content:** Articles, e-news, and updates on relevant websites and social media platforms to reach a broader audience.

Dynamics of protected cropping adoption

The adoption of PC systems is influenced by a variety of general factors that apply globally, as well as to Australia and regions like northern Australia. Key factors shaping the dynamics of PC expansion throughout the world are included in Figure 4.

Global trends in PC. Consumer preferences for year-round availability of high-quality fresh produce have driven significant growth in PC development and investment worldwide, including in Australia. Although PC is not a new technology and is well-established in many countries and climates—China alone has over 3.3 million hectares of PC area—Australia has seen varied adoption rates across its regions. The largest PC areas are found in countries such as China, Spain, South Korea, Japan, and Turkey, which together account for approximately 96% of global PC coverage.

Expansion of PC technologies to new climates. Initially, technology development focused on temperate (e.g., The Netherlands) and desert (e.g., Israel) climates, as well as mild winter climates (e.g., southern Spain), but it has recently expanded to subtropical and tropical regions. Improved technologies that are fit-for-purpose are enhancing PC productivity in both cold and warm climates. Today, PC systems range from simple to advanced, featuring varying levels of environmental control, automation, and mechanisation.

Protected cropping in Australia. In Australia, PC adoption began in southern temperate regions before expanding to subtropical climates on the east and west coasts. Only a relatively small number of horticultural businesses have adopted PC in the wet, dry, and desert climates of the Australian tropics. High-value horticultural crops, such as vegetables, berries, nursery plants, flowers, herbs, and fruit trees, are the primary candidates for PC, with blueberries in northern Queensland being a notable example, currently covering more than 80 hectares.

Key drivers of adoption in warm and mild climates. Despite technology enabling horticultural crops to grow anywhere and at any time, adoption of PC in regions with warm and mild winter climates is shaped by several factors. These include proximity to large markets, competitive production costs, minimal energy and labour inputs, and low infrastructure costs, all of which influence PC adoption dynamics.

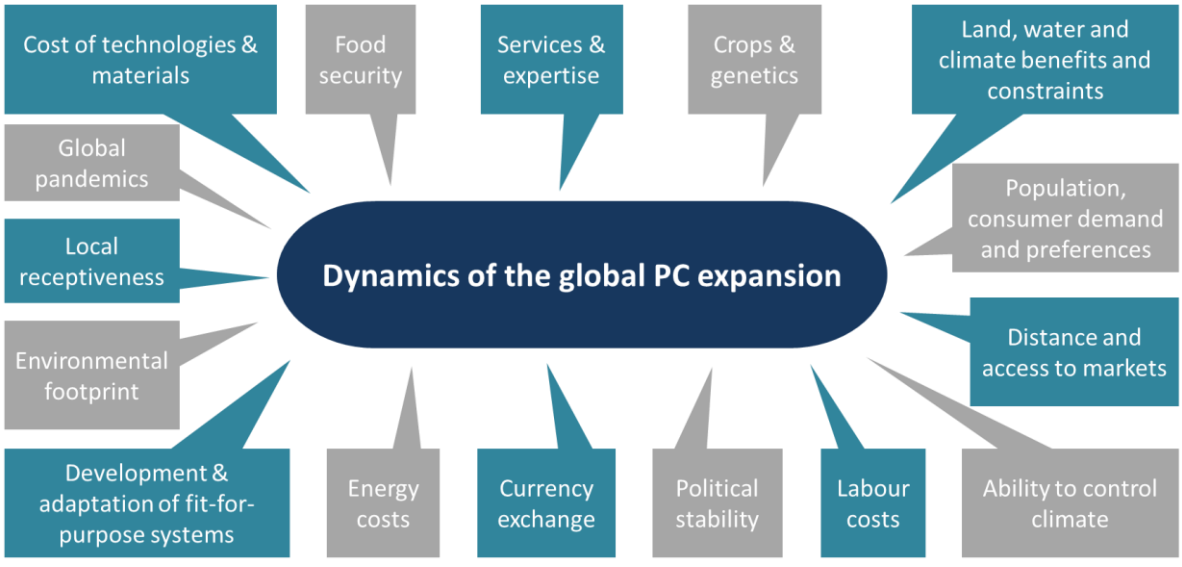


Figure 4: Worldwide factors shaping the dynamics of the protected cropping expansion (modified from the Australian Protected Cropping Strategy 2021-2030.

Recent developments in warm climate PC systems. The expansion of PC to the tropics and subtropics is relatively recent, beginning in the 1980s and 1990s. In warm climates, PC mitigates crop failure by excluding rain and pests and moderating extreme environmental conditions like wind, heat, and solar radiation. Fit-for-purpose PC technologies provide significant benefits, even though production might be lower than in temperate climates with advanced environmental control.

Corporate Investments in warm climate PC. Enhanced transport efficiency has attracted large corporate PC investments to countries with warm climates and low labour costs. Capital investments in these regions are lower than in temperate climates due to less expensive technology requirements and reduced operating costs.

Risk mitigation through PC in Australia. PC is unparalleled in reducing risks in horticultural production, driving its growth in Australia. Recent investments have focused on tomato and berry infrastructure, as well as crops like cucumbers, eggplants, capsicums, leafy vegetables, and herbs, often grown in substrates or hydroponics. Fruit trees and grapes are also being tested in PC systems with hail or shade screens, high-density planting, dwarfing rootstocks, and trellising to minimise risks and reduce labour.

Challenges facing small-scale PC businesses. Smaller PC businesses (<1 ha) in Australia began with simple glasshouses in temperate regions but now face challenges accessing long-term markets and competing with larger enterprises. These businesses often lack technologies that boost efficiency and require skilled labour, training, value chain knowledge, strong business plans, and public RD&E support to adapt technologies and practices. Collaborating with peers and forming groups to enhance market volume or continuity, both domestically and for export, can be beneficial. This growth follows a stepwise technology adoption journey tailored for family-owned businesses, although it may take time. Some smaller businesses will merge, be bought out, or close, while traditional outdoor growers increasingly adopt PC as part of holistic business plans.

Labour, energy, and market dynamics in the Australian PC sector. Labour and energy remain significant production costs across all scales of PC businesses. In warm regions, fossil fuels for heating are unnecessary, and solar radiation is generally sufficient. Specific structural designs and simple cooling systems help remove heat from crops. The diversity of crops grown with PC is increasing but with 26.7 million consumers and a competitive horticulture sector, the Australian market will reach saturation if traditional horticultural products do not access export markets. As PC use increases, some high-value differentiated produce may become lower-value commodities, necessitating flexible business models. Growers may need to invest in labour-saving technologies, diversify products, or target competitive markets. The sector must also address environmental issues, such as adopting technologies to capture and recycle runoff, reducing pesticide use, and managing disposable plastics through reduction, biodegradable alternatives, and recycling.

Opportunities for PC in northern Australia. This synopsis of PC expansion globally and in Australia should be considered when assessing opportunities in northern Australia. Various broader factors will influence PC expansion within northern Australian regions, with specific dynamics identified in this project (Figure 5).

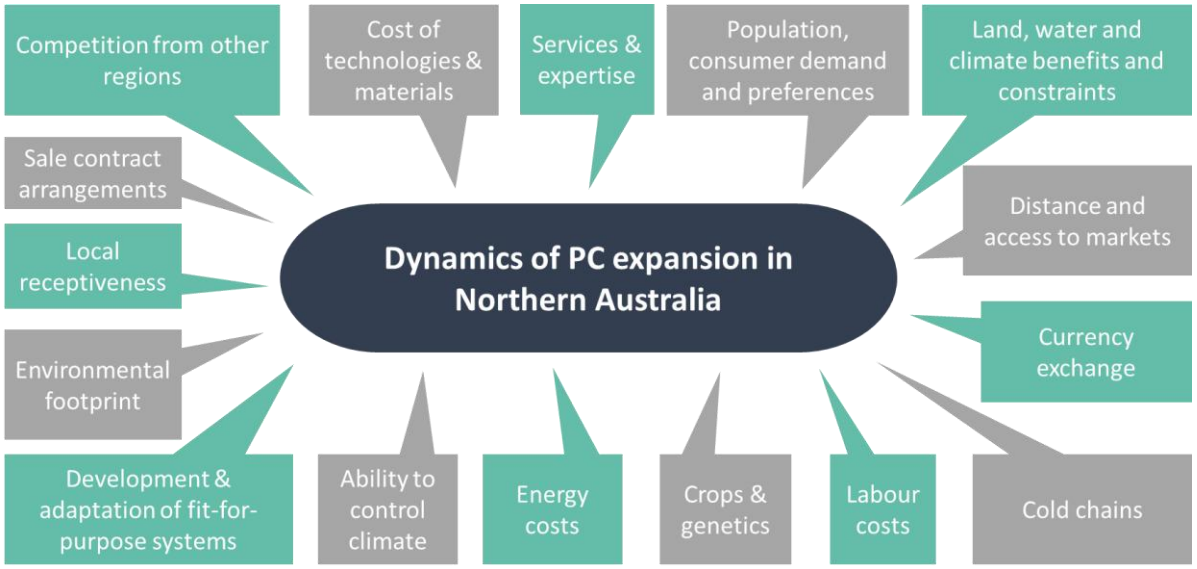


Figure 5: Factors shaping the dynamics of the protected cropping expansion in the Australian tropics.

Protected cropping in the Australian Tropics

The use of PC in the Australian tropics is currently scattered and covers relatively small areas (Figure 6), but it has increased over the past ten years. Further adoption of PC systems will help improve yield and quality consistency in horticultural commodities such as vegetables, melons, and berries, which are often affected by challenging climatic conditions in outdoor crops. Simultaneously, both domestic and overseas markets are increasingly demanding reliable sources of high-quality vegetables.

Untapped value chain partnerships that focus on raising awareness and enhancing the technical knowledge of PC stakeholders are critical for developing pathways to wider PC adoption. Such partnerships will bring increased benefits to farmers and communities.

Innovative agronomic practices and new technologies for warm climates, such as retractable roof structures and cladding with insect exclusion screens and shade screens, can effectively mitigate extreme crop environments and biological constraints. Expanding fit-for-purpose PC systems in tropical regions could provide significant economic benefits for farmers and position the Australian tropics as a key export hub for high-value vegetables and other horticultural products—either year-round or seasonally.

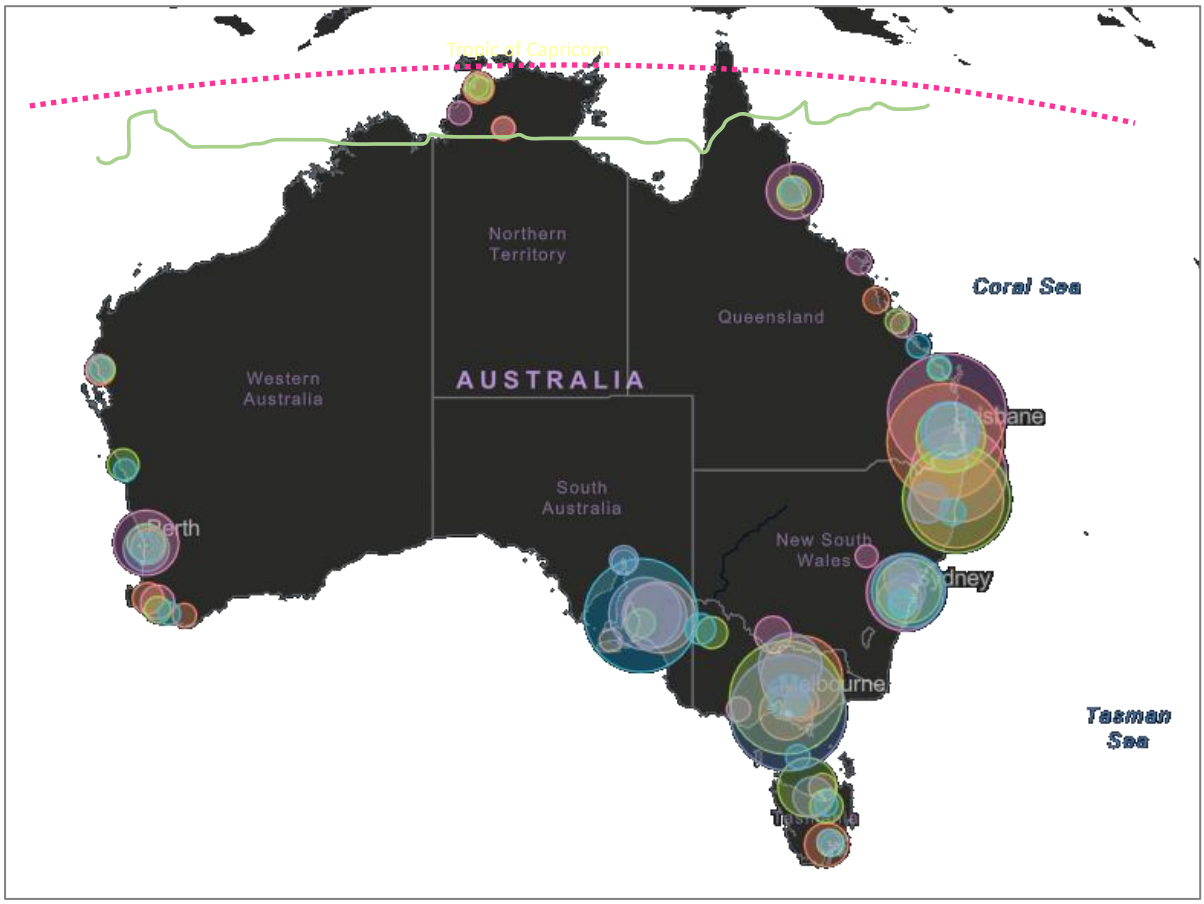


Figure 6: Areas with protected cropping structures in Australia as shown on the Protected Cropping Map Dashboard (Applied Agric. Remote Sensing Centre, 2022). The superimposed pink dotted line represents the Tropic of Capricorn, and the green line delineates Northern Australia. Larger circles indicate larger areas with structures established, and different colours denote various structure design types.

Area with protected cropping

In 2023, Northern Australia had 689 hectares of PC structures, contributing to a total of 13,932 hectares of PC structures across Australia (Tables 3 and 4). These values were obtained from the National Map of Protected Cropping Structures developed by the Applied Agricultural Remote Sensing Centre at the University of New England (Applied Agric. Remote Sensing Centre, 2022). This map utilised satellite imaging, recognition software, and on-ground validation to gather data. Such baseline data can support future decision-making regarding annual growth, forward selling, labour, transport, and storage requirements. It also serves as an essential tool for improved biosecurity preparedness and natural disaster response. The PC cropping map dashboard could be updated in the future to reflect the dynamics of the area and types of structures used in Australia.

In the Australian tropics, PC structures are mostly simple designs like shade screens and polytunnels. In the QLD tropics, polytunnels are primarily used for blueberry production in the Atherton Tablelands, while net and shade houses are mainly used for protected orchards such as lychees and rambutans. In northern WA and NT, nets and shadehouses are used for both vegetable crops and orchards, with polytunnels being a small area used for vegetable crops. The main vegetable crops grown in shade and net houses in Carnarvon, WA, include capsicums, eggplants, and tomatoes. Notably, glasshouse structures are not used in the Australian tropics.

Table 3: Areas with key protected cropping structure designs in the Australian tropics in 2023.

	Australian Tropics regions in States and Territory (ha)			
Structure design[1]	QLD[2]	WA[3]	NT[4]	Total
Glasshouse	0	0	0	0
Polyhouse	8	0	0	8
Polytunnel	106	1	1	108
Net	27	27	12	66
Shadehouse	231	204	72	507
Total	372	232	85	689

[1] Data extracted from the Protected Cropping Map Dashboard represents commercial buildings covering over 0.2 hectares, featuring designs such as nets, polytunnels, shadehouses, and glasshouses.

[2] Region near south and north the Tropic of Capricorn in QLD includes data from the Protected cropping Map Dashboard for subregions Livingstone (north of Rockhampton), Mackay, Whitsunday, Burdekin, Townsville, Hinchinbrook, Cassowary Coast, Cairns, Tablelands, Mareeba, Douglas, and Cook.

[3] Region near south and north the Tropic of Capricorn in WA includes data from the Protected cropping Map Dashboard for subregions Wyndham-East Kimberley, and Carnarvon.

[4] Regions in NT includes data from the Protected cropping Map Dashboard for subregions Unincorporated NT, Litchfield, Coomalie, and Katherine.

Table 4: Percentage of area with protected cropping structure designs in the Australian tropics relative to the total PC area in Australia in 2023.

	Australian Tropics regions in States and Territory (ha)			
Structure design[1]	QLD[2]	WA[3]	NT[4]	Total
Glasshouse	0.0	0.0	0.0	0.0
Polyhouse	0.4	0.0	0.0	0.4
Polytunnel	4.9	0.0	0.0	5.0
Net	2.6	2.3	0.8	5.6
Shadehouse	6.3	6.3	2.8	15.3
Total	2.7	1.7	0.6	4.9

[1] Data extracted from the Protected Cropping Map Dashboard is based on the total area of protected cropping structures in Australia (13,932 ha), focusing on commercial buildings covering more than 0.2 hectares, with designs such as nets, polytunnels, shadehouses and glasshouses.
[2] Region near south and north the Tropic of Capricorn in QLD includes data from the Protected cropping Map Dashboard for subregions Livingstone (north of Rockhampton), Mackay, Whitsunday, Burdekin, Townsville, Hinchinbrook, Cassowary Coast, Cairns, Tablelands, Mareeba, Douglas, and Cook.
[3] Region near south and north the Tropic of Capricorn in WA includes data from the Protected cropping Map Dashboard for subregions Wyndham-East Kimberley, and Carnarvon.
[4] Regions in NT includes data from the Protected cropping Map Dashboard for subregions Unincorporated NT, Litchfield, Coomalie, and Katherine.

Structure designs and common technology classifications

A variety of PC structure designs can address specific environmental constraints and production objectives. Figure 7 illustrates examples of typical PC structure designs, including glasshouses, polyhouses, polytunnels, and net and shadehouses.

Structures suitable for expanding horticultural production in the tropics include: a) Walk-in, multi-bay polyethylene-covered tunnels, b) High passively ventilated greenhouses, c) Retractable roof structures, d) Net and shade houses.

Each design has its advantages and drawbacks, with variations within each category. A detailed discussion and comparison of these structures for the Australian tropics can be found in Appendix 1. Generally, the cost of PC structures increases with their efficiency in managing the plant environment, durability, and wind resistance.

PC structures and systems can be grouped into technology categories based on structure design and inputs that control the crop environment. These categories are:

- **Low Tech:** e.g., polytunnels, nethouses and shadehouses
- **Medium Tech:** e.g., polyhouses and high roof passively ventilated structures
- **High Tech:** e.g., tall structures cladded with glass or polycarbonate, equipped to manage crop environments

As technology levels increase from ‘low’ to ‘high,’ control over the environment and plant growth improves, but so do investment costs and the skills required to manage the technologies. The classification is not strict as it is also common to combine components from different categories, such as using advanced hydroponic setups in simple polytunnel structures. PC technology levels can also be discussed in terms of investment per square meter of cropping area and potential payback periods (e.g., 3, 5, and 10 or more years).

