Protected cropping in subtropical climates

A report for

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Executive Summary

Protected cropping is an important method for horticultural production in Australia and around the globe. Protected cropping practices provide numerous advantages over conventional farming, allowing for a more controlled, sustainable approach to crop management and increased production. With global population forecast expected to reach 9.8 billion by 2050, the global demand for food, feed and fibre is expected to grow by 70%. The majority of growth in production is expected to come from higher yields and increased cropping intensity, the remaining 10% from land expansion. This increase in production needs to be achieved with limited access to land and agricultural resources, a reduced rural labour force, increasing climate variability and the unknown effects of climate change.

Protected cropping offers solutions to many of these challenges including a suite of technological options for improved natural resource management; improved water and labour-saving technologies, increased yields, improved crop quality and reliability, reduced crop losses and waste, and protection from adverse effects of climate change and climate variability. Protected cropping practices provide a sustainable adaptation strategy for crop production in an increasingly uncertain climate as crops grown using this method are less affected by climate variability and weather extremes. Sustainable food production is an imperative for the future of food production and protected cropping has the potential to play a significant role in the future of food security.

This report summarises the variety of protected cropping practices and associated technologies being utilised for horticulture production in subtropical climates including an assessment of the challenges and barriers to adoption in horticulture.

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Foreword

I did not grow up on the land and my parents were not farmers, although mum grew up on a sheep farm in WA. I grew up in the leafy suburbs of Brisbane. I have always held a natural affinity to the natural environment. At 17, I took my first opportunity to leave the traffic and pollution of the city and move to the Blackall Ranges on the Sunshine Coast Hinterland. I have never looked back. I have never felt so at home on this modest mountain range where annual rainfall can exceed 2000mm and landscape ranges from dry sclerophyll eucalypt scrub to lush rainforests and waterfalls. The valleys and flood plains surrounding the range provide some of the most fertile farming land in southeast Queensland (Qld). The perfect environment for growing plants, self and a family. It was here I started a family.

After the birth of my first son, my love for the outdoors and natural environment led me to complete a Bachelor of Science (majoring in environmental management) at the University of the Sunshine Coast (USC). I later returned to complete first-class honours in horticulture. I then began working as a research scientist in ornamental horticulture complimented by teaching scientific research methods at USC. My role was post-harvest research scientist before becoming project manager and then research manager. My research into the domestication of Australian native umbrella fern, a high value cut foliage product, led to the first successful propagation and cultivation methods for this unique species which is now cultivated commercially on the Sunshine Coast and in the Mary Valley for cut foliage and whole plant production. Prior to this, there was no successful method to propagate and cultivate this valuable species.

I became aware of Nuffield only a short time before applications closed in 2015. With encouragement I submitted an application. From the onset I was concerned I did not fit the requirements as I identified first as a research scientist before ‘farmer’ although my work is by definition, primary industries. In my first interview I was told Nuffield would have to ‘break the mould’ to award a scholarship to me, but as was duly noted in my first interview, ‘moulds are made to be broken’. Receiving a scholarship has opened doors to more agricultural researchers to apply for scholarships. I am truly honoured to have been accepted into the Nuffield family as one of the first.

The world of agriculture is rapidly changing to meet the needs of a growing population, the consumers of today (and tomorrow) and an increasingly uncertain climate. Alongside these, the image of farmers is also evolving. As times in farming change rapidly Nuffield are supporting the next generation to adapt and evolve to growing global populations, uncertain climates, digital disruption and reduced resources (i.e. land water, labour etc).

With increased uncertainty in climate variability I chose to research protected cropping for subtropical climates and to investigate the potential for new or underutilised crop species. I visited growers and researchers in humid subtropical climate regions of China, United States (Florida) and Costa Rica (tropical climate) and Mediterranean subtropical climate regions including Italy, Spain and Israel. It also included attendance at the International Symposia for Tropical and Temperate Horticulture held in Cairns, Australia (November 2016).

My journey has taken me away from home, and my family. My knowledge and growth has been expanded on a personal and professional level across a broad range of topics relating to global agriculture. My scholarship has broadened my horizons by taking me outside of my comfort zone and really pushing my boundaries. For this I am truly thankful.

Acknowledgments

I am forever grateful to Jim Geltch and my selection panels for their belief in me to ‘break the mould’ of the typical Nuffield Farming Scholar.

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Abbreviations

EC	Electrical conductivity
GVP	Gross value of production
HA	Hectares
HSP	High pressure sodium
IBC	Irrigation by condensation
IPM	Integrated pest management
KPH	Kilometres per hour
LED	Light emitting diode
MPH	Miles per hour
PA	Per annum
PAR	Photosynthetic active radiation
Qld	Queensland
R&D	Research and development
R,D&E	Research, development and extension
RFID	Radio frequency identification device
USA	United States of America
UV	Ultra violet

Objectives

1. Identify the variety of protected cropping structures and associated technologies being utilised for horticulture production in subtropical climates.
2. Investigate challenges for protected cropping in subtropical climates.
3. Determine barriers to adoption and investment in protected cropping technology for horticultural production.
4. Identify current and new technology being developed for more efficient and sustainable protected cropping in subtropical climates.
5. Investigate forest farming practices and their potential as an effective form of 'zero-tech' protected cropping.
6. Identify potential new or under-utilised crop species suitable for production in subtropical climates.

Chapter 1: Introduction

Protected cropping is an important method for horticultural production in Australia and around the globe. This method of cultivation refers to crops grown in a managed environment ‘protected’ from the natural elements. Protected cropping is utilised for high value horticultural crops ranging from vegetable and leafy greens through to soft fruits, ornamentals and cut flowers. Protected cropping has gained increasing popularity because of the numerous advantages it offers over conventional farming practices, allowing for a more controlled, sustainable approach to crop management and production. This provides a sustainable adaptation strategy for crop production in an increasingly uncertain climate as the crops are less affected by climate variability and weather extremes. Sustainable food production is an imperative for the future and protected cropping has the potential to play a significant role in the future of food security.

The current global population of 7.6 billion is increasing by 1.1% per year and is projected to increase to 8.6 billion by 2030 and 9.8 billion by 2050 (United Nations, 2017). During this time, global demand for food, feed and fibre is expected to grow by 70%; 90% of the growth in global crop production is expected to come from higher yields and increased cropping intensity, the remaining 10% from land expansion (FAO, 2009). Alarmingly 80% of this total growth is predicted to come from developing countries (FAO, 2009). This increase needs to be achieved with limited access to land and agricultural resources, a reduced rural labour force, increasing climate variability and the unknown effects of climate change.

Climate change and increases in climate variability pose significant threats to reliable food production in the future. To achieve the required increases in production, cultivation methods will need to increase yields from smaller production areas alongside reduced resources (e.g. water, labour etc) with adequate protection from the effects of climate change and increasing climate variability. Protected cropping offers solutions to many of these challenges including a suite of technological options for improved natural resource management; improved water and labour-saving technologies, increased yields, improved crop quality and reliability, reduced crop losses and waste, and protection from adverse effects of climate change and climate variability.

Protected cropping benefits can be achieved by various levels of investment. Generally, it can broadly be broken down into three levels (categories) including: low-tech, medium-tech and high-tech structures. For the purpose of this research a fourth level of protected cropping was also considered which involves a form of multi-cropping known as forest farming (a form of agroforestry). This involves cultivation of high-value specialty crops under protection of an over-storey or canopy crop that has been modified to 'protect' the crop below. Climatic conditions affect agricultural production by affecting yields and product quality at harvest. All levels of protected cropping modify the environmental conditions of the microclimate surrounding the crop to provide more optimum conditions for enhanced production. Protected cropping under the unique characteristics of subtropical climates are required to address different needs in comparison to protected cropping in temperate regions. Subtropical climates experience high solar radiation, heat stress, drought, winds and storms that can all lead to morphological, anatomical, physiological and/or biochemical changes in plant tissue (Fadel, 2016). Due to these inherent differences in climatic conditions protected cropping methods in subtropical climates vary in their design and construction.