In tropical regions, warm weather favours vegetable crops, often requiring protective structures to mitigate high temperatures and act as rain barriers. Suitable designs for warm environments include low (e.g., tall polytunnel structures >3m) and medium to high-level technologies (e.g., tall greenhouses >5m with passive ventilation and retractable roof structures). Maximising air exchange rates to reduce crop temperatures is key. Fixed or retractable shades are effective for year-round production where high radiation, high air temperatures, and low relative humidity are the main challenges.

Glasshouses, typically used in temperate and sometimes subtropical climates, have also been employed in warm environments abroad. In Bundaberg, QLD, a commercial glasshouse is used just below the Tropic of Capricorn. However, glasshouses in the Australian tropics would need advanced components (e.g., air cooling systems) to manage high temperatures cost-effectively and withstand cyclonic winds. Elements of glasshouse technology, like automation, mechanisation, and closed irrigation systems, can improve productivity and sustainability and be adapted for medium-level PC technologies.

In northern Australia, high tunnels are primarily used for blueberries and to a lesser extent for cucumbers and Asian greens. A few high passively ventilated greenhouses are used for cucumber production, while other high-value vegetables like tomatoes, capsicums, eggplants, beans, and melons have been grown successfully. In Carnarvon, WA, net and shade houses are common for vegetables like capsicums, eggplants, and tomatoes. Tall shade houses also protect trees and fruits (e.g., from birds and bats) in orchards across the north.

Until the commencement of the CRCNA project, there were no retractable roof structures for evaluating vegetable and fruit production in the Australian tropics. These designs were first set up to test and demonstrate vegetable production in small units (1,000 m^2) through investments by DPI in Ayr, QLD, and DPIRD in Carnarvon, WA.

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Figure 7: Images of typical structure designs surveyed in Australia (i.e., Glasshouse, Polyhouse, Polytunnel, Net, and Shadehouse) in the National Map of Protected Cropping Structures project. In the survey, retractable roof structures were included in the Polyhouse category.

Establishing protected cropping systems

Even for tropical climates, the options for possible PC systems are varied. The best design for a producer depends on several factors, including:

- Crop species and plant growing system
- Specific environmental and biological constraints of the location
- Desired level of environmental control
- Expected strength and durability of the structure
- Future scale-up potential
- Investment budget and acceptable return on investment (ROI) and repayment period, as well as broader value chain considerations

Protected cropping systems are very intensive horticultural systems, requiring large capital investments and having high operating costs. The design of a PC system should respond to market-driven opportunities, with an understanding of the specifications for the desired fresh product (including its quality and the supply volumes and periods), expected prices, and contracts.

Businesses new to PC in the tropics often focus too much or too little on the structure design. While important, the PC structure design is just one component of the business. It is critical for stakeholders assessing the commercial use of PC over a few thousand square meters to engage a PC specialist consultant knowledgeable about systems for warm climates and capable of preparing a comprehensive investment analysis. During proposal development, consulting a team of experts and stakeholders associated with the business is also important.

Specific dimensions for structure width and spatial arrangement of crop rows must be considered to ensure cost-effective crop management practices (e.g., options for mechanisation and improvement of environmental conditions) to maximise marketable yield per square meter. The cost of materials for selected structures varies, and structures have specific economies of scale relative to the area covered. The structure's cost is only part of the investment, sometimes representing a small portion of the overall infrastructure investment. Construction and related costs for fitting associated growing technologies will more than double the cost of the structure's materials. Cost-effective technologies to manage environmental conditions are needed to extend harvesting periods in crops. The overall investment will also include costs for connectivity to water, electricity, and internet services, as well as costs for adjacent building infrastructure and equipment for packaging and cold storing produce.

Without the need to heat crops in the tropics, labour costs are the highest operating cost impacting productivity. Investments must consider technologies that can mechanise practices to increase labour productivity. Some structure design decisions will relate to selected growing systems and labour practices. For example, taller structures provide better ventilation and allow trellising vine crops to reach greater heights, increasing production. Increased yields materialise when workers can easily reach heights daily, requiring the use of elevating moving platforms.

Small to medium-sized growers may consider gradually expanding their PC business rather than adopting a larger area and more advanced technologies upfront. When planning to use advanced technologies, ensuring service support from suppliers and agronomists is critical, especially if structures are in remote locations. The availability of skilled labour and cold storage transport in these regions throughout the year are also critical factors.

As of 2024, Australia does not have a unified building classification for horticultural buildings within the National Construction Code (NCC). This means greenhouses or grow structures can sometimes be classified under onerous and inappropriate building types. Changes to the current NCC will help create certainty in the assessment and approval processes and encourage further PC investments. Information about approval requirements for PC structures may be limited in regional councils where these structures are uncommon. Specific restrictions may apply to building structures, such as their proximity to urban areas. Depending on the scale of the PC investment, there will be regulations for managing water and nutrient egress from the production system, particularly in regions where discharge impacts waterways and reefs. Early in the planning process, investors should engage and consult with groups that need to provide approvals at the local and state or territory levels.

Effective crop management is a critical aspect of business planning. Daily agronomy decisions may be handled by the grower-business owner or a hired agronomist, with or without consultant support. The level of investment in management capability typically depends on the scale of the operation. Regardless of the setup, businesses should establish a plan to help crop managers acquire and expand their knowledge. For those unfamiliar with PC, particularly soilless systems, the learning curve can be steep. This should be considered when estimating returns on investment, especially in the initial years when yield expectations may be affected.

Operating in remote locations

Remoteness can be a significant issue in the tropics. While certain environmental advantages may be present in specific locations, managing intensive horticulture in remote areas poses challenges. These include difficulties in accessing skilled labour and obtaining prompt assistance with parts and repair services. Access to consultants, extension, and research officers with experience in PC systems can also be problematic. Although current communication methods can sometimes substitute for site visits, long distances to markets and export centres (airports and ports) by road inevitably increase the costs of inputs and services.

For most crops grown in PC systems, the fresh produce is harvested at a stage where it has the highest visual and eating quality. However, this quality begins to deteriorate after harvest, making it critical to maintain optimal storage conditions until the produce reaches the consumer. This can be particularly challenging when production is far from the consumer.

While operating in remote locations presents challenges, a degree of isolation from field production regions can be beneficial, as it reduces insect and disease pressure from nearby agricultural sites. In soilless production systems, location selection is independent of soil quality—an important factor in traditional farming. In some cases, placing PC investments in or near urban areas offers advantages such as access to transport, repair services, and labour.

Good water quality is essential for soilless systems but can be enhanced through appropriate treatment methods. Water availability is also critical, as large vegetable plants grown in containers with soilless media may require up to 3 litres per plant per day. While PC systems demonstrate greater water use efficiency (litres of water delivered per kg of marketable fruit harvested) compared to field crops, their water use per square metre is higher due to larger plants and high population densities.

Plant growing systems and agronomy

There are several options for plant and tree growing systems suitable for PC in tropical environments. Soilless systems and fertigation help reduce variability in crops and improve quality in the fresh produce. For example, blueberries are now grown in plant containers with soilless media. For vegetables, systems can range from simple setups, such as growing plants in soil under shade or net structures with vertical supports up to 1.8 meters, to more intensive systems where plants are grown in containers with soilless media, supported on twines up to 3 meters high, and in some cases, with stems lowered to the ground, reaching lengths over 10 meters . Maintaining productive vegetable crops for longer periods is easier in vine crops (e.g., cucumber) but can also be practiced in crops like tomatoes, capsicums, and eggplants by pruning shoots and supporting the canopies vertically.

Some crops will continue growing and flowering while fruits are harvested. For these crops, increased yields per square meter with PC are achieved compared to outdoor production, as a result from maintaining plant growth and fruit production for longer periods. In other crops, the higher yields per square metre compared to outdoor production can also be the result of using higher plant population density, and achieving greater marketable yields. Given the significant capital investment in PC, comparing different cropping scenarios using units of $/m²/day is advisable, as it considers revenue relative to annual production.

Tree crops and grapes will most likely be grown in soil, but there are examples of fig crops grown as annual crops in soilless systems. Increased plant population density, the use of rootstocks, and modified smaller canopies created through pruning and trellising can make trees produce earlier in an orchard and facilitate harvesting.

Warm temperatures favour maintaining productive crops for longer periods. However, if extreme temperatures and solar radiation are not mitigated, plant establishment and crop growth will be affected, resulting in fewer flowers setting fruit and unmarketable produce.

The introduction of pests and diseases into crops under structures can also be challenging to manage. A good PC hygiene plan, knowledge of pests and diseases, frequent monitoring, and an integrated management plan that includes plant genetics with genetic resistance are critical. Unmanaged pests and diseases are generally the main reason for terminating a crop cycle in the tropics. Knowledge of integrated pest and disease management, including using low toxicity active ingredients and biological control, is essential. Excessive use of chemicals as the sole management tool has often led to unsustainable production systems.

Infrastructure and cyclonic events

Tropical cyclones are a significant concern for farmers using or considering PC systems in the tropics. Wind speed is the primary aspect of tropical cyclones impacting protective structures. Wind speed design values have been updated in 2021. The Australian Standards AS/NZS 1170:2:2021 indicates design specifications for the different Wind Regions in locations in coastal areas and inland (Holmes et al., 2023). Terrain and reference height will affect these values.

Destructive winds can damage frames, especially when film and screen materials are left attached. High poly-tunnels have low resistance to such winds, while passively ventilated greenhouses and retractable roof structures offer superior resistance. Procedures to protect frame structures from strong winds are complex. In small to medium-scale operations, it may be feasible to remove covering materials to prevent frame deformation, as the steel frame alone can withstand higher wind speeds. Retractable roof structures have a significant advantage, as they can retract roof and sidewall cladding quickly.

Selecting and modifying structure types to meet regional wind speed levels requires considering several factors, including geographical location, terrain, council regulatory building codes, insurance linked to loans, investment costs, potential payback period, manageable risk levels, and advice from engineers and suppliers.

Historic cyclone information by state is available from the Bureau of Meteorology (BOM) website (http://www.bom.gov.au/cyclone/history/index.shtml). For example, BOM reports a strong relationship between eastern Australian tropical cyclone impacts and the El Niño-Southern Oscillation phenomenon, with almost twice as many impacts during La Niña than El Niño. This information can be valuable for financial and risk analyses when planning PC investments, particularly if the crop grown with PC compete with a similar crop grown outdoors.

Heavy precipitation from severe weather systems, including tropical cyclones, significantly impacts vegetables grown outdoors. When PC structures protect crops, the technology's benefits during rainy weather increase, as reduced supply from outdoor crops commands higher market prices. These scenarios often shorten the payback period of a PC investment.

Several extreme climatic events affected the Australian tropics during the summer of 2020/21, including the tropical low system Niran in north QLD (Figure 8), strong winds from ex-Tropical Cyclone Mangga impacting the mid-west region of WA and cyclone Seroja along the north coast of WA.



Figure 8: In March 2021, a farm with bananas and a PC structure was impacted by wind gusts of 90-110 km/h from Tropical Cyclone Niran. While the wind damaged outdoor crops, the passive ventilated greenhouse structure remained intact and continued operating with vegetable crops. DPI project participants have been assisting the collaborating grower in the wet tropics with agronomy advice and on-farm evaluations.

In early February 2021, some crops in Carnarvon were affected by heavy rain and floods from the Gascoyne River (which peaked at 7.1m at Nine Mile bridge) as a result from the tropical low affecting the region. In April 2021, winds, and rain from cyclone Seroja affected Carnarvon. Greater damage to PC structures occurred in southern towns on the coast, such as Geraldton, where there are approximately 85 ha with PC.

Adoption of protected cropping in the tropics

The Australian Protected Cropping Strategy 2021-2030

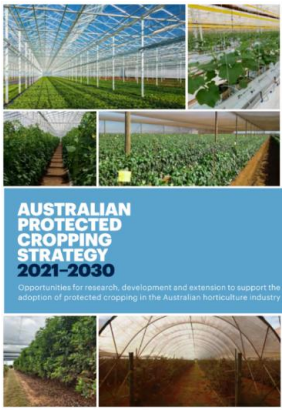
The Australian Protected Cropping Strategy 2021-2030 (Hort Innovation Australia, 2021) provides a comprehensive approach to increasing and supporting the adoption of PC in Australia. It outlines opportunities for Research, Development, and Extension (RD&E) as well as other changes required to support the adoption of PC in the Australian horticulture industry, addressing challenges specific to tropical regions. Developed during the life of this project, the Strategy discusses many aspects relevant to the expansion of PC in the tropics. It is based on extensive consultation with industry stakeholders across Australia carried out during 2020-21 and an analysis of global trends in PC within horticulture. The Strategy engaged 47 groups/organisations and more than 100 individuals, including State and Territory agricultural departments, industry associations, universities and educational centres, growers, producer and marketer groups, consultants, and agricultural product and service suppliers.

The Strategy identified three priority outcomes and key aims:

- **Value Chains:** Developing profitable, diversified value chains.
- **People:** Increasing knowledge, capacity, and practice change.
- **Technologies:** Applying fit-for-purpose, cost-effective PC technologies and systems.

Investment priorities, strategic activities, possible deliveries, and key performance indicators (KPIs) are outlined within the Strategy.

The Australian Protected Cropping Strategy 2021-2030 was funded through the project 'AS19005 Australian Protected Cropping RD&E Strategy 2030' by the Hort Frontiers Advanced Production Systems fund (part of the Hort Frontiers strategic partnership initiative developed by Hort Innovation), with co-investment from DPI and contributions from the Australian Government and Food Innovation Australia Limited (FIAL). The Department of Agriculture, Water and the Environment (DAWE) formally released the Strategy in November 2021. The Strategy document is available on the Protected Cropping Australia website and can be accessed through the following weblink: Australian Protected Cropping Strategy 2021-2030.





Drivers, barriers and possible enablers to adoption in the tropics

Drivers and barriers influencing the adoption (or consideration) of PC systems were identified through discussions with growers, value chain members, and industry stakeholders and are summarised in Table 5. A major bottleneck to broader adoption in the region is the limited availability of information for growers and value-chain actors regarding PC opportunities, technological and crop options, crop management practices, and their economic viability in tropical climates. Vegetable producers and other stakeholders considering PC investments have highlighted this as a critical gap.

Technologies and practices used in temperate regions of Australia are often unsuitable for warm climates. Tropical extremes in air temperature, rainfall, relative humidity, wind, solar radiation, and pest and disease pressures necessitate specific structure designs and crop management practices. These challenges, along with potential pathways to facilitate PC adoption in the tropics, were highlighted in recent reports (Hort Innovation Australia, 2018; 2021).

Across northern Australia, the demand for additional information is growing. Growers, Grower Associations, and Departments of Agriculture in Queensland, Western Australia, and the Northern Territory are actively exploring opportunities to expand PC. These barriers highlight the need for comprehensive support, training, and research—including demonstration sites equipped with suitable PC infrastructure—to enable successful adoption in the region. Proposed solutions to overcome these obstacles and facilitate PC adoption, ensuring sustainable and productive horticulture farming across northern Australia, are detailed in Table 6.

Table 5: Drivers and barriers to adoption of protected cropping systems in the tropics.

Drivers to adopting or considering adoption of protected cropping technologies	Barriers to adopting or considering adoption of protected cropping technologies
Risk reduction and Yield stability: • Reduction in risks of yield losses from climate variability. • Methods to extend the production season and reduce risks of losses in early and late periods of the season. **Improved production and Supply assurance:** • More efficient planning for production and increased assurance of supply (volume and quality). • Management practices and technologies that enable greater control of crop growth and production. • Production systems that allow better negotiation of desirable supply contracts with buyers. • Technologies that complement existing field production during challenging outdoor production periods. **Market access and Quality:** • Possibility to access niche markets with specialty commodities that are difficult to grow outdoors. • Increased demand for consistent quality. • Potential to access export markets with specific commodities demanded by overseas buyers. • Technologies that complement supply from southern regions with lower costs and energy inputs. **Technological Integration and Efficiency:** • Technologies that better integrate biological control practices and improve management of pests and diseases with fewer chemical inputs. **Early adoption and learning:** • An early start in learning the production systems with the anticipation that it will become more standard in the years to	**Knowledge and Understanding barriers:** • Limited understanding of PC: its potential and the range of technologies to address production constraints in warm environments. • Misunderstanding that PC is not just placing a structure over a field crop, but a comprehensive system of production. • Lack of familiarity with opportunities to visit regions with similar environments using the technology. • Insufficient regional knowledge to support the expansion of PC. • Limited access to demonstration sites for developing and demonstrating proof-of-concept cropping systems to de-risk investments. • Limited knowledge on effective methods to manage pests and diseases without relying solely on agrochemicals. **Feasibility and Risk barriers:** • Uncertainty about the feasibility of these technologies, as they are relatively new with few examples in the tropics. • Lack of sufficient evaluations and commercial examples to determine feasibility. • Risk of failure if adequate training support is not available. • High cost and time investment associated with a steep learning curve. • Competitiveness in the sector making it difficult to access regional information and share experiences. • Risks associated with cyclonic weather events • Biosecurity or trade restrictions **Financial and Economic barries:** • High capital investment required for

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 PC.	implementing PC technologies. • Need for acceptable prices for higher quality produce to offset higher production costs. • Limited and costly support from input and service suppliers for investments in remote locations. **Infrastructure and Logistics barriers:** • Remoteness and long distances to southern domestic markets. • Challenges related to infrastructure, knowledge, and logistics for supporting export opportunities. • Need for clear planning procedures and consent for development in regions where PC is uncommon. **Labour and Skill barriers:** • Shortage of operators skilled in intensive production systems. • Irregular or seasonal labour availability with varying skill levels.

Table 6: Possible solutions to overcome barriers to adopting or considering the adoption of protected cropping technologies, along with their potential industry outcomes.