The ability to modify environmental conditions reduces or removes these adverse conditions allowing crops to be grown in regions that would not typically support crop production under field conditions, as well as providing extended growing seasons and harvest periods resulting in significant yield increases. The capacity to manipulate and modify environmental conditions within the growing microclimate using protected cropping techniques is determined by the level of technology invested. While high-tech protected cropping provides the highest potential yield increases through intensive production and greater control over the growing climate, high capital investment is a major barrier to adoption across the globe, particularly in developing countries where 80% of the required growth in production is predicted by 2050 (FAO, 2009). As such, it is important to also develop optimised low-tech and/or low-cost alternatives to improve product yields, quality, reliability and resource management for future global food security. When determining the appropriate level of investment for protected cropping cultivation it is paramount that the level of investment is economically justified (Arbel, 2017).

In Australia, protected cropping accounts for a significant portion of the vegetable and flower industries, with a current annual GVP of approximately $1.6 billion (Smith, 2017), about 15% of the total GVP for horticulture of $10.6 billion (Hort Innovation, 2017). Australia has approximately 1,350 ha of greenhouses, expanding at a rate of 25 ha of new structures per year (graemesmithconsulting.com, 2017). Australian growers are keen to develop and utilise current and emerging technologies and Australia's most successful protected cropping growers are at the forefront of sustainable, efficient production, investing in new and emerging innovative technologies and cultivation practices. With Australia's rapidly growing protected cropping industry, it is paramount to continually assess the technologies available, support and adopt innovative new technologies and contribute to research, development and extension (R,D&E) to provide further gains in quality, productivity and sustainability in protected cropping.

This report provides an overview of the protected cropping methods utilised in subtropical climates around the globe, including forest farming practices. Potential new and emerging technologies are also discussed as well as the inherent barriers and challenges to the adoption of more sophisticated protected cropping technologies now and in the future. The unknown effects of climate change and increasing climate variability are also considered to ensure protected cropping practices can provide food security for a rapidly expanding global population.

Chapter 2: Protected Cropping in Subtropical Climates

Subtropical climates

Subtropical climates are characterised by hot summers and cool to mild winters with infrequent frost. No winter month has an average temperature below 0 °C (Ritter, 2006). The geographic location for subtropical regions (the Subtropics) refers to the climatic zone located between the tropics (Tropic of Cancer and the Tropic of Capricorn) and the temperate zones with approximate latitudinal boundaries of 35–66.5° north and south of the equator (See Figure 1); however continental influence and landscapes result in significant variability to these boundaries (Glossary.ametsoc.org, 2017).

Figure 1: Distribution of subtropical climates around the world (Image By Maphobbyist - Own work, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=14504468).

The Subtropics are divided into two basic sub-groups: 1) humid subtropical, and 2) dry summer or Mediterranean climates. Humid subtropical regions are characterized by hot, humid summers and frequently dry winters. Rainfall is seasonal, consisting of frequent tropical downpours of short durations, concentrated in the summer months. Humid subtropical regions are typically located on the east coast of continents (Ritter, 2006). Mediterranean (or dry summer) subtropical climates are typically located on the western side of subtropical continents and on the coast of the Mediterranean Sea; the climate is defined by hot dry summers with rainfall concentrated in the winter months (Ritter, 2006).

The unique environmental conditions of subtropical climates impose different requirements of protected cropping systems compared to protected cropping in other climatic regions. In temperate regions, protection from low temperatures and optimum/supplemental lighting are usually a priority for greenhouse design and ventilation is not required (Arbel, 2017). In subtropical regions, protection is needed from extreme temperatures, solar radiation, heavy rainfall, storms, wind and pests. Summer months are characterised by high temperatures, resulting in high water needs, combined with high insect, disease and weed pressures. For humid subtropical regions