Possible solutions to address barriers to adopting or considering adoption of protected cropping technologies	Potential outcomes from applied solutions supporting the adoption of protected cropping technologies
Infrastructure and Research for Development: • PC infrastructure investments and RD&E with stakeholders to demonstrate crops and technologies, and develop solutions. • On-farm research and development with peers and expert groups. • Funding initiatives to support collaborative RD&E to address issues in diverse climatic regions and farming scales. **Knowledge and Information sharing:** • Knowledge and information sharing across RD&E and demonstration sites. • Knowledge and information sharing at regional and national events. • Collaborative engagement among growers, input and service suppliers, researchers, and other value chain participants to develop PC proof-of-concepts. • Sharing of experiences and outcomes in adoption pathways. • Development of PC systems for new crops. • Communication materials, including formats suitable for groups where English is not the primary language. **Training and Skill development:** • Training opportunities to skill-up PC managers and workers. • Information sessions to understand possible pathways to adoption. • Information sessions for stakeholders considering adoption and using PC, focusing on technologies, potential crops, agronomy (including crop requirements such as optimal environment, fertigation, and pest & disease management), automation, crop and climate data interpretation, recordkeeping, and financial analyses.	**Awareness and Understanding** • Increased awareness and understanding of the services provided by PC systems for the Australian tropics. • Growers able to identify fit-for-purpose technologies for their business plans. • Accessible information on PC systems for the tropics. • Fast-tracked industry adoption assisted by participative learning. **Effectiveness and Support:** • PC systems are effective because they have been informed by a range of value chain participants. • Supported pathways to adoption from the RD&E continuum that adapts to industry needs • Effective solutions identified from a systems approach to addressing issues and specific business needs. **Decision Making and Risk management:** • Growers understand crop constraints and can identify technologies and practices to solve or mitigate problems. • Stakeholders can make informed decisions in their investments and businesses. • First-hand observation of long-term PC systems with a better understanding of the benefits and challenges. • Lower risk investments. **Competitiveness and Market opportunities:** • Competitiveness from new opportunities, such as new crops and markets. • Acceptable prices from recognized quality or value-added marketing strategies. • Produce quality maintained along the supply chain. • Potential to access export markets with specific commodities demanded by overseas buyers. **Skilled workforce:**

• Study tours (national and international) to expose growers to peers using PC systems in locations with similar challenges and where they have been used for a long time. **Networking and Engagement:** • Increased networking in the sector using PC through grower participation at industry events, demonstration sites, and on-farm research. • Growers attending and participating in industry events that discuss PC systems. **Support from Input and Service suppliers:** • Input and service suppliers expanding the area where they provide support. • Input and service suppliers becoming involved in developing proof-of-concepts. **Market and Logistics:** • Seeking advice from marketing experts to differentiate produce based on quality attributes and help negotiate acceptable prices. • Transport infrastructure, cold storage, and efficient logistics to enable cost-effective delivery of fresh produce to domestic and export markets.	• Skilled workforce. • Increased adoption of PC by horticultural businesses will increase the demand for a suitably skilled regional workforce. • Training opportunities to skill-up PC managers and workers. **Networking and Efficiency:** • Efficiencies gained from an extended industry network. **Confidence in managing Sustainable business:** • Confidence in operating PC systems knowing that expertise is available if required. • Adopted practices conducive to economic, environmental, and social benefits.

Project activities to support adoption

The selected project activities were guided by industry needs (Table 5) and aimed at some of the outcomes outlined in Table 6. A summary of ten groups of activities in the project are provided in the following sections:

1. **Setup of PC infrastructure in Ayr and Carnarvon**
2. **Crop production evaluations and demonstrations**
3. **On-farm research, technical advice, and training**
4. **Potential new crops for export markets**
5. **Collaboration across value chains**
6. **Information sharing at industry events**
7. **Information sharing in educational programs**
8. **Situation analysis of vegetable export supply chains in north Queensland**
9. **Communication materials**
    a. Publications and abstracts
    b. Video production
    c. Webinar
    d. Production opportunity and Crop case studies
    e. Grower case studies
    f. CRCNA media releases and e-newsletters articles
    g. Articles by external groups that relate to project activities

1. Setup of PC infrastructure in Ayr and Carnarvon

Discussions with industry stakeholders prior to this project revealed the need for fit-for-purpose RD&E infrastructure to validate and demonstrate the performance of PC systems. These sites, along with associated resources and expertise, would assist in de-risking investments, developing and demonstrating systems for new crops, testing new technologies, and facilitating research that is more difficult to conduct on commercial farms (e.g., managing a variety of crop plots with specific fertigation programs and plant canopy management, different crop environment scenarios, plant genetics and strategies for managing pests and diseases). The sites would also provide a common place for growers to access training activities, discussions, and engagement with other value chain participants, such as PC input and service suppliers.

During the project's life, two major PC infrastructure investments were completed in 2020 to enhance RD&E activities using novel fit-for-purpose structures at research facilities in Ayr, North QLD, and Carnarvon, North WA.

DPI Research Facility at Ayr, QLD.

In 2020, DPI established an innovative retractable roof greenhouse structure at the Ayr Research Facility. The structure, designed by Cravo Equipment Ltd, was selected to address climate variability constraints and extreme events in the dry and wet tropics. This tall structure can protect crops from rain and provides a high air exchange rate to reduce air temperature. The cladding can completely retract rapidly in the event of cyclonic winds, preventing damage to the structure. An internal insect exclusion screen is also retractable.

The structure's crop-growing components include an advanced control system to automate fertigation, a fogging system to cool canopies, and the movement of the retractable cladding. The growing area under the structure is set up to grow crops in soilless media and fertigate them with nutrient solutions. Data on irrigation schedules and volumes, drainage volumes from plant containers, media moisture, air temperature and relative humidity, and solar radiation are collected by sensors and displayed on a computer dashboard, which can also be accessed remotely.

The PC structure, construction, and site investment were funded by DPI, with a portion of operational support funded by DPI-led projects, including this CRCNA project. Construction was completed in September 2020, with the first crops established in October 2020 (Figure 9). This site has been used since 2020 to test a variety of traditional vegetable crops, as well as some crops that are not commonly grown using PC systems in Australia.



Figure 9: The retractable roof structure established by DPI at Ayr, QLD, was being completed in 2020. The fertigation system allows for different nutrient formulations to be delivered to small plots, demonstrating production across various crops. The movements of the roof cladding, side curtains, and the fertigation system are automated. Crops were planted at the end of October 2020, and grower visits followed during the summer.

DPIRD Research Facility at Carnarvon, WA.

DPIRD funded and established a 1.3-hectare net house at the Carnarvon Research Facility in August 2020 (Figure 10). The structure has areas with different shading levels and a water misting system that allows the manipulation of air humidity and crop canopy temperature. This structure is used for RD&E on fruit trees and vegetables. A retractable roof greenhouse structure with a ground area of 1000 square meters and similar design characteristics to the one in Ayr was built next to the net house. The automated irrigation system can also deliver nutrients to small plots. Initial trials were conducted in soil (a common practice in the region), and in 2022, evaluations were also conducted using a soilless crop growing system.

Both retractable roof structures in Ayr and Carnarvon have unique designs that had not been tested in the Australian tropics, generating much interest among regional growers looking at potential PC investments. The two retractable roof structures are currently the only ones supporting RD&E in the tropics.



Figure 10: A 1.3-hectare screen house was set up by DPIRD to conduct trials for intensive orchard systems and vegetables at the Carnarvon Research Facility (left). Additionally, a retractable roof structure was completed to commence trials with vegetables (right). These two structures are part of the new PC RD&E and demonstration site at the research station in Carnarvon, WA.

2. Crop production evaluations and demonstrations

Crop evaluations at research sites in Ayr and Carnarvon included common crops grown in the region as well as tests of new potential crops. Demonstrations included different fruit types and cultivars, planting seasons, and agronomic practices such as fertigation schedules, crop environment management, plant population density, and canopy management practices, as well as sustainable approaches to managing pests and diseases.

In Ayr, DPI established soilless crop plots of cucumbers, tomatoes, capsicums and eggplants which can be found in PC in temperate and subtropical climates. Novel demonstrations to growers were displays of crops using PC systems for specialty beans, zucchini, specialty melons, small watermelons, Kabocha pumpkin, turmeric, ginger, and dragon fruit. The site in Ayr had weekly visits of regional growers, as well as visits by input and service suppliers. Information about these crops have been shared with stakeholders through industry events, communication materials and one-to-one visits and discussions. Vegetables and fruits grown at Ayr were displayed in the booths of DPI and seed companies at Hort Connections and PCA conference events.

In Carnarvon, DPIRD established crop plots of tomatoes, capsicums, cucumbers, eggplants, and zucchini. There were also several evaluations of tropical fruit trees under the larger shade structure. This site was regularly visited by growers and used in regional industry events.

NT Farmers followed the progress of commercial crops with growers who were already using PC systems as well as growers who were new to these production systems.

Crops evaluated in Ayr, QLD.

Eggplant, melon, and cucumber crops transplanted in October 2020 were maintained throughout the summer and finished by March 2021 (Figure 11). These crops provided the first evidence of yield and quality that could be achieved during a warm and rainy summer season using a retractable roof structure in North QLD. The quality of eggplants, beans, and cucumbers matched premium commercial standards (Figure 12). The roof operation was set to lower temperatures above 27°C, while cooling and relative humidity were managed using a fine misting system. The horizontal insect screen was opened when bees were needed for pollination in crops such as melons. Pests were managed using biological control in conjunction with low-toxicity active ingredients in integrated management programs. Various agronomic practices were demonstrated to stakeholders who visited the site weekly.

Plants under the retractable roof structure were pruned, trellised vertically, and regularly harvested during the summer period. They were grown in containers with roots in soilless media (e.g., coconut coir, perlite, and pine bark) and irrigated with a complete nutrient solution. The controller triggered the start of fertigation events when a cumulative solar radiation setpoint value was reached. With this method, plants received more frequent irrigation events when solar radiation was greater, and vice versa. Overhead misting was used to cool the plant canopies, and the very short sprays were also scheduled by solar radiation setpoints in the controller.

In the QLD tropics, all field-grown vegetable crops are terminated at the end of November. During the cropping period, outdoor mean day air temperatures were 30 °C, and rainfall was 520 mm from December 2020 to January 2021 in the Burdekin region. With a late planting under the new greenhouse, the project team demonstrated that production is possible under high temperatures and intense rain conditions.

High prices for low-quality melon fruit were offered to consumers in retail markets in March 2021. The crop evaluations carried out throughout the 2020-21 summer by DPI in North QLD indicated that PC can lead to high visual and eating quality in differentiated specialty melons (Figure 13). These specialty fruits can be very sweet (up to 16 °Brix) and will attract high prices in the southern niche markets in Australia (up to $20/fruit or higher). There are also potential opportunities to export these fruits to Asian markets.

The second set of crop plots in Ayr were planted in March and April 2021. These plots included tomatoes, capsicums, eggplants, melons, and cucumbers (Figures 14). The specialty melon crops planted in late March were harvested in mid-June. The fruits also had excellent visual and eating quality, with sugar levels reaching up to 16 °Brix. Cold storage evaluations were conducted onsite, with fruits maintaining good visual and eating quality for up to 25 days when kept at 8 °C and 85% RH.

Capsicums of the bullhorn fruit type, planted in early March 2021, had their first fruit pick at the end of May. The fruit quality of these capsicums was excellent, matching or surpassing commercial standards (Figure 15). These crops provided the first evidence of yield and quality that could be achieved using a retractable roof structure in North QLD. Crop plots of tomatoes and eggplants were maintained and harvested weekly.

In capsicums, plant canopies were initially formed with early pruning that left 3 to 4 shoots and where the first flowers were removed. This allowed the development of a larger canopy that later led to greater yields. The canopy support system involves little labour as they are supported vertically by horizontal twines and poles. Brix levels in the juice of these fruits were 8. Capsicum yields in trials and small commercial crops in the tropics have been in the range of 9 to 15 kg/m². These first crop evaluations by DPI in North QLD demonstrated the very good performance of vegetable and melon crops, highlighting the potential for using PC systems to meet the visual and eating quality demanded by consumers.

Alternatives to exclusive chemical control of pests and diseases are uncommon in the tropics. Demonstrations in this project showcased how biological control practices can support the management of typical pests. Fungus gnats (*Bradysia* sp.) were controlled through an integrated approach, including a drench containing *Bacillus thuringiensis* subsp. israelensis (strain AM65-52), the release of specific predatory mites and nematodes into the media, yellow sticky traps, and a layer of fine sand placed over the growing medium.

A predatory mite, *Neoseiulus californicus*, was introduced to effectively reduce broadmite (*Polyphagotarsonemus latus*) populations. Broadmite is a key pest in warm, humid tropical climates, where it can damage the canopies and fruits of multiple crop species, including capsicums and eggplants, and occasionally cucurbits such as cucumbers (Figure 16). Other beneficial insects released included the parasitic wasps *Aphidius colemani* to manage Cotton/Melon Aphid (Aphis gossypii) and Green Peach Aphid (*Myzus persicae*), as well as *Eretmocerus hayati* to control silverleaf whitefly (*Bemisia tabaci*).

Banker plant systems were also implemented to assist in managing melon aphids. These systems involve growing grass in containers that are deliberately infested with host-specific aphids, allowing parasitic wasps to multiply and subsequently parasitize other aphid species within the crop. The grass pots were strategically placed near the crops.



Figure 11: The first plots with vegetables were planted in the new structure at the DPI Ayr Research Facility in October 2020.



Figure 12: The fruit quality of eggplants, trellising beans, and cucumbers was excellent considering the high temperatures and frequent rainfall during the 2020-21 summer in Ayr, QLD.



Figure 13: Fruit quality of field-grown rockmelons in retail markets during March 2021 (top two images) contrasted with the quality of specialty melon fruit grown in North QLD evaluations in a greenhouse at Ayr (bottom four images).



Figure 14: In March 2021, capsicum and tomato crops were transplanted at the DPI Ayr Research Facility. Plants are grown in pine bark medium and irrigated with a complete nutrient solution.



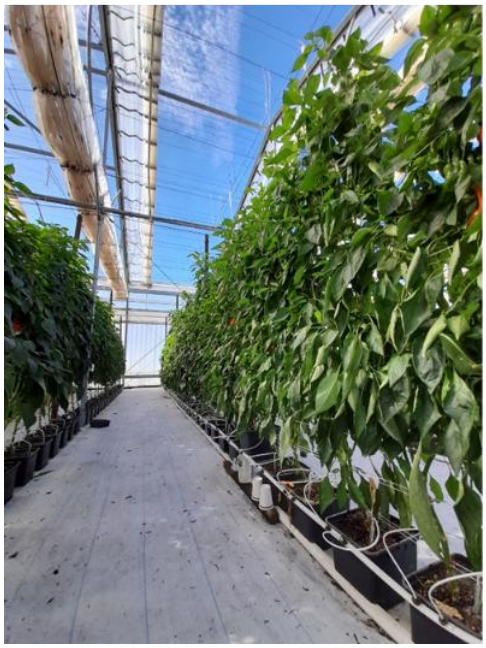




Figure 15: The fruit quality of bullhorn capsicums during May-June 2021 was excellent in the North QLD evaluations under the retractable roof structure at the DPI Ayr Research Facility.



Figure 16: The project team followed integrated pest management programs that use reduced pesticide inputs. Pest thresholds in crops in the new retractable roof structure at Ayr, QLD, were maintained at low levels with a combination of preventative releases of commercial biological control agents and spot sprays using active ingredients of low toxicity.

In low and mid-tech systems, Lebanese-type cucumbers are trellised to a height just below 2 meters, so plants and fruits can be reached by workers. However, to increase yields, the growth of cucumber vines can be prolonged by trellising to greater heights and by sequentially lowering the sections of the vines that have been harvested, similar to the practice used with PC-grown tomatoes. This method was tested in a cucumber crop established in November 2020 and terminated after 29 harvests in March 2021 (Figure 17). The total length of the vines was approximately 6 meters, and the total marketable fruit yield reached 20 kg/m². As a comparison, yields in low-cost tunnels with crops trellised to 1.8-2 meters high are in the range of 5 to 8 kg/m².

For workers to trellis plants to heights greater than 1.8-2 meters, it will be necessary to invest in elevating work platforms, which are not common in mid- and low-tech systems. This type of equipment and other mechanised practices will be critical to increasing productivity in the tropics.

Overall, evaluations conducted under retractable roof structures and validated through on-farm trials demonstrated year-round production capabilities and notable yields. These included capsicums (15 kg/m²), eggplants (18 kg/m²), cucumbers (10 to 20 kg/m², depending on short or long crop cycles), zucchini (15 kg/m²), beans (6 kg/m²), and specialty melons (3 fruits/m²), with fruit flesh reaching up to 16 °Brix of Total Soluble Solids, a measure of sweetness.



Figure 17: In this Lebanese cucumber crop in north QLD, the lower sections of the cucumber vines were defoliated and layered to maintain growth and increase production.

The climate and crop data gathered have provided valuable primary information to develop recommendations for managing the retractable roof structure and crops during the summer in the QLD tropics.

Growers, agriculture input suppliers, and technology services representatives have been visiting the demonstration site with great interest in what can be achieved using PC in the QLD tropics. The opportunity to discuss systems with stakeholders is also used to emphasise that these systems are labour-intensive and require specific skills, such as understanding and modifying nutrient solutions, managing plant canopies, and frequently monitoring pests and diseases (Figures 18 and 19).



Figure 18: DPI project participants Heidi Wiggenhauser, Matt Tinai, and Elio Jovicich trellis plants while inspecting first flowers and fruit set in a melon crop (left image) next to another crop ready to be harvested (right image) in February 2021 in North QLD.



Figure 19: The activities conducted by the project team at the DPI Research Facility in QLD resemble commercial production systems but are conducted on a small scale. During stakeholder visits, the team demonstrated the agronomy practices required to effectively manage these intensive production systems. The stakeholders included regional growers using or considering the adoption of PC in the tropics, potential investors from other regions, and PC input suppliers.

In 2022 and 2023, crops like turmeric, ginger, and dragon fruit were planted (Figure 20). These crops have longer periods to harvest compared to vegetables and they benefit from the warm environments, plant growing systems, and fertigation. The crops also require less labour than vegetable crops. They could be grown in lower cost structures too. Yields of ginger and turmeric were similar, reaching close to 6 kg/m² after 13 months. Dragon fruit, which is becoming increasingly popular worldwide, is grown using high plant population densities under greenhouses in Spain. Small crop plots at Ayr have been delivering first fruits with excellent visual and eating quality in two cultivars, with white and red flesh with production starting earlier than in outdoor crops.

Kabocha pumpkins, a sweet and delicious fruit in demand in Asian markets, were also tested by growing plants at high population densities and trellising vines vertically. The yields were promising (2-3 fruits per plant at a population density of 3 plants per square metre), but the cultivar grown was very susceptible to powdery mildew disease.



Figure 20: Crops like dragon fruit, turmeric, and ginger, which benefit from using PC systems and are uncommon in these production systems, were displayed at the DPI Research Facility at Ayr.

Crops evaluated in Carnarvon, WA.

In Carnarvon, DPIRD initially conducted evaluations of vegetables (eggplants and zucchini) under the new shade structure. Capsicums and tomatoes were then evaluated in soil-grown crops under the retractable roof structure. These first crops were established to determine optimum agronomy practices with PC in a region where high wind speeds and solar radiation levels, and eventual rainfall events, restrict open-field crop production (Figure 21).



Figure 21: First vegetable crops grown under the shade structure and the retractable roof structure at the DIPIRD Carnarvon Research Facility.

Eggplants were planted in March 2021 and grown under different shade levels (11%, 21%, and 30%) to identify conditions that maximise fruit yield and quality (Figure 22). In this evaluation, using 21% shading led to marketable yields 54% greater than in plants grown in open-field plot (Nguyen and Lantzke, 2022a).

The first crops under the retractable roof also helped measure the environmental conditions provided by this structure and compare yields between protected crops and field-grown crops. The structure allowed to provide variations in the amount of solar radiation to the crops and protect crops from rain events. One evaluation compared capsicum production under the retractable roof structure (9.7 kg/m²) with outdoor production (3.9 kg/m²) (Figure 23). DPIRD published these findings and presented research on eggplants and capsicums at industry events such as PCA2022 and PCA2023 (Nguyen and Lantzke, 2022a; 2022b; 2023).



Figure 22: DPIRD compared production of eggplants under screens providing different levels of shade and with open field production. Image from Nguyen and Lantzke (2022a).



Figure 23: Capsicum crops were grown in soil under the retractable roof structure in Carnarvon and their production was compared to a capsicum crop plot grown in the open-field. Growers visited the crops and discussed the technologies and trial outcomes with DPIRD researchers.

In 2022, a soilless system was set up in an area of the retractable roof structure to evaluate tomato, cucumber, and capsicum (Figure 24). Production systems using media and hydroponics, which are not commonly used by growers in the region, were important demonstrations led by DPIRD. Experience from using soilless systems in north QLD was shared by DPI participants.



Figure 24: DPIRD commenced conducting evaluations of vegetable crops using soilless systems in 2022.

Crops followed in Northern Territory.

NT Farmers engaged with vegetable growers in the Darwin, Marrakai, and Lake Bennett regions, supporting their adoption of PC systems. Greg Owens (NT Farmers) helped growers near Darwin establish a trial site to demonstrate the benefits of using PC on snake beans (*Vigna unguiculata* subsp. *sesquipedalis*). Red-wing parrots can consume up to 25% of marketable beans, impacting profitability due to constant patrol costs. One grower adapted a cucumber shade house with bird netting instead of shade cloth, allowing more sunlight while excluding birds (Figure 25).

In 2020, a grower in Marrakai established simple PC structures covering nearly 2,300 square meters. NT Farmers collaborated with this grower, a leader in the regional Cambodian community, advancing IPDM practices and water efficiency projects. This grower transitioned from outdoor production of okra, zucchini, and snake beans to Lebanese cucumber under shade structures, testing soilless production (Figure 26). NT Farmers documented these efforts in a case study.

NT Farmers monitored a high-density rambutan orchard under a netted structure (Figure 27). The PC structure provides shade, reduces wind, and excludes flying foxes and birds. In September 2020, NT Farmers organised an orchard field walk for regional growers at the Tropical Fruit Net in Coastal Plains. Stakeholders learned about managing high-density rambutan trees, with discussions on canopy pruning, and using native bees to increase fruit set. Participants examined tree growth, canopy management, flowering, and fruit set.

Additionally, NT Farmers supported a large grower (16+ ha) in Lake Bennett using simple but effective PC systems for vegetables for many years. This grower used net structures over cucumber and bean crops but grew various vegetables in a soilless system with gutters holding plant containers off the ground (Figure 27). The grower targeted production for southern markets during winter. High horizontal nets were preferred over polyethylene tunnels, which create too hot an environment for crops. While nets don't protect plants from rain, they offered more benefits than growing outdoors and polytunnels. However, due to the large pores in the net screens and the open structures around the crops (to improve ventilation), pests and diseases remained a challenge in these tropical environments.



Figure 25: A grower in NT used a bird exclusion net on snake beans as a PC structure.



Figure 26: A grower in Marrakai built low, simple PC structures to test cucumber crops in soil and soilless conditions. This was a steep learning curve with some ups and downs during the uptake of intensive practices and while using structures with insufficient ventilation.



Figure 27: A net structure is used on a rambutan orchard to provide shade and exclude birds in NT (left). A grower in Lake Benett developed a system for growing cucumbers in soilless systems under a net structure (right).

3. On-farm research, technical advice and training

Project participants assisted PC users and new adopters by sharing technical advice to ensure their business sustainability and de-risk investments in technologies and practices that are new in the tropics. These activities also supported network creation among stakeholders and identified specific opportunities for training. They helped better understand the drivers and barriers to adoption. Participants regularly visited farms and responded to inquiries about crop issues and potential new PC investments. During periods with travel restrictions due to COVID-19, social platforms were used to exchange information, including photos and videos of crops and webinars.

DPI participants carried out on-farm commercial evaluations in the QLD wet and dry tropics, particularly on farms using PC in Atherton, South Johnston, Ayr, and Gumlu. Crops on these farms included eggplant, specialty melons, capsicums, chillies, and cucumber grown in soilless media. Some of the regular topics discussed with growers included fertigation and adjusting nutrient delivery, pest and disease management, pollination, plant canopy management, new crops, and ways to reduce labour inputs.

DPI participants also followed product samples that were sent to markets in Australia and overseas. The feedback provided from these markets helped adjust agronomy practices and build confidence that the PC systems can deliver high-quality products from the tropics (Figure 28).

The on-farm evaluations conducted in collaboration with growers and other industry stakeholders increased knowledge of value chains. Eggplants transplanted in mid-April in the wet tropics started being harvested in June and continued until late spring (Figure 29). In the Burdekin, up to five crops a year could be grown in the same area when trellising the vines up to a height of 2 meters (Figure 30). Small volumes of eggplants were also sent to Asia by a grower as a pilot export trial. Capsicums and chillies also grew well during warm periods. Capsicums and chillies, normally grown outdoors in north QLD, were tested by growers under different PC structures (Figure 31). Produce quality was excellent in all these regions, and it was delivered to regional and southern markets.

Regional stakeholders from areas near the Burdekin and Tablelands (QLD), Carnarvon and Geraldton (WA), and Berrimah and Lake Bennett (NT) participated in field days, workshops, and training events organised by project participants in each state or territory. These events provided valuable opportunities for growers to network and learn through presentations, face-to-face discussions, and hands-on activities (Figure 32). Case studies were developed for selected vegetable producers in the tropics (Appendix 3) and for various production systems and crops (Appendix 4).



Figure 28: DPI project participant Heidi Wiggenhauser establishes a specialty melon crop in collaboration with a grower in Ayr, QLD. Samples of these crops were sent to Asian markets and niche domestic markets to gather feedback on fruit quality and consumer acceptance.



Figure 29: DPI project participants assisted outdoor production growers who decided to test PC systems for growing vegetables and fruit in the wet tropics. A grower collaborating on the project has successfully cultivated eggplants in a large, passively ventilated greenhouse over the past four years, achieving excellent quality and yields despite the region's annual precipitation exceeding 3,500 mm. The grower received excellent feedback on fruit quality from samples sent to domestic and Asian markets. The project team has

been working closely with the collaborating grower, discussing suitable agronomy practices for these environments.



Figure 30: DPI project participants have been assisting regional growers in their PC adoption journey with agronomy advice and on-farm evaluations. Pirrone Brothers in Ayr first commenced evaluating PC systems growing cucumbers in soil under a passively ventilated greenhouse structure. The team setup a simple fertigation system to demonstrate vegetable production with soilless systems and compare yield outcomes with crops grown in soil. After the grower saw positive results in the on-farm demonstrations, he decided to expand using soilless systems. Increased yields and the possibility to rapidly establish sequential crops enabled the business to demonstrate year round production in the Burdekin Dry Tropics.



Figure 31: On-farm crop evaluations revealed the potential for capsicum production using PC in the dry tropics of north QLD. DPI project participants provided training on capsicum production on farms using soilless systems in Ayr, Gumlu, South Johnston, and Atherton, QLD. Some of the key topics of discussion with growers included fertigation, plant canopy management, and pest and disease management.



Figure 32: Training activities such as monitoring and recognising pest and diseases in PC systems were carried in conjunction with another DPI project, Area wide management of vegetable diseases: viruses and bacteria (VG16086) at the DPI Research Facility at Ayr, QLD.

DPIRD participants carried out on-farm evaluations on fruit trees and vegetables. Examples of these support activities included assisting a grower in testing the use of screenhouses on grapefruit, which create a beneficial environment for canopy growth and fruit set. On the commercial farm, it was evident that the protection of the screens benefited the trees compared to nearby trees outside the net (Figure 33). The strong unidirectional winds created a side of the tree canopy with fewer, smaller leaves and decreased fruit set. On-farm work on vegetables included monitoring environments by placing weather stations under different structures and showing growers the usefulness of having the data to manage crops and identify climate factors impacting production (Figure 34).



Figure 33: DPIRD followed the performance of a grapefruit orchard that had an area under a net house in Carnarvon, WA.



Figure 34: The WA project team, DPIRD, and CGA assisted PC investments by conducting commercial evaluations with cucumber production under shade structures and poly-tunnels. They also maintained visits to farms that use net and shadehouses, the most common structures used over crops in Carnarvon, WA.

4. Potential new crops for export markets

DPI project participants explored new potential crops that could benefit from PC systems in the tropics. Some of these crops included specialty melons, specialty capsicums, specialty pumpkins, ginger, turmeric, and dragon fruit. Focus was put on specialty melons, as earlier crop evaluations indicated that high-quality fruits, such as those desired in Asian markets, could be obtained in the tropics (Jovicich and Wittl, 2018). The project activities involved evaluating crops and production systems at the DPI Ayr Research Facility and on-farm. This was carried out in collaboration with growers in Ayr, Gumlu, and South Johnston and included other industry stakeholders, to better understand potential export value chains and increase awareness of opportunities to de-risk adoption journeys.

The production of melons (*Cucumis melo* L.), typically rockmelon and honeydew fruits, in the tropics of Australia is seasonal and practiced entirely outdoors. The horticulture industry has limited knowledge about using PC as a technology to mitigate the effects of climate variability in melon crops. Some new specialty melon types now available in Australia require favourable environmental conditions and specific growing practices to obtain fruits with good visual and eating quality (Figure 35).

The DPI team has been working with value chain participants, including representatives from seed companies, marketing consultants, fresh produce distributors, retail and food service, transport businesses, TIQ representatives in QLD and overseas, and packaging (Figure 36). Fruits obtained from trials and small commercial plots were tested for quality and subsequently sent to niche domestic markets, including distributors and retail stores. Fruit samples were also sent to overseas markets in Japan, Singapore, and Hong Kong. Produce with high visual and eating quality was obtained, and excellent feedback was received from testing panels and groups that assessed fruit samples.

This project contributed to other initiatives that are supporting the development of agronomy recommendations. Information about PC melons has been shared with industry stakeholders. Growers who have decided to test this crop under their structures (including in QLD, WA, and NT) have been assisted by DPI participants in crop evaluations (Figures 36 and 37). A video titled **Specialty Melons: A Protected Cropping Opportunity for the Tropics** was produced by the DPI project team and summarises the opportunities for growing specialty melons in the tropics. Please refer to section 10- Communication Materials, Video Production, in this report.



Figure 35: A variety of specialty melons can benefit from using PC systems in warm climates.



Figure 36: The collaboration across projects and value chain participants allowed to develop proof of concept systems for growing high quality specialty melons. The quality of fruits was prised when samples were assessed in Japan, Singapore and Hong Kong. The work included understanding of product specifications, finetuning agronomy practices, cultivar evaluations with seed companies, cold storage evaluations, marketing strategies, share of information with industry and hands-on transfer of knowledge to growers. This RD&E work is being continued beyond the end of this CRCNA project.

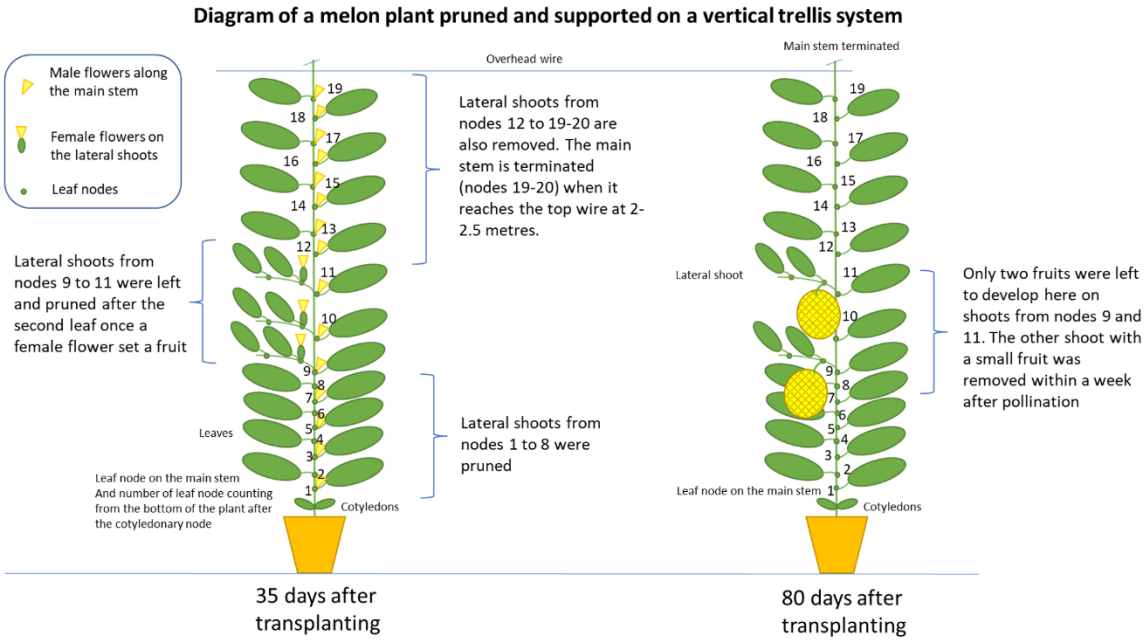




Figure 37: Growers interested in evaluating specialty melons using PC systems received training and information such as this diagram showing how to manage a melon plant canopy (top). Growers could also visit the demonstration site at Ayr to assess crop and cultivar performance and receive hands-on training (bottom). Fruit samples from this crop in 2022 were sent to market distributors in Brisbane and Sydney.

The following are selected key learnings and outcomes from the work with melon production under PC systems

- Engagement with value chain stakeholders, including growers, businesses in production and distribution, transport and cold chain services, marketing consultants, domestic and overseas buyers, market access and trade experts, and food service groups, has provided critical knowledge.
- Asian markets have diverse melon categories, each with specific quality descriptors and pricing.
- Knowledge from cultivar and agronomy trials is refining agronomy recommendations to meet defined fruit specifications.
- Crop management requirements are specific to fruit type and cultivar.
- Positive and valuable overseas feedback received on fruit quality from initial samples.
- Significant networks developed with domestic and overseas melon industry stakeholders.
- Promising primary cold storage evaluations (25-30 days) will aid in cultivar selection and feasibility studies.
- Estimated production costs in tested systems
- There are also opportunities for using PC to grow melons for niche domestic markets. The interest from distributors and retailers has been increasing in the recent years.
- A few growers tested small plots following advice and training from DPI project participants and additional growers are testing the production system at small scale.

5. Collaboration across value chains

During the project, participants in Queensland, Western Australia, and Northern Territory collaborated extensively with numerous value chain stakeholders. Key groups involved included companies and distributors of PC input supplies, builders of PC structures, regional council representatives, seed companies, fresh produce buyers, transport companies, marketing consultants, trade officers, investment consultants, PC capacity building providers, and horticulture industry peak bodies. These collaborations were crucial in validating and demonstrating the performance of PC systems, supporting growers, and promoting new crops and technologies.

6. Information sharing at industry events

To increase awareness about the opportunities for using PC systems in the tropics the project delivered numerous presentations to industry stakeholders. These presentations discussed PC potential technical solutions, challenges, production outputs from crop evaluations and proof-of-concept demonstrations, and technology adoption pathways. Presentations (both face-to-face and virtual) and discussions occurred at regional and national events. Farm visits by project participants in QLD, WA, and NT facilitated discussions with growers on-site about specific issues and potential solutions. Some of these key activities included:

Regional and national presentations in QLD, WA and NT

Presentations focused on PC technologies and practices in the tropics as well as opportunity crops, including examples of high value horticultural commodities for domestic and export markets

Regional events

- **Protected cropping in the tropics: addressing challenges to access current and new markets** (Elio Jovicich, DPI), and **Opportunities for protected cropping in Carnarvon** (Neil Lantzke, DPIRD). Growers' meeting at the DPIRD research station in Carnarvon (24 Oct 2019). The event was organised by DPIRD with an emphasis on pest and disease management in Carnarvon. Presenters included DPI plant pathologists and virologists Cherie Gambley and Denis Persley, and Professor Jane Polston, a plant virologist from the University of Florida, USA. The meeting was part of a larger area-wide pest and disease management project funded by Hort Innovation. Elio distributed 10X handheld magnifying lenses to growers attending the meeting and explained how to use them to detect small pests, such as broad mites. Growers practiced using these lenses for scouting pests in their crops.

- **Protected cropping in North QLD** (Elio Jovicich); **Pest management in PC systems** (Greg Owens) Protected Cropping Workshop organised by NT Farmers and NT DPI, Berrimah Farm (February 2020).

- **Opportunities for exporting melons from North QLD** (Elio Jovicich, DPI)**; Simulated cold storage transport to Asia** (Heidi Wiggenhauser, DPI)**; Overview of their shipping services and infrastructure for North QLD** (Ali Collier and Maria James, Port of Townsville). From Paddock to Port 2019 industry event at the Port of Townsville. Highlights included the advantages of using sea freight from Townsville, aligning with the growing interest in fresh produce exports from North QLD.

- **Protected cropping systems in the tropics: addressing challenges and advantages of climate, and supporting access to domestic and export markets** (Elio Jovicich). DPI Bowen Research Station (16 Sept 2019). Presented to Bowen industry representatives, Bowen Gumlu Growers Association (BGGA), and DPI Horticulture and Forestry Science Management Team.

- **Protected cropping in the tropics: are there any advantages?** (Elio Jovicich, DPI and Josh Pirrone, Pirrone Brothers). Discussed research highlights and introduced the CRCNA project to regional vegetable industry stakeholders and **Working in horticulture and pest and disease management with stakeholders who speak other language than English** (Greg Owens, NT Farmers) and **Sea freight opportunities from North Queensland** (Alison Collier and Maria James, Port of Townsville), at DPI Ayr Research Station (24 Sept 2019).

- **Protected cropping in the tropics: addressing challenges to access current and new markets.** (Elio Jovicich) Carnarvon (25 Oct 2019). Presentations and discussions took place during meetings with representatives of DPIRD, Gascoyne Development Commission (GDC), Carnarvon Growers Association (CGA), input suppliers, and growers.

- **Protected cropping systems in the Queensland tropics and subtropics – Addressing challenges and advantages of climate to support access to domestic and export markets**. (Elio Jovicich) Queensland Government Winter Harvest Trade – Virtual Agriculture Trade Mission QLD - Japan. Townsville and simultaneously virtually delivered online to QLD Trade and Investment offices in Japan. Townsville (3 Sept 2020).

National events

Protected Cropping Australia (PCA) conferences

- **PCA2019 Gold Coast, QLD (7-10 July 2019).** The conference brought together 500 national and international stakeholders from PC industry who networked through presentations, discussions, technology displays and farm tours.
    - **Protected cropping in the Australian tropics** (Elio Jovicich)
    - **A grower's real-life experiences and reasons of why I adopted PC** (Josh Pirrone)
    - **Display of and tasting specialty melons grown in north QLD** (Heidi Wittl)
    - **Stand-up to acknowledge the DPI's and project initiative's support and an explanation of his PC evaluations in the QLD Wet Tropics** (Tony Camuglia)
    - **A worldwide update on retractable roof technology for berries, vegetables and cannabis** (Bede Miller and Richard Vollebregt)
- **PCA2022 conference, Coffs Harbour (28-31 March 2022).** The conference brought 500 delegates. Project participants from QLD, NT and WA attended the event and delivered the following presentations:
    - **Expanding Protected Cropping in the Australian Tropics** (Elio Jovicich, Heidi Wittl and Matthew Tinai)
    - **Can protected cropping ensure an export and domestic niche market supply of high-quality melons from the tropics?** (Heidi Wittl, Elio Jovicich and Matthew Tinai)
    - **Setting the course for protected cropping** (Elio Jovicich, Vicki Lane and Gary Saliba)
    - **Effects of shade nets on microclimatic conditions, growth, fruit yield, and quality of eggplant** (Giao Nguyen and Neil Lantzke)
- **PCA2023 conference, Brisbane QLD (17-20 July 2023).** The conference brought the record number of 620 delegates, 100 booths, 90 speakers, and 3 farm tours. Elio Jovicich was a member in the conference organising committee.
    - **Transitioning from Soil to Soilless Media.** Session Grower Workshop (Tony Bundock, Zak Iqbal, Josh Pirrone, Cheyne Clarke).
    - **Specialty crops for the tropics** Session New Crops and Production Systems. (Heidi Wiggenhauser).
    - **RD&E supporting adoption in the tropics/subtropics.** Session New Crops and Production Systems. (Elio Jovicich)
    - **Strategies to improve the profitability of tree fruit production in temperate and tropical climates with protected cropping systems.** Session New Crops and Production Systems. (Bede Miller)
    - **Effects of planting dates on the growth and fruit yield of capsicum varieties in a retractable roof production system under semi-arid climatic conditions Session New Crops and Production Systems.** (Giao Nguyen)

TropAg Conferences, Brisbane, QLD

- **TropAg2019 (11-13 Nov 2019).** Elio Jovicich organised **Symposium 8.2 'Strengthening value chains in tropical Australia with protected cropping systems'** under Theme 5: AgFutures—A showcase of innovation and investment in Queensland agriculture. The aim of the symposium was to highlight the potential of PC in the tropics and the different value chain considerations in PC systems in warm climates. The event was also an opportunity to meet with Australian researchers and students involved in PC and to have discussions with CRCNA staff attending this conference.
    - **Benefits and challenges for expanding protected cropping in the Australian tropics.** (Elio Jovicich and Heidi Wittl)
    - **How can protected cropping ensure an export supply of high quality melons in the tropics?** (Heidi Wittl and Elio Jovicich)
    - **Our experiences testing protected cropping where nobody uses it.** (Josh Pirrone, Ross Pirrone and Chris Pirrone).
    - **Innovative cost-effective protected cropping structure designs for the tropics.** (Bede Miller)
    - **Ensuring you make a profit – 6 steps to engage customers that make it rewarding: A case study for high value export melons.** (Michael Evans, Fresh Partners)
    - **Innovative control systems for protected cropping in the tropics.** (Odin Franssen, Power Plants Australia)
- **TropAg2022 incorporating HarlanIV and AgFutures (31 Oct 2 Nov 2022).** Elio Jovicich was invited to deliver a presentation on **Opportunities for developing protected cropping in Australia – National RD&E Strategy overview**. In his presentation and during the conference discussions focused on the opportunities for expanding the use of PC in the tropics.

Australian Organic 2022 conference

- **Opportunities for complementing protected cropping technologies in organic production systems.** Elio Jovicich was invited as a panel member to discuss PC systems and how they can be used following organic production protocols. (21 July 2022) Australian Organic Conference 2022 Brisbane – Panel Session – Standards and Innovation

Other events and travel

Grower stand-ups at events and grower group meetings

Pirrone Brothers directors Josh and Ross Pirrone shared their experiences and journey of incorporating PC into their field cropping operations in the Burdekin, QLD, at regional and national industry events. Their presentations and 'stand-ups' provided valuable insights from a grower's perspective and were very well received by regional stakeholders.

Hort Connections 2019-2023.

Project participants attended Hort Connections in 2019, 2021, 2022, and 2023. Protected cropping research activities were highlighted at DPI's booth through screen photo and video displays and fresh produce samples. Each year, the event attracts approximately 4,000 delegates, including growers,

produce retail representatives, marketers, distributors, input suppliers, technical service providers, technology developers, grower associations, and R&D organizations. These displays prompted discussions on the challenges and opportunities for using PC in northern Australia. Cravo also had a booth where project participant Bede Miller discussed the advantages of retractable roof structures for managing crop environments in the tropics.

Project meetings and site and farm visits.

Numerous virtual meetings took place between project participants in DPI and DPIRD, along with meetings at national industry events, and three visits from the project leader to Carnarvon and one to Darwin. The DPIRD researcher visited Gatton in 2022. Additionally, the NT Farmers Industry developer visited Ayr on three occasions. These meetings and visits facilitated the assessment of production systems and crops, farm visits, and discussions on issues impacting PC adoption, PC structure designs, technology inputs, and crop management. Selected travel and industry visits were:

- Giao Nguyen participated in a 4.5-d Protected Cropping Masterclass in Gatton organised by DPI in 2022. The CRCNA paid for the registration for Dr Nguyen.
- Elio Jovicich visited horticulture producers in Carnarvon WA, meeting with DPIRD and CGA representatives, stakeholder interviews and delivered a presentation in a regional industry event. 20-25 Oct 2019.
- Elio Jovicich, Giao Nguyen and Neil Lantzke visited horticulture producers in Carnarvon and Geraldton, WA. Elio, Giao and regional grower discussed capsicum evaluations under the retractable roof structure at Carnarvon. 23-27 August 2022.
- Elio Jovicich and Greg Owens participated in the day-long PC Workshop organised by NT Farmers and NT DPI at the Berrimah Farm and visited regional growers using PC systems. February 2020.
- Greg Owens visited the PC site at the DPI Research Facility. 2022.

7. Information sharing in educational programs

The project team shared information with students, teachers, and faculty at universities and high schools (Figure 38).

Since 2019, Dr. Elio Jovicich has been invited to deliver an hour-long lecture discussing PC production in the Tropics and Subtropics during the Guest-Lecture Week in their new PC study programs: ‘Advanced Greenhouse Technology’ and ‘Plant-climate interaction in controlled environment’. Dates and student number: 11 Dec 2020 (11 students); Sept 2021 (50 students); Sept 2022 (70 students); Sept 2023 (120 students) and Sept 2024 (100 students). Dr. Jovicich was also asked to review and provide feedback on this new study program at WSU.

University of Queensland (UQ) agronomy students visited the DPI RD&E and demonstration site at Ayr as part of a study tour organized by UQ. Project leader Elio Jovicich discussed RD&E on (PC crops in the tropics, showcasing tomato, capsicum, and eggplant crop plots growing under the retractable roof structure. This visit provided students with insights into innovative technologies addressing climate variability issues in horticultural systems. Discussions also covered career opportunities, the nature of RD&E work, and how research projects support the regional and national industry. Elio shared his career pathway experiences with students completing their degrees in agriculture.

Home Hill State students visited the DPI RD&E and demonstration site at Ayr in 2021 and 2022. Project team member Heidi Wiggenhauser guided the students through the entire process of managing a vegetable crop, highlighting the skills required for horticulturists managing PC systems. A lecture on horticultural career opportunities was also delivered at the school. The school applied for public and private funding to establish a PC educational site, which included a small retractable roof structure completed in 2024. The school plans to offer horticulture certificates, with the project team providing advice on infrastructure designs, industry contacts, and agronomy advice.

Presentations about the use of PC in the tropics were also delivered to students at Pimlico State High School during Science Week sessions.



Figure 38: A group of 11 agronomy students and two faculty members from the University of Queensland visited the DPI RD&E and demonstration site at Ayr (left). Project team members also shared knowledge with students and staff at Home Hill State School (centre). This school invested in a small retractable roof structure, similar to the one at DPI's Ayr research facility (right).

8. Situation analysis of vegetable export supply chains in north Queensland

A situation analysis of vegetable export supply chains in North Queensland was prepared by the Port of Townsville. To determine current processes, expert knowledge and discussions with value chain participants were used to gather information on existing supply chains. These processes were then evaluated against best practice guidelines. Key strengths and weaknesses in current export supply chains were identified, and the ability of supply chains to accommodate the transport of fresh produce grown with PC systems was assessed. The report for this analysis can be found in Appendix 2.

The opportunities to ship high-value produce grown using protected cropping systems in refrigerated containers from north Queensland must consider the perishable nature of the fresh product (e.g., shelf life and quality deterioration), shipping timelines for pick-up and arrival at the destination, and risks associated with potential schedule changes.

9. Communication materials

Publications and abstracts produced by the project

Jovicich, E. and Wittl, H. (2020). Benefits and Challenges for Expanding Protected Cropping in the Australian Tropics. Proceedings 2020, 36, 107. https://www.mdpi.com/2504-3900/36/1/107

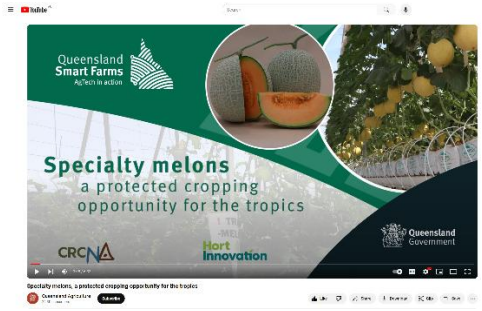
Wittl, H. and Jovicich, E. (2019). How Can Protected Cropping Ensure an Export Supply of High Quality Melons in the Tropics? Proceedings 2019, 36, 110. https://doi.org/10.3390/proceedings2019036110

Jovicich, E., Lane, V., Wiggenhauser, H., Perkins, M., and Saliba, G. (2022). Opportunities for developing protected cropping in Australia – National RD&E Strategy overview. Proceedings 2022 206. TropAg Conference incorporating HarlanIV and AgFutures 31 Oct-2 Nov 2022. Brisbane QLD. https://era.daf.qld.gov.au/id/eprint/9180/ https://tropagconference.org/wp-content/uploads/2022/02/TropAg-2022-program-241022.pdf

Nguyen, G.N., and Lantzke, N. (2022), Mitigating the adverse effects of semi-arid climate on capsicum cultivation by using the retractable roof production system. Plants, 11 (20), 2794. https://library.dpird.wa.gov.au/hc_researchart/2

Video production

Specialty melons, a protected cropping opportunity for the tropics (6.3 min video). DPI has been developing intensive melon production systems and produced a video that provides an overview of the benefits and opportunities for using PC in warm climates. The growing methods can produce high-quality specialty melons for niche domestic and export markets, where these fruits attract high prices. The warm environments in the Australian tropics are ideal for growing melons with high eating and visual quality. In these regions, PC structures allow year-round production as they mitigate climate variability and the constraints of outdoor farming. Most importantly, the specific agronomy practices ensure high yields of fruits with consistent high quality. The video includes a start-to-end journey in a crop with highlights of the intensive crop management required to achieve the desirable fruit quality outcomes. It also stresses the importance of a marketing plan to differentiate the fresh product and make it attractive to consumers.

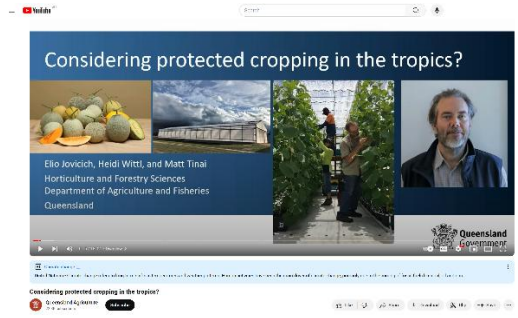


The video is available on the YouTube Queensland Agriculture channel and can be accessed here: **Specialty melons, a protected cropping opportunity for the tropics.**

The video was released on May 29, 2024, and shared with industry stakeholders. It was first displayed at DPI's booth at Hort Connections 2024 (Melbourne, June 3-5, 2024); Lockyer Valley Growers Association EXPO (Gatton, June 14-15, 2024); PC Masterclass (Gatton, October 21-25, 2024); and PC Fertigation Workshop (Gatton, November 19, 2024). The video was promoted by CRCNA social media platforms, Melons Australia in their Melon E-News and social media platforms, and by Protected Cropping Australia in their Growing Undercover E-News, Soilless Australia Magazine, and social media platforms. By the end of 2024, the video had 890 views. At least four known agricultural businesses across Australia decided to carry out evaluations of specialty melons under their structures to assess production and economic feasibility.

Webinar

Protected cropping in the tropics? (18 min video) Delivered by Dr. Elio Jovicich (DPI) as part of the webinar 'Protected cropping—viruses, bacteria, and tropical production' held on December 1, 2021. The video is available on the YouTube Queensland Agriculture channel and can be accessed here: Considering protected cropping in the tropics?



Production opportunity and Crop case studies

The DPI team prepared the following case studies to highlight opportunities for PC and selected crops. These case studies can be found in Appendix 4:

- Increased support to expand protected cropping in the Australian Tropics
- Protected cropping to ensure supply of high quality coloured capsicums from Queensland
- Protected cropping to support export supply of high quality melons from Queensland

These documents have been shared at industry events and adapted for articles in industry magazines.

Grower case studies

The following case studies were developed with information shared by vegetable producers who have adopted PC systems in the Australian tropics. These growers shared their experiences with project participants, and their stories may support those considering investments in PC systems in the tropics. The information was compiled by Elio Jovicich (DPI), Greg Owens (NT Farmers), and Giao Nguyen (DPIRD). These case studies can be found in Appendix 3:

- Pirrone Brothers – Ayr, Queensland
- Protected cropping – some key challenges for the beginner in NT
- Protected cropping for vegetables in Carnarvon: A conversation with grower Thang Vo

Articles by external groups that relate to project activities

The following are selected media releases linked to activities carried out in the project.

- **A greenhouse is just one piece of the puzzle**. 19 Aug 2019. Weblink: https://www.hortidaily.com/article/9134723/a-greenhouse-is-just-one-piece-of-the-puzzle/
- **One in a melon chance to grow Queensland exports from Townsville**. Queensland Government. 9 Oct 2019. https://statements.qld.gov.au/statements/88589
- **Setting the course for protected cropping. Hort Innovation Australia**. 25 Nov 2021. Weblink: https://www.horticulture.com.au/hort-innovation/news-events/Setting-the-course-for-protected-cropping/
- **Setting the course for protected cropping. CRC Future food Systems.** 25 March 2022. Weblink: https://www.futurefoodsystems.com.au/setting-the-course-for-protected-cropping-2/
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Project participants recognised by industry

During the life of the project, several participants were recognised by the Australian horticulture industry for their contributions to knowledge development, information sharing, and market supply performance. Some participants were also invited to become service members of PCA, where they have been supporting the horticulture industry using PC systems.

Awards and links to related media articles

- **Elio Jovicich, Program Leader PC, DPI:** Awarded 2022 Protected Cropping Industry Development, Protected Cropping Australia, Coffs Harbour, 30 Mar 2022.
- **Josh Pirrone, Director Pirrone Brothers**: Awarded 2023 Grower of the Year, Protected Cropping Australia, Brisbane, 18 July 2023.
- **Pirrone Brothers:**
    - Awarded 2023 Syngenta Grower of the Year. Hort Connections, Melbourne, 5 June 2023. Weblink: https://ausveg.com.au/media-releases/horticulture-industrys-best-and-brightest-recognised-at-hort-connections-horticulture-awards-for-excellence/
    - Awarded 2023 Coles Fresh Produce Supplier of the Year, Coles Media Release, 28 July 2023. Weblink: https://www.colesgroup.com.au/media-releases/?page=coles-celebrates-suppliers-championing-quality-value-and-community
- **Ross Pirrone, Director Pirrone Brothers:** Finalist for the 2022 Corteva Agriscience Young Grower of the Year, Hort Connections, Brisbane, 31 May 2022. Weblink: https://ausveg.com.au/media-releases/best-and-brightest-in-australian-horticulture-to-be-celebrated-at-hort-connections-2022/
- **Greg Owens, Project Officer NT Farmers Association:** Industry Service Recognition, 25 Nov 2021. Weblink: https://ausveg.com.au/articles/recognising-greg-owens-a-farmers-friend/

Contributions to industry using PC systems

- **Elio Jovicich, Program Leader PC, DPI:** Board Director member and member of the Organising Conference Committee and Education and Training Committee since 2022.
- **Josh Pirrone, Director of Pirrone Brothers:** Member of the Industry Advisory Committee PCA since 2023.
- **Giao Nguyen, Research Scientist DPIRD:** Member of the Education and Training Committee PCA since 2023.

Project contributions to other RD&E initiatives and investments

This project followed RD&E initiatives to support the adoption of PC systems by the Department of Primary Industries. Recognised industry contributions through the CRCNA project complemented existing initiatives and facilitated the development of new projects. During the project, three key initiatives led or co-led by the Department of Primary Industries supported the adoption of PC in northern Queensland and across Australia

- **The Australian Protected Cropping RD&E Strategy 2030 (AS19005)**, was funded by the Hort Frontiers Advanced Production Systems Fund. This fund is part of the Hort Frontiers strategic partnership initiative developed by Horticulture Innovation Australia (Hort Innovation), with co-investment from the Department of Primary Industries, and contributions from the Australian Government and the Food Innovation Australia Limited (FIAL).
  The development of the Australian Protected Cropping Strategy 2021-2030, from mid-2020 to mid-2021, involved extensive consultation with agricultural industry groups. These included state and territory agricultural departments, industry associations, universities, educational centres, growers, producer and marketer groups, consultants, and input and service suppliers. The knowledge gained during the strategy development confirmed findings in this project, particularly regarding stakeholder insights on perceived challenges and opportunities for expanding the use of PC in warm climatic regions. Much of the work was completed through virtual meetings and interviews during COVID19 travel restrictions.

- **A collaborative value chain evaluation to demonstrate the feasibility of exporting high quality melons from North Queensland**, was funded by Queensland Government through the Growing Queensland's Foods for Export pilot program. This project was led by VF+ and included participation from the Department of Primary Industries, Fresh Partners, Port of Townsville, regional producers and Trade and Investment Queensland.

- **Driving Ag-Tech Adoption across Australia (AS20007)**, funded by the Hort Frontiers Advanced Production Systems Fund as part of the Hort Frontiers strategic partnership initiative developed by Horticulture Innovation Australia (Hort Innovation), with co-investment from Department of Primary Industries, includes a PC component with RD&E activities aimed at driving the adoption of technologies and practices. Some of these research activities extend from work initiated in this CRCNA project.

Outcomes in this project

This project has contributed to industry and participants different ways:

***Within the life of this project and in the next few years*:**

For growers and cropping industry value chain actors engaged in the project:

- Increased awareness, understanding, and knowledge about potential opportunities (e.g., innovative technologies and agronomic practices, export market potential) and challenges for adopting PC.
- Increased interest (motivation) and enhanced skills to adapt PC practices and improve value chain efficiencies.
- Beginning to engage with each other to identify ways to facilitate the adoption of PC in key regions of the Australian Tropics.
- Contributed to articulating a vision of the industry benefiting from using PC systems in the Australian Tropics and a roadmap for adoption in key regions.
- Better recognition of the value of RD&E in enhancing understanding of the whole value chain for PC in the Australian Tropics.

For RD&E organisations and other industry participants:

- Increased knowledge of PC opportunities and challenges in the Australian Tropics.
- Improved understanding of the role they can play in supporting PC adoption.

***Longer-term outcomes for the Australian Tropics and Australia (over 6-10 years)*:**

- Strengthened networking among industry stakeholders with regional presence.
- Sound business investments (financially and environmentally) supported by early awareness and knowledge provided to early adopters.
- Better-supported export opportunities with the availability and knowledge of cost-effective technologies that assure supply commitments.
- Increased adoption of new and transformational production systems contributing to the long-term sustainability of the horticulture industry.

***Longer-term outcomes specific to stakeholders*:**

- Removed barriers and improved supply and value chains for new and existing northern agricultural industries.
- Improved supply chain efficiencies.
- Increased investment.
- Increased gross domestic product (GDP).
- Generation of new jobs and skills to assist population growth.

These outcomes will contribute to impacts, including changes in the economy, investment, employment, markets, skilled population, and the wellbeing status of beneficiaries.

Recommendations to support PC adoption in the Australian tropics

This project highlighted opportunities for growers in the Australian tropics to benefit from PC technologies that mitigate risks associated with climate variability and assist in accessing domestic and export markets. It also underscored the risks growers face when investing in new technologies to intensify horticultural systems.

The horticulture industry in the tropics is diverse in crops, constraints, and scale. Many complementary activities will assist stakeholders in de-risking investments and supporting the sustainability of their businesses when adopting PC systems. The strategies to address key outcomes align with those proposed to address three main outcomes—Value Chains, People, and Technologies—in the Australian Protected Cropping Strategy 2021-2030 (Hort Innovation Australia, 2021). The strategies listed below are considered critical to benefit PC adoption in northern Australia:

Value Chains —*Outcome: Develop profitable, diversified value chains*

- Identify profitable value chain opportunities for PC products.
- Identify opportunities to grow exports through PC.
- Showcase potential for product development and diversification through PC.
- Optimize postharvest quality of PC products.

People —*Outcome: Increased knowledge, capacity, and practice change*

- Understand and address barriers to PC adoption.
- Build industry capacity and capability to adopt PC systems across a range of crops, regions, climates, business models, and markets.
- Identify approaches to building a skilled PC workforce.

Technologies —*Outcome: Fit-for-purpose, cost-effective PC technologies and systems*

- Identify and adapt cost-effective technologies suitable for use in tropical regions.
- Apply a whole-of-enterprise approach when developing PC systems and agronomy to suit specific circumstances and needs (e.g., market, crop, climate, regions, business model, and constraints).
- Address current issues and limitations in PC systems, such as labour efficiencies, energy efficiency, and natural resource use.
- Advance technologies and protocols for the environmental sustainability of PC systems.
- Understand the economics of PC systems.

PC systems have often been suggested as a means for members of remote communities across the Australian tropics to grow fresh produce. If food production for consumption or sale is of interest in these locations, it is critical that PC systems are considered carefully and discussed with users. These systems should be simple, low-risk, and low-cost, making them adoptable and capable of producing healthy fresh vegetables and fruits that consumers desire and can afford.

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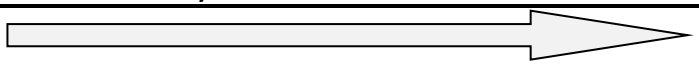
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Appendices

Appendix 1. Summary of characteristics of four selected protective structure designs used for horticultural production in the tropics.

This table present a summary of purposes and characteristics of structures used in warm climates. The table content has been modified from a table in project report VG16024 (Hort Innovation Australia, 2018). Reference prices are not included as economies of scale will apply on material costs.

		Net and Shade houses	Polytunnels	Greenhouses	Retractable roof
Improved crop environment					
Typical use in warm environments		Desert areas, long dry seasons and orchards in the wet tropics. Production is more challenging during hot and wet summers. Pest exclusion	Dry seasons with variable rainfall and wet tropics May have limited use where strong winds are frequent, and dust darkens films. Production is challenging during hot summers particularly in low structures.	Dry season with variable rain. Wet tropics when equipped with large roof vents. 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. Rain protection may not be an issue in orchards	Yes, but ground drainage is required when rain gutters are absent. Lateral curtains commonly 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 screens with mechanised and automated operation.
	Wind	Good protection but provided by screens only. May require a wind break.	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. Side curtains can be closed.
	Heat *(cooling advantage)*	All screens clad the frame. Passive ventilation.	Improved when tunnels are high. Shading increases humidity. Automation of	Passively ventilated through roof vent and sidewalls. Curtains on side walls and roof vent can be automated	Passively ventilated with roof opening at many different retraction levels. Roof retraction and sidewalls are

		Net and Shade houses	Polytunnels	Greenhouses	Retractable roof
		Provides shading but dense screen pattern reduces ventilation and increases humidity (may be good or bad) and reduces light over crop.	cladding movement not available.	on climate parameters. Movable shades can moderately assist with cooling. Fogging may be added to cool canopies.	automated by climate parameters. Humidity can be managed with roof retraction and retractable shading screen. Fogging may be added to cool canopies.
	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 excluding pests (e.g. insects and birds)	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 1170:2:2002)*	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 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.	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 cladding is retracted. Retraction of cladding is automated supporting management during possible strong wind conditions. Fixed screens may need to be removed manually.

	Net and Shade houses	Polytunnels	Greenhouses	Retractable roof
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. Plant gutters can hang from frame in some designs. With some trellis systems, poles may be required to support some crops.	The stronger frames are designed to support crops. Plant gutters can hang from frame in some designs. With some trellis systems, poles may be required to support some crops such as capsicums.
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)	+20 years (maintenance required, especially on movable components). Expected replacement of roof cladding is every 3-4 years (polyethylene film) or 5-8 years (polyweave film)	+20 years (maintenance required, especially on movable components). Expected replacement of roof cladding should be every 5-8 years (polyweave film)
Availability in Australia	Yes	Yes	Yes	Yes

Appendix 2. Situation analysis of vegetable export supply chains in north Queensland

Prepared by Alison Collier, ex-Trade Development Officer, Port of Townsville Limited (POTL)

This report seeks to undertake a situation analysis of vegetable export supply chains in north Queensland. To determine current processes, existing expert knowledge and discussions with value chain participants were used to collate information on current supply chains. Current supply chain processes were then evaluated against best practice guidelines. Key strengths and weaknesses in current export supply chains were identified and the ability for supply chains to accommodate the transport of fresh produce grown with protected cropping systems was assessed.

Best Practice Supply Chains

Best practice export supply chains address load conditions, transport conditions and regulatory conditions to ensure produce quality is preserved during transport. Load conditions relate to adequate packing and packaging as well as post-harvest management. Transport conditions relate to the tasks and safeguards undertaken to ensure cold chain integrity during land and sea transport, at distribution centres and point of export. Regulatory conditions relate to phytosanitary measures which meet export regulations and importing country requirements.

Load Conditions

Preservation of produce quality during transport is impacted by packing, packaging and post-harvest management. Appropriate load conditions extend produce shelf-life by avoiding damage, reducing water loss and limiting metabolic activity. Best practice load conditions include pre-cooling, appropriate packaging to withstand export handling, packing to maximise the effects of cold air flow, and careful consideration of temperature and atmosphere compatibility of mixed produce loads.

Advanced post-harvest management techniques and technologies, such as controlled atmosphere storage, may be used to maintain high quality produce at optimal freshness for extended periods. Controlled atmosphere environments actively control the storage atmosphere to limit metabolic activity by reducing O_2 and/or increasing CO_2. Controlled atmosphere storage and controlled atmosphere shipping containers may be utilised to extend storage periods, improve supply chain flexibility, and allow for more cost-effective sea transportation.

Transport Conditions

Best practice transport conditions include transporting produce in vehicles with effective insulation and cooling systems, loading produce in a temperature-controlled environment (i.e., cold tunnel loading facilities), monitoring and record keeping during transit, and minimising transport time to ensure total time in transit does not exceed produce shelf-life.

Best practice supply chains may utilise a range of transport modes including land-side truck and/or train transport, air freight, sea freight or a combination of both air and sea freight. Choice of transport mode will depend on several factors including, produce shelf-life, distance to market, distribution channel, consumer preference, post-harvest management and price of freight.

Regulatory conditions

Export of horticultural produce is governed by a range of Australian and importing country regulatory requirements. Best practice supply chains incorporate phytosanitary treatment and inspection measures which comply with these regulations. This includes ensuring; appropriate treatments and pest control measures are undertaken; facilities that handle fresh fruit and vegetable exports are registered with the Department of Agriculture and Water Resources; and produce is inspected and certified by trained and authorised individuals.

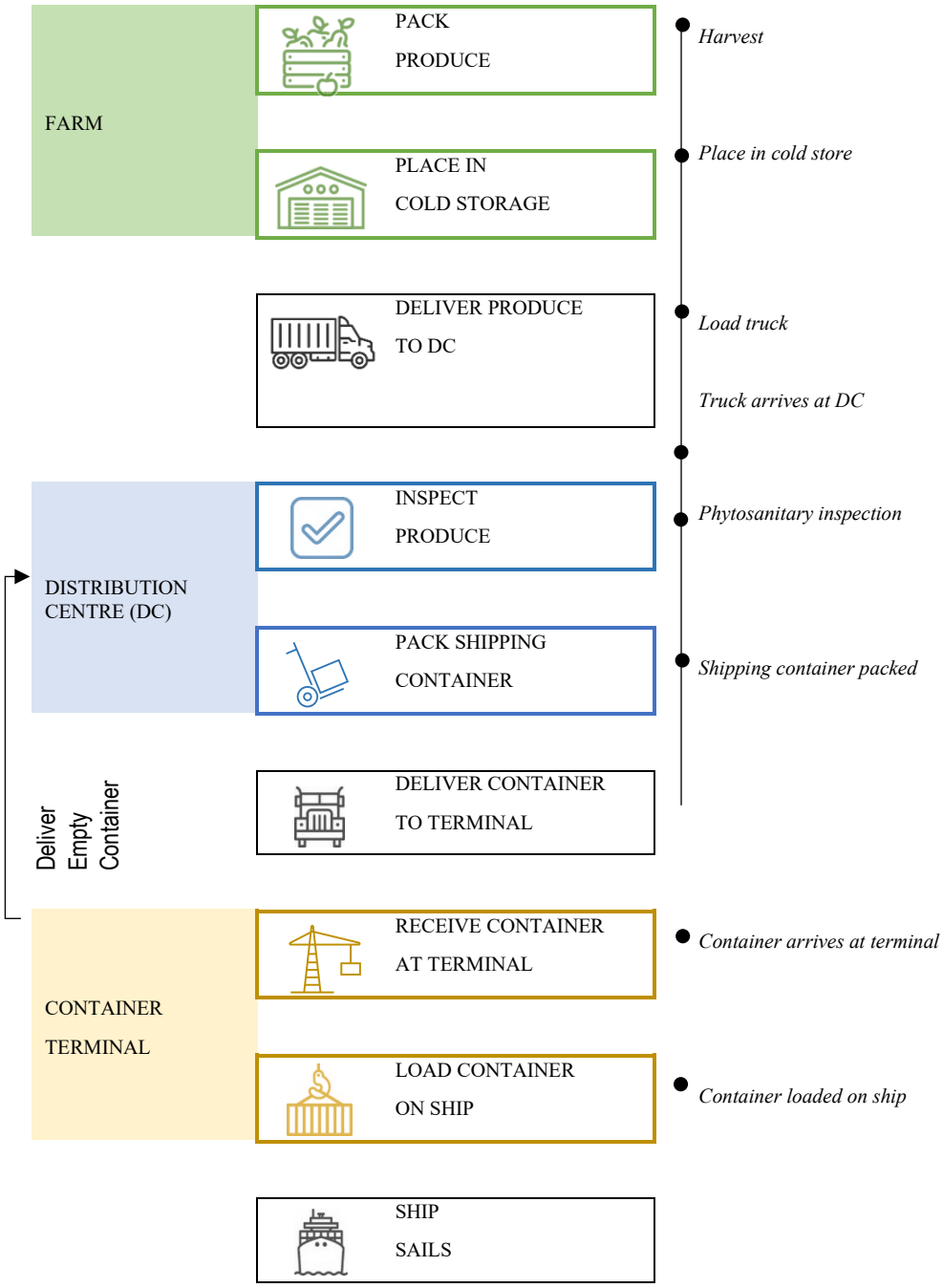
Phytosanitary treatments can include a range of processes depending on the type of produce and importing country requirements. Treatments include onshore and/or in-transit cold treatment, irradiation treatment, methyl bromide fumigation, and vapour heat treatment. Treatment requirements and the location and availability of specific treatments will impact on choice of distribution channel, mode of transport and point of export.

Export Supply Chains in North Queensland

Currently, there is almost no export of horticultural produce from north Queensland air or seaports. Except for small volumes of horticultural produce exported from Port of Townsville and Cairns airport in recent years, nearly all export of perishable goods from north Queensland is by a combination of predominantly air and some sea freight from Brisbane, Sydney, Melbourne port/airport.

A typical export supply chain for north Queensland grown produce exported by sea freight from Port of Brisbane is depicted in Figure A2-1.

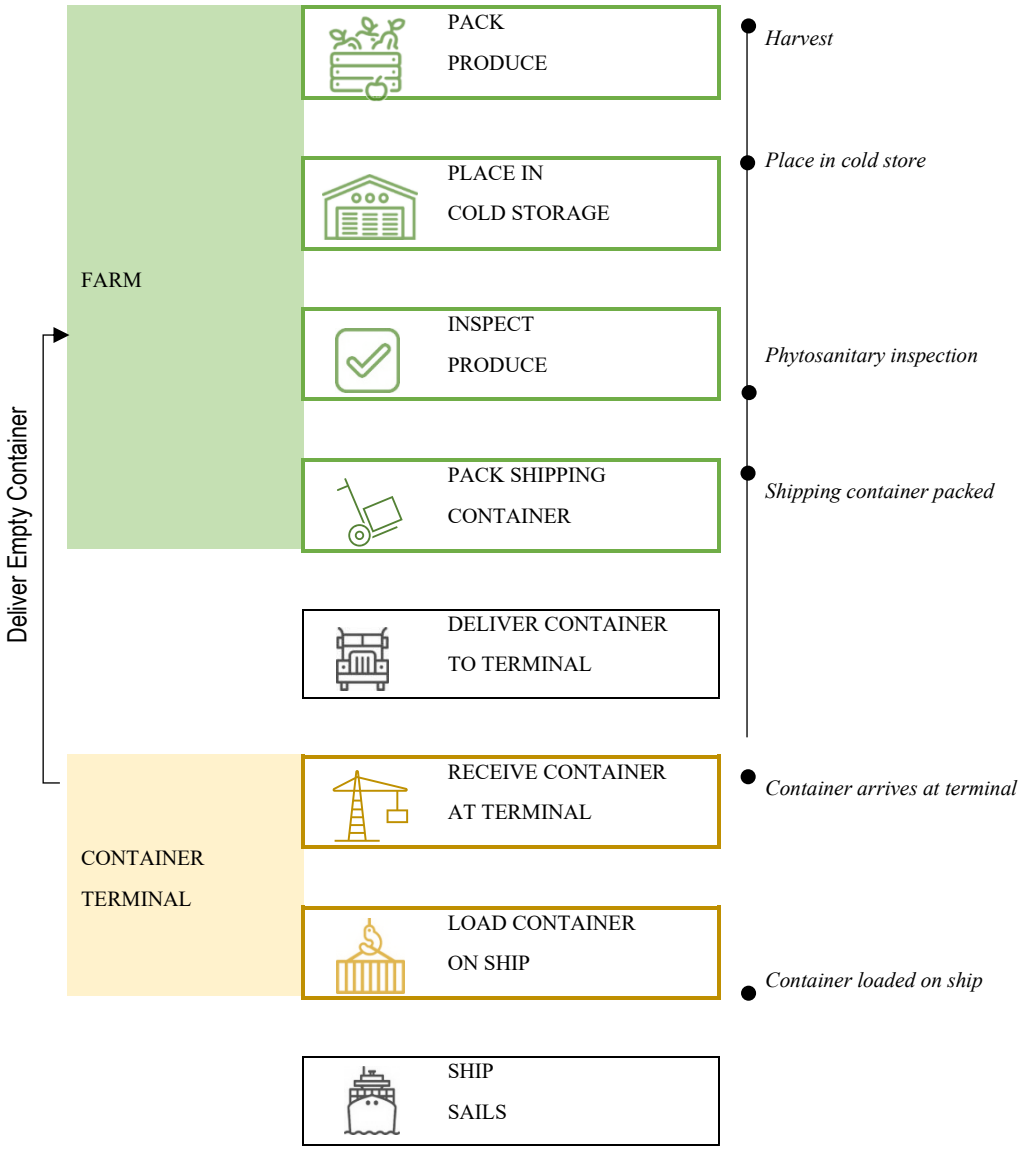
Figure A2-1: Export by sea freight from Port of Brisbane.



In Figure A2-1, produce is packed on farm and placed in cold storage. Produce is then transported by road to a third-party cold storage/distribution centre, usually close to the point of export, in Brisbane. Produce is inspected and loaded into a shipping container at the distribution centre and the shipping container is then transported to a container terminal at Brisbane port. The container will remain on power in the container terminal until the ship is ready for loading.

Export supply chains in north Queensland may also utilise on-farm facilities to pack and load produce in shipping containers on farm. Figure A2-2 depicts a supply chain where produce is packed on farm and exported by sea freight from Port of Townsville.

Figure A2-2: Export by sea freight from Port of Townsville.



In Figure A2-2, produce is packed on farm and placed in cold storage. An empty shipping container is delivered to the farm ready to be loaded for export. Produce is inspected on farm before being loaded into the shipping container for export. The container is delivered to the container terminal at Townsville Port where it will remain on power in the container terminal until the ship is ready for loading.

The supply chain depicted in Figure A2-2 is most typical when individual producers manage their own export operations. For producers in north Queensland, packing produce for export on farm usually requires the use of air and seaports in north Queensland for export. This is because packing shipping containers on farm is most efficient/cost-effective when packing occurs relatively near to the point of export.

Export Supply Chains in North Queensland versus Best Practice

Current export supply chains in north Queensland were mapped against best practice to identify possible gaps in current processes. Table A2-1 provides a summary of factors which may impact on the cost, efficiency and reliability of export supply chains in north Queensland. Factors identified may be broadly applicable and/or unique to individual producers.

Table A2-1: Current Export Supply Chains vs. Best Practice.

	Best Practice	Current Practice
Load Conditions	• Appropriate packaging is used to withstand export handling. • Pallets are within refrigerated container dimensions with no cargo overhang and pallets are International Standards for Phytosanitary Measures (ISPM) 15 compliant. • Appropriate post-harvest management is undertaken. • Load is configured to maximise the effects of cold air flow; container weight capacity limit and 'load line' is not exceeded; and load is secured to prevent movement on land and at sea. • Container is loaded in a temperature-controlled environment (i.e., using cold tunnel loading facilities). • Temperature and atmosphere compatibility of mixed cargo loads is carefully considered.	• Pallets which are export compliant are difficult to source locally. Produce may be repacked on export complaint pallets at distribution centre. • No on-farm forced air-cooling capability. Instead, cargo is cooled in cold store to load temperature which takes 24 hours. • No on-farm weigh bridge, pallets weighed individually and added to container mass. • Container/truck loaded outdoors (no temperature-controlled container pack facility). • Loading dock height not compatible with shipping container loading. • Mixed produce with differing temperature/atmosphere requirements loaded for land transport to Brisbane DCs.
Transport Conditions	• Produce is transported in vehicles with effective insulation and cooling systems. • Vehicle is loaded in a temperature-controlled environment. • For inland transport of refrigerated containers greater than 2 hours a clip-on portable generating unit is used. • Cargo is monitored appropriately during transport and records are maintained. • Transport time is minimised ensuring total time in transit does not exceed produce shelf life.	• Shipping containers received on farm and returned to container terminal off power as generator not available. • No cargo monitoring during land transport. • Excessive land transportation time to southern points of export from north Queensland. • Infrequent air/sea-freight services in north Queensland impacts wait/storage time and total time in transit.
Regulatory Conditions	• Cargo is inspected and certified by an Authorised Officer in a registered establishment. • Appropriate phytosanitary treatment is undertaken according to importing country's requirements.	• Limited availability of treatment facilities in north Queensland.

Key challenges relating to load conditions include difficulties sourcing appropriate equipment (i.e., export-grade pallets); insufficient on-farm infrastructure (i.e., loading facilities); and improper handling techniques. Challenges relating to transport conditions included excessive land transportation; improper cold-chain management (i.e., temperature monitoring); and infrequent air/sea freight services. The limited availability of phytosanitary treatment facilities in north Queensland was also identified.

Remarks

Export market demand and PC industry development is critically dependent on high quality export supply chains, which safe-guard product quality during transport. Existing export supply chains in north Queensland may be insufficient to accommodate the transport of high-quality horticultural produce and possible supply chain gaps should be examined against best practice.

Expert knowledge and discussions with value chain participants indicate that both equipment, services and on-farm infrastructure are key inhibitors to best practice. Meanwhile excessive land transportation to southern points of export may compromise best practice load and transport conditions by increasing produce handling and time in transit.

Currently, export of horticultural produce from north Queensland is mostly from Brisbane/Sydney/Melbourne air and seaports. This is largely due to under-developed export capability in north Queensland, highly competitive road/rail backloading rates for landside transport to southern points of export, and poorly developed inter-regional distribution systems. In future, points of export in closer proximity to production regions in north Queensland could allow greater use of sea-freight as a cost-effective alternative by reducing land transportation time and offsetting long transit times by sea.

Appendix 3. Grower case studies.

Several funding initiatives and key projects have been supporting protected cropping in the tropics and subtropics. DPI, DPIRD, and NT Farmers have been leading projects resourced or co-resourced by government and funding organisations, including the Cooperative Research Centre for Developing Northern Australia (CRCNA).

Pirrone Brothers – Ayr, Queensland

Pirrone Brothers is a family business farming over 300 hectares near the town of Ayr in the Dry Tropics of North Queensland. After sixty years of sugar cane production, they have worked to diversify and strengthen their business by the inclusion of vegetable crops. Ross Shane, Josh and Chris, sons of Ross Wayne and Giovanna Pirrone, take great satisfaction from their work. After a steady business growth in recent years, they have decided to commit to life as vegetable growers.

Pirrone Brothers is passionate about understanding how to evolve their enterprise to the dynamics of horticultural value chains and share their learnings with others in the industry. Through training, networking and experimentation, Pirrone Brothers has developed proof-of-concept systems for field and greenhouse production scenarios to achieve profitable and sustainable year-round vegetable supply from the tropics. Their business planning is guided by constantly questioning how to attain continuity and growth in the future. While doing this, they consider changing factors like farm scale, markets, efficiencies and the challenges and opportunities to come. Now, after 10 years, they have transitioned entirely out of sugar cane and produce only vegetables.



Figure A3-1. Brothers Josh, Ross, and Chris Pirrone (left to right) at their farm which now has shifted entirely to vegetable production. (Image courtesy Pirrone Brothers)

Finding an adoption model that suits the business. The Pirrone Brothers have been following a swift step-by-step adoption approach to intensify and expand vegetable production. In 2016, they incorporated protected cropping into their business plans. It was the effects of climate variability and market prices that inspired them to develop a proof-of-concept for protected cropping to test, and then demonstrate, that year-round production is possible in the tropics. They gained knowledge trialling a range of crops (e.g., cucumbers, capsicums, tomatoes, eggplants, beans, chillies, and specialty melons), cultivars and agronomic practices. They started protected cropping systems growing in the soil and as they increased their growing skills, they adopted soilless production and

incorporated biological control practices for the management of pests. They have also identified fit-for-purpose technologies to mitigate the effects of extreme environmental conditions on crops.

Early benefits from testing protected cropping. Knowledge gained from the more intensive protected cropping production system was readily transferable to outdoor production, making them better growers overall. Being able to produce an assured supply of cucumbers through protected cropping has helped Pirrone Brothers to secure contracts with retailers, in turn attracting orders for a wider range of vegetable crops. Their success has supported investments in a large packing facility, mechanisation and automation practices, labour force accommodation, and expansion of their growing area. Their growth and innovation have helped raise the profile of North Queensland vegetable production and driven input suppliers to increase the frequency of their services to the region. Starting small and finding an adoption pathway. The Pirrone Brothers example is a case study of how young farmers are shaping the future of Australian horticulture. Back in 2013, when they first considered growing a small block of pumpkins, Ross, Josh, and Chris Pirrone were in their mid-twenties. The three brothers had completed trade qualifications in related disciplines of mechanics. Over the last decade they have never stopped developing their farming and business skills. With immense support from their Mum and Dad, the brothers have recognized and embody the significance of lifelong learning, networking, as well as collaborating in research, development, and extension (RD&E) projects and programs.

Ayr is a town near the coast located about 1,300 km north of Brisbane, in Queensland. The dry tropics region including Bowen, Gumlu and Ayr in the Burdekin region is a key horticultural district in QLD with about 13,000 hectares of land dedicated to vegetables. The district grows a variety of vegetable crops such as tomatoes, capsicum, eggplants, zucchini, beans, sweetcorn, pumpkins, melons, and watermelons, which are mainly supplied to southern Australian markets during their offseason (May to Dec). Fresh produce from this region had a total value of more than $600 million in the year 2021/22.

Ayr experiences a tropical savanna climate, with a short, hot wet season between December and March; and a long, warm dry season between April and November. Rainfall, wind, and high temperatures can cause an impact on the yield and quality of vegetable crops, leading to reduced economic profits for growers and affecting vegetable supply chains. Protected cropping systems that include fit-for-purpose structure designs can mitigate extremes in climate variability and assist with the production and supply of high value vegetables in this region.

Capacity building and involvement in industry events. Ross was awarded a Nuffield scholarship in 2016 that allowed him to visit protected cropping facilities in many different regions overseas to explore and consider the viability of protected cropping for the Pirrone's situation in the Dry Tropics. The brothers embraced the opportunity to build a greenhouse at their farm in 2016 and as soon as they finished it, they conducted crop evaluations and sent produce samples to markets. Josh was subsequently awarded a scholarship and completed a Diploma of Business in Horticulture with UTAS. Chris recently developed and implemented a new business model to secure labour force and provide workers with accommodation both on and off-farm. The brothers have become regular attendees at Hort Connections and Protected Cropping Australia (PCA) events. Josh is now a member of the PCA grower advisory committee. Furthermore the brothers have participated in study tours in Australia and internationally. They host and are valued collaborators for on-farm experimentation with researchers and enthusiastically provide advice and training through delivery of presentations by sharing their grower journey with peers.




Figure A3-2. Ross Pirrone inspects a long season tomato crop during the summer in Culiacan, Mexico, as part of a study tour organised in 2016 under project VG16024. In addition, Ross visited different crops and technologies used overseas in warm climatic regions through a Nuffield scholarship. (Image courtesy DPI). Josh and Chris Pirrone with cucumbers harvested in their proof-of-concept greenhouse.




Figure A3-3. Josh Pirrone delivers a presentation at PCA2019 sharing Pirrone Brothers experience of evaluating protected cropping systems in the tropics. (Image courtesy DPI)

Collaborating in research, development, and extension (RD&E). The Pirrone Brothers have been project participants and contributed to RD&E initiatives, including one CRC for Developing Northern Australia project (Strengthening Northern Australia's horticultural sector through assessing protected cropping), four Hort Innovation levy and Frontiers projects (VG16024, AS19005, VG16086, and AS20007), as well as two Australian Centre for Agriculture Research projects, all of which had co-investments from the Queensland Department of Agriculture and Fisheries. Their involvement in research projects has helped them increase their knowledge, expand their industry networks, and contribute to peers' adoption of improved practices. As an example of research contribution, Pirrone Brothers and researchers conducted greenhouse evaluations of specialty melons, a novel and increasingly explored growing practice in Australia. Fruit samples from trials at their farm received excellent feedback on visual and eating quality in Asian markets. These evaluations were activities in projects 'Developing production guidelines for growing high-value specialty melons for domestic and export markets' (an Agri-Science Queensland funding initiative) and 'A collaborative value chain evaluation to demonstrate the feasibility of exporting high quality melons from North Queensland' (a

Growing Queensland's Food for Export pilot program). Recently Pirrone Brothers conducted pilot exports of other outdoor-grown cucurbit crops to NZ and aim to expand production for this market.



Figure A3-4. Pirrone Brothers have been evaluating a variety of crops and production methods for warm environments through experimentation with researchers. (Image courtesy DPI)

Adapting to changes in the business environment. When COVID-19 reached Australia the Pirrone's struggled with labour access and retention as did most producers. They addressed this by setting up on-farm accommodation for Pacific workers and became pioneers of this solution in the tropics. They now have nearly 100 workers and are adding more accommodation sites. Their drive to improve has been supported by a commitment to learning, planning and experimentation which positions their business for subsequent larger investments in outdoor production as well as protected cropping. The Pirrone Brothers efforts have been recognised with several industry awards, including the Hort Connections Grower of the Year in 2023, Protected Cropping Australia Grower of the Year 2023, and Coles Fresh Produce Supplier of the Year in 2023.

Sharing experiences during the learning journey. The brothers have been highly active in sharing their learnings with the broader industry. Josh has delivered several presentations and stand-up talks at regional events and at national conferences, including Protected Cropping Australia conferences (PCA2016, PCA2019, PCA2022, and PCA 2023) and TropAg2019. The family has hosted farm visits with national and international stakeholders.

Pirrone Brothers is now among North Queensland's key vegetable suppliers to regional and southern markets. Their business is an outstanding example of relentless innovation and continuous growth to address the challenges that affect all producers of fresh vegetable. With their efforts, vision, sharing of knowledge and industry leadership, Pirrone Brothers set a standard for the current and next generation producers who will supply fresh food in Australia and overseas.

This case study was prepared by Elio Jovicich (DPI). Contact for additional information. Elio Jovicich, Program Leader – Protected Cropping Queensland Department of Agriculture and Fisheries, email: elio.jovicich@daf.qld.gov.au

Protected cropping – some key challenges for the beginner in NT

This case study reports on a grower's less-than-ideal first experience using protected cropping. The grower has experience growing snake bean, okra, and zucchini outdoors. The vegetable grower farms in Marrakai, a locality in the Northern Territory of Australia situated about 76 kilometres east of the territorial capital of Darwin.

Background. The grower decided to build two protected cropping structures to find if the protection from rain would minimise issues t such as soil compaction, nematodes, and weeds that were constraining productivity of field systems and to prevent crop damage caused by birds. The high prices of Lebanese cucumber in 2021 also prompted the decision to evaluate a more intensive cropping system.

Marrakai is town located 89 km southeast from Darwin, in Northern Territory. The region is one of the key horticultural districts in NT with farms growing a variety of tropical fruit trees and Asian vegetables, which are supplied to southern markets in Australia.

Marrakai is and within the hot humid summer climate zone, with a wet and a dry season. There are high maximum day air temperatures year-round ranging averages between 32.4°C (Jun) and 37.3°C (Oct). Minimum day air temperatures range from 14.4°C (July) to 24.2°C (Jan). The rainy season occurs in the period from December to March and the dry season occurs from May to September. Average annual precipitation is 1,412 mm. These conditions can cause an impact on the yield and quality of some vegetable crops and production seasons, limiting economic profits for growers and affecting vegetable supply chains. Protected cropping systems that include fit-for-purpose structure designs can mitigate extremes in climate variability and assist with the production and supply of high value vegetables in this region.

The grower selected a structure design and agronomy practices, apparently without reaching out for expert advice but knowing that there were growers using similar simple protected cropping technologies near to his farm. Neighbouring growers were experienced, successful and are open to showing their technology setups. These growers use taller screened structures which provide relatively good air exchange.

The grower in this case study is of Cambodian descent but growing up from early childhood in Australia has excellent English and good relationships with the major resellers and with support groups such as NT Farmers.

Selected structure design and issues with environmental conditions. The two structures that were constructed were very basic tunnels with sloped roofs and polyethylene film cladding. The structures did not have roof vents. The side walls of the structure were covered with a fine mesh to exclude insects . These screens, although used with a good purpose, would considerably limit air exchange. The quality of the frame was good, and the structure was of a relatively low cost. However, even during the dry season in NT, the design was not suitable for reducing high air temperature and humidity levels inside the structure. Consequently air temperature and relative humidity frequently reached levels that were far too high to produce good cucumber crops. Remedial crop management practices such as removing lower leaves to improve ventilation were not effective, leading to fungal disease outbreaks and poor-quality fruit. The first crop of cucumbers indicated that the structure design was unsuitable for the tropics.

Testing soil and soilless production. The same grower also wanted to test two plant growing systems, soil, and soilless production. In one structure, cucumbers were planted in the soil. The planting beds had no previous cover crop or organic matter incorporated into the soil. In the second structure, cucumbers were planted into 1-m long coco peat bags which were placed on raised gutters. Crops in both structures were irrigated via drip irrigation systems.

Crop performance and issues. Early in the evaluation, the cucumber crop in the soil production area was abandoned. The cucumber plants struggled to grow in compacted soil and under high temperatures. Considering it was the first attempt using this system plants in the soilless system grew to produce a satisfactory yield of cucumbers. The grower followed recommendations from a local input supplier when preparing and delivering nutrients with irrigation. The A and B tanks with concentrated nutrient solutions were correctly installed. The nutrient solutions delivered to the bags and the solution that drained from the bags were monitored regularly for suitable levels of electrical conductivity (EC), pH, and volume. However the high plant population density and narrow interrow spacing decreased air flow and were not suitable for warm environments. The closeness of the rows also contributed to plant damage during harvesting operations. It was difficult to deliver chemical sprays, and harvesting was inefficient because the trolley to carry boxes and the sprayer could not be used effectively in between rows.

As plants grew through warm and humid periods, there were problems with marginal leaf scorch and soft fruits. Air temperatures inside the structure reached above 37 ^{o}C on many days. There was low water uptake by the plants and calcium deficiencies were detected from nutrient testing in leaves. Calcium is up taken with water therefore corrective applications of nutrients provided little improvement. In addition, and despite having sidewalls with screens, caterpillars were present and damaged the crop.



Figure A3-5. Two similar structures setup by a grower in Marrakai, NT, where cucumber soilless and soil production were tested. Crops reported here were unproductive and results associated with a structure design selection and practices that were unsuitable for achieving acceptable production under simple protected cropping systems in the warm tropics.

A few lessons from this grower's experience. Probably the key learning would be seeking advice on the importance of structure height and ensuring effective ventilation. The insect screen selection is also important since larger pores in the screen provide better ventilation, but the exclusion of small insects is less effective. Soil production systems can deliver good crops and yields if the soil is tilled accordingly, organic amendments are applied regularly, and crop species are alternated in planting schedules. Weeds still need to be managed in soil systems, particularly if no organic or plastic mulch is used. Following simple design selections and practices would have made a big difference to the outcome of the grower's first use of protected cropping. There may be several ways to de-risk simple pitfalls when attempting to test protected cropping by farmers. The following points are key considerations:

- Seek advice from stakeholders who have been using protected cropping in warm environments. This includes reaching out to growers, researchers and input and service suppliers. Visit other farms in the region and if also possible, farms in other regions with warm environments. Be patient with the multiple discussions as you will find some different opinions.
- Tall structures that have roof vents will be more effective to evacuate the hot air since hot air rises.
- Screened sides must allow for adequate air flow, even shade cloth can be very restrictive in the NT. The structure will need simple ventilation like roll-up curtains. Openings in the structure and the crop rows can be aligned so that the prevailing SE breeze can move air through the crop. In large, covered areas, side ventilation has little cooling effect in the centre areas of the greenhouse. It may be better to have more units of smaller greenhouses.
- Rows must be far enough apart to provide for routine management and harvest with good trolley access. You may have to test a couple plant population densities to determine what works best to maximise productivity. Labour is the biggest cost; any option to mechanise practises is worth considering.
- If you are planning to cover large areas, consider structures with retractable roof systems. Besides the environmental control in warm climates, they can retract quickly in the event of strong winds (the frame and cladding may be saved in a cyclone).
- Take every opportunity to learn (e.g., taking training courses, attending industry events, having discussions with peers and experts). Failures in protected cropping are expensive.

Access to RD&E and demonstration sites operating in the region has been shown to be beneficial to growers. During the CRC for Developing Northern Australia project, sites have been built by DPI at Ayr, QLD and DPIRD at Carnarvon, WA. Setting up demonstration sites operated by people with expertise and in collaboration with growers and industry stakeholders will help reduce the risks of failure by providing training and demonstrating technologies and agronomy that is suitable for tropical climates. In NT, examples of groups who could assist with support services include NT Farmers, through the VegNET program, as well as through RD&E collaboration with experts and industry stakeholders. Farm visits and study tours to existing demonstration facilities would also assist new and existing growers interested in protected cropping.

This case study was prepared by Greg Owens (previously NT Farmers) and had inputs from Elio Jovicich (DPI). Contact for additional information. Greg Owens, email: gregowens46@gmail.com

Protected cropping for vegetables in Carnarvon: A conversation with grower Thang Vo

Giao Nguyen, DPIRD Horticulturist had a conversation with Mr. Thang Vo, an experienced farmer who has been living in Carnarvon, WA, for over 20 years. Thang has been using his 5-hectare net house for growing vegetables since 2010. In the first few years, Thang grew eggplants. He later switched to growing only capsicums as he found better economic returns. He kept growing capsicums under the net house, and he also planted tomatoes and chillies in open field.



Figure A3-6. Mr Thang Vo grows capsicums in his net house in Carnarvon, WA

Carnarvon is a coastal town located about 900 km north of Perth, in Western Australia. The region is one of the key horticultural districts in WA with about 170 farms covering 2,000 hectares of land along the Gascoyne River. The district grows a variety of vegetable crops such as tomatoes, capsicum, eggplants, zucchini, and pumpkins, which are mainly supplied to the Perth market. Annually, Carnarvon produces about 22,000 tons of vegetables with a total value of more than $69 million in the year 2022.

Carnarvon has a hot semi-arid climate, with mild winters, and spring-summer characterised by high temperatures, high solar radiation, and strong winds. Rainfall and relative humidity are low year-round. These adverse conditions can cause an impact on the yield and quality of vegetable crops, leading to reduced economic profits for growers and affecting vegetable supply chains. Protected cropping systems that include fit-for-purpose structure designs can mitigate extremes in climate variability and assist with the production and supply of high value vegetables in this region.

Thang commented: 'Carnarvon's climate is dry; it has low air humidity and very high solar radiation. So, if you want to grow a crop like capsicum, you must have a net house. If you plant them in the open field, you only have a short harvest window, of about 2 to 3 months per crop, and the fruit quality is low. When you grow capsicums under a net house, the plants grow much better and get taller; the yield is less variable, and the harvest period can last 6 to 8 months per crop.'

Thang would like to extend the harvesting season with protected cropping structures and grow fresh produce with good quality all year round. However, he shared two important challenges he faces to achieve this goal: better methods to manage pests and diseases and access to markets. 'High insect pest and disease pressure critically affect the vegetable production under the nets. When you rely only on frequent sprays of pesticides and fungicides, the production costs increased considerably. The repeated sprays also contribute to development of genetic resistance in the pests and diseases to the sprayed active ingredients. In the long term, you still have pests and diseases, but the chemicals are less effective. The excessive use of chemicals will also negatively affect the environment and the health of workers and consumers,' Thang said.

The second challenge mentioned by Thang is the market access. 'Now that the high-quality produce has been grown, they can be sold at unwanted prices or even cannot be sold sometimes. Because an excessive volume has been produced locally, making the Perth market saturated. Growers need a new and stable market where the sale of their products can be guaranteed,' he indicated.

Thang also mentioned the shortage and instability of the labour force. 'Due to the impact of COVID-19, worker availability for the vegetable industry in Carnarvon became small. Meanwhile the worker's hourly pay increased which has put pressure in the small farming business,' he said.

Thang stressed the importance of having research groups helping farmers. He considered important to identify fit-for-purpose protected cropping systems that are suitable for Carnarvon environmental conditions. Currently, the simple net houses used by growers in Carnarvon are still cost effective. However, net houses have limitations. They are unable to prevent rain, flood, and strong wind. The net houses can be completely damaged with cyclonic winds. Moreover, net houses are ineffective to exclude insect pests. 'If there is a protected cropping system that is financially affordable and able to resolve those issues in net houses, it will greatly help growers in Carnarvon,' Thang added. He said further: 'growers really need information on alternative crops, rather than relying on only one or two crops for the protected cultivation.' This is also a business strategy to diversify the outputs that growers can supply in response to an increasingly diverse and demanding consumer market.



Figure A3-7. Mr. Thang Vo's at his net house with capsicum crops and collaborative work with DPIRD researchers. (A) Monitoring sensors (left to right: light and temperature, wind, soil moisture); (B) A meeting with DPIRD staff (left to right) Neil Lantzke, Thang Vo, Saleh Adnan, and Giao Nguyen (taking the photo).

Thang emphasized: 'to reduce the pest pressure, the best solution is to follow an area wide management program in the region, involving all farmers.' Thang praised a recent policy of DPIRD, partially funding vegetable growers to build their new net houses. 'This initiative will clearly encourage more small growers to invest in protected cultivation, which can help them grow more high-quality vegetables, which in turn will increase their income and contribute to the economic development of Carnarvon.' Thang is currently actively participating and supporting DPIRD's scientists in the protected cropping research for fruiting vegetables in Carnarvon.

This case study was prepared by Giao Nguyen (DPIRD) with a few inputs from Elio Jovicich (DPI). Contact for additional information. Giao Nguyen, email: Giao.Nguyen@dpird.wa.gov.au

Appendix 4. Production system and Crop case studies.

These three documents were prepared in templates and are also attached to this report submission

Increased support to expand protected cropping in the Australian Tropics

Increased support to expand protected cropping in the Australian Tropics

Protected cropping (PC); an emerging production system in the Australian tropics

Historically, growers in tropical Australia have been slow to embrace PC technologies, mainly because temperatures and light levels are suitable for extensive open field fruit and vegetable production. More recently, PC technologies have become more prevalent in the tropics as they can mitigate risks associated with climate variability and assist in accessing domestic and export markets. Adoption of PC in northern regions of WA, NT and QLD has increased in the past 10 years, mainly with investments in what is considered low and medium technology systems (e.g., those that include structures such as high passively ventilated greenhouses, high poly tunnels and shade/screen houses). PC is being used widely in blueberries and, to a lesser extent, in high value vegetables and tropical fruit trees. Although the new areas under PC in the tropics are small compared to southern regions in Australia, they represent a proof-of-concept that has been generating interest from regional outdoor growers, produce distributors and other investors (Figure 1). There are many aspects of these farming systems that still need to be advanced for warm climatic regions.

The Queensland Department of Agriculture and Fisheries (DAF) PC team has been working with regional farmers in on-farm crop evaluations in north Queensland since 2009. To enable PC adoption, research activities have been considering economic and environmental aspects within the context of resource diversity and availability and target markets. Research by DAF and collaborators across northern Australia suggests that, for some high value fresh products, fit-for-purpose PC technologies are a cost-effective way for growers to mitigate the effects of extreme temperature, rainfall, changes in humidity, wind, solar radiation and pest and disease pressures which can negatively impact yield, quality, and consistency of supply.

Research and development of suitable PC systems for growers in northern Australia has been focusing on awareness, proof of concepts, structure designs, advice, and information sharing. Discussions with industry stakeholders, expert advice, on-farm demonstrations and trials, and industry study tours have been critical for the identification of cost-effective structure designs, suitable crops, and agronomy practices.



Figure 1. PC in the tropics has lower costs than in temperate regions because fuel for heating is not required. A good knowledge about cost effective technologies and agronomic practices is essential to grow good crops in warm environments. Mechanisation will be critical to reduce labour costs and improve efficiencies in larger covered areas.

Growing in a challenging environment

In the tropics and where many high-value crops benefit from rain protection, cladded PC structure designs need to be high and capable of evacuating heat efficiently. At times, structures

may need screens to shade crops and misting/fogging systems to cool canopies and/or increase relative humidity levels. Plants grow fast and evapotranspiration is high, which requires a well-managed fertigation system. Issues with pests and some diseases can limit production in warm environments if they are not managed with an integrated approach. The design of the PC structure is an especially important consideration due to the elevated risk of structural damage from cyclonic winds in these regions. The extent of damage can be mitigated if the structure's roof and sidewalls can be rapidly retracted ahead of weather events.

New infrastructure and resources to support industry growth

To further support PC adoption in the Australian tropics, DAF established a new PC research and demonstration site at the Ayr Research Facility (ARF) in north QLD in mid-2020. The selected structure is a fit-for-purpose retractable roof structure with a floor area of 900 m^2 (Figure 2). The Ayr facility is a showcase for novel technologies in the tropics, which can demonstrate improved ventilation, crop environment, and reduced risk of structural damage in the event of a cyclone. Regular stakeholder visits to the site are helping industry with critical decision-making support on PC systems in warm environments.

The current crop growing area has been setup for soilless production in different plant containers placed on-ground and on raised gutter systems. We have been using coconut coir fibre, perlite, and pine bark as root media. The fertigation system was designed to independently schedule water and nutrients to small crop plots. Media moisture and solar radiation sensors and an automated drainage collection system are used to schedule fertigation events. The retractable roof has clear cladding and has a retractable insect-exclusion screen underneath. The retraction of roof cladding and roll-up side curtains allow management of the crop environment through passive ventilation. Sensor-gathered data for rainfall, wind, temperature, relative humidity, solar radiation, and media temperature along with user-activation setpoints is used by the controller to operate the roof and curtains through electric motors. The structure's frame has insect exclusion screens fixed all-around. Inside, an overhead



Figure 2. A retractable roof structure was set up at the DAF Ayr Research Facility to showcase novel technologies for the tropics that can mitigate risks associated with climate variability and assist accessing domestic and export markets. Crop evaluations are carried out and regular stakeholder visits to the site are helping industry with the much-needed decision making support for PC systems in warm environments.

misting system was added to provide additional cooling to the plant canopies. Misting also helps increase air relative humidity from July to November.

This research site represents a significant capital investment, for the materials structure, construction, office and support infrastructure and equipment it was close to $0.5M. DAF also allocated new staff to specifically work on PC systems for vegetables, fruit trees, and berries, as well as potential tropical crops.

Early results are promising

To date, the DAF PC team has grown crop plots of cucumbers, capsicums, eggplants, climbing beans, specialty melons, and tomatoes at the ARF (Figure 3 and 4). Since the first crops were established in September 2020, results are indicating that year-round production in the north QLD tropics is possible. Summer-grown crops produced very well under the applied technology and agronomic practices in high temperatures and intense rain conditions that would have severely impacted outdoor production.

We grew capsicums in single rows and supported plant canopies using a modification of the traditional Spanish trellis system (i.e., layers of horizontal strings extended along both sides of the plant row). This system uses very little pruning of shoots compared to the "V" trellis system; therefore, it creates plant canopies with a greater number of branches and leaves (Figure 5). Reduced pruning of capsicum in warm environments results in greater profitability (lower labour inputs and lower incidence of blossom-end rot in fruits. The denser canopy also creates a better host environment for beneficial insects and mites. Plants grown with less invasive pruning management have more growing points, and a better chance to recover from broadmite (*Polyphagotarsonemus latus*) infestations if these are managed with biological control and, if necessary, sprays that can be directed to only the top of the plant canopies.

The harvesting periods in cucumbers (both Lebanese and continental types) and tomatoes were extended when we layered plants after the main stems reached the 3-m overhead wire. Lebanese cucumber crops can easily reach yields of 20 kg/m^2 under this management system. We pruned and trellised eggplants to the "V" system and were able to incline stems gradually to about 60 degrees to harvest additional fruit. In large production areas, the adoption of high trellising practices (e.g., >1.8 m) would benefit from using pipe-rail trollies. Growers will need to assess the cost-benefit of mechanization if they aim to harvest crops for longer periods (which reduce unproductive time and labour inputs) and compare it to growing several crops trellised to lower heights (which creates a longer unproductive period and increased labour inputs).



Figure 3. (Back to front) DAF protected cropping team members working on a specialty melon crop plot in the new retractable roof structure at the Ayr Research Facility.



Figure 4. The first crop plots were established at the DAF Ayr Research Facility in late 2020. A small fertigation unit can deliver water and nutrients to different plots.

To date, we have indication that in north Queensland, a retractable roof structure design allows improved environmental management compared to growing crops in tall polytunnels or highly passively ventilated greenhouses (e.g., saw tooth design with vertical roof vents). The improved passive ventilation and longer harvesting periods under a retractable roof should better support the consideration of mechanization. Biological control practices have been used to effectively manage pests when used in integrated management programs. We are looking at testing more 'banker plant systems' which help maintain a population of beneficial insects on crops grown under the structure.

Overall, fruit quality in crops harvested so far has been excellent. A range of non-traditional crops that could benefit from PC technology have been identified, e.g., specialty melons, beans, ginger, turmeric, and tropical fruit species (Figure 6 and 7). We are encouraged by the progress made with these initial crop evaluations and will continue to adapt agronomic practices and explore production methods for new crops.



Figure 5. A crop plot of long sweet capsicums ready for the first fruit pick at the DAF Ayr Research Facility.

Benefits to a range of stakeholder groups

Regional growers, PC input and service suppliers, researchers, university, and high school students,



Figure 6. A specialty melon crop in a warm sunny day at the DAF Ayr Research Facility. Only the insect exclusion net was left extended. Overhead misting can be used in some crops to lower leaf temperature.



Figure 7. Specialty melon trials have been conducted to fine tune agronomy practices and compare productivity and quality of fruit types and cultivars. Because fruit number is limited to a position in the plant, they can be managed to reach total soluble solids with estimates of 12 to 16 °Brix.

and state government representatives have been inspecting crop plots grown under the retractable roof structure. Visitors have been able to assess visual and eating quality of fruit and observe the improved productivity per square metre. Visitors can learn about fit-for-purpose technologies and practices that mitigate climate variability and create new opportunities for supplying domestic and export markets. One-on-one and group visits have been allowing growers to discuss whole-of-enterprise PC systems relevant to their specific situation. For example, during the visits they discussed aspects of targeting production for specific markets; marketing and product differentiation; business scale; geographical location; appropriate technology; inputs and services; labour and skills; PC knowledge; and data gathering and interpretation. Agronomy practices are frequently discussed and include environmentally sustainable options for managing pests, diseases, water, and nutrients. These events are allowing us to gather feedback on a range of constraints to adoption and expansion of PC in northern Australia.

As with PC investments in other climatic regions, infrastructure and agronomy need be fit-for-purpose. For commercial businesses, economically and environmentally sustainable PC production in the tropics require a systems approach to management and sound business plans.

Funding initiatives and key projects have been supporting protected cropping in the tropics and subtropics. DAF has been leading several projects resourced or co-resourced by Queensland Government, Horticulture Innovation Australia Limited, Australian Centre for International Agriculture Research (ACIAR), and the Cooperative Research Centre for Developing Northern Australia (CRCNA).

Contact for additional information.

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Protected cropping to ensure supply of high quality coloured capsicums from Queensland

Queensland growers are looking at innovative technologies to increase yields of quality capsicums for high-value markets.

Researchers at the Department of Agriculture and Fisheries are developing protected cropping systems for the tropics and sub-tropics so farmers can produce high-quality capsicums that meet Australian and Asian market demands.

Climate variability and extreme weather events are challenging for Queensland vegetable growers. Extremes in solar radiation, air temperatures, wind speed and rainfall limit yields and quality of field-grown capsicum. Insect pests further reduce marketable production and can restrict access to markets. Protected cropping systems are a promising alternative for capsicum growers in Queensland.

Project leader, Dr Elio Jovicich, says the research is supporting an emerging industry using a range of protected cropping technologies. 'We have tested soilless systems and soil-grown crops in high passively ventilated greenhouses and tunnels. More recently, we have been evaluating production of capsicums under a retractable roof structure. With minimum energy inputs, we can achieve five-fold increases in yields', he said.

Structure designs, management of the crop environment and agronomy determine how long you can keep the continuum created with flowers and mature fruits along the plant stems in capsicum. Because plant canopies are supported vertically, the longer a crop is producing marketable fruits, the greater the yield.

'For example, total yields with soilless production, using medium to low technology levels range from 8 to 20 kg per square metre, compared with around 2.5 kg per square metre in capsicums grown outdoors.



A crop plot of long sweet capsicums ready for the first fruit pick under a retractable roof structure at the DAF Ayr Research Facility.

'In Queensland climates capsicums produce well under suitable structures and agronomic practices. The industry we support is spread from the Atherton Tablelands to Bundaberg and the Lockyer Valley. We work with input and service suppliers and with research groups and growers across warm climatic regions.'

'Our work is focused on adapting practices that are cost effective for farmers, providing advice and capacity building. In terms of tools we evaluate cultivars and address pest and disease problems with an emphasis on biological control and reduced pesticide use.'

The horticulture industry has limited knowledge on using protected cropping and related agronomic practices to reduce the impact of climate variability in capsicum crops. Along with industry partners and growers, the research team are

developing guidelines for producing high quality capsicums under protected cropping structures.

Protected cropping in the tropics and subtropics has been supported by DAF leading several projects resourced or co-resourced by Queensland Government, Horticulture Innovation Australia Limited, Australian Centre for International Agriculture Research (ACIAR), and the Cooperative Research Centre for Developing Northern Australia (CRCNA).

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A crop plot of blocky capsicums in a high polytunnel can extend outdoor seasonality and assure supply with quality fruits.



A good fruit load of long sweet capsicums ready for the first fruit pick under a retractable roof structure at the DAF Ayr Research Facility.

Protected cropping to support export supply of high quality melons from Queensland

High-value melons grown in Queensland using innovative techniques could soon be making their way onto supermarket shelves across Asia.

Researchers at the Department of Agriculture and Fisheries (DAF) are developing innovative protected cropping systems for the tropics and sub-tropics so that farmers can produce high-quality fruit for discerning customers in Asian.

Project leader, Dr Elio Jovicich, says the research has been supporting growers to produce specialty melons in protected cropping systems. High-value melon cultivars have been trialled on vertical trellises inside protective structures suited to tropical environments.

According to Dr Jovicich, the work has yielded very promising results.



Speciality 'Galia' melons growing on vertical trellis in a passively ventilated protective cropping structure in Queensland. Crop evaluations produced fruits with high visual and eating quality and received positive feedback from overseas markets where fruits attract high prices.

'Growing specialty melons, such as Galia, Charentais and Asian fruit types, we achieved up to three times the yield of conventional outdoor rockmelon crops,' he said.

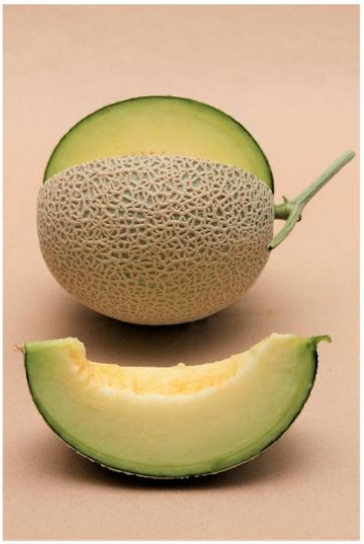
'Even more important than yield, harvested fruit had no blemishes and were very sweet. The crop is planned and managed so that flowers set fruits at the same location in plants; fruits are all harvested at the same time and with the same high visual and eating quality parameters. Consistent quality means a higher price at market.'

'By growing for quality while targeting sales into premium markets the higher labour and production costs with protected cropping are offset by higher dollar returns per square metre.'

An additional benefit for growers and consumers is that protected cropping systems use biological pest control practices, leading to less chemical use. Powdery mildew (*Podosphaera xanthii*) is a key disease in greenhouses, but some melon cultivars now have genetic resistance to the disease which makes it possible to grow crops without the use of fungicides.

Since current production of melons in Queensland is typically based on rockmelon and honeydew fruits in a seasonal and field production system our horticulture industry has limited knowledge on using protected cropping to grow quality fruit and manage the effects of climate variability. DAF researchers are working with industry stakeholders to develop guidelines for producing these specialty melons under protected cropping structures and for growers to be able to access new premium markets.

Melon crops perform well, and fruit quality is high when plants are grown under the warm and stable environments created inside protective structures. There are opportunities for growing new melon types and cultivars with protected cropping technologies in the tropics and subtropics of Queensland. In north Queensland it is possible to grow crops year-round without the need of artificial heating through the burning of fossil fuels. Harvest during the summer months in the tropics and subtropics could supply high value fruits into Asian winter markets.



The a of protected cropping will add diversity in fruit appearance, flavour and aroma, and guarantee consistent quality of superior melons grown for high-value export markets as well as niche domestic markets.

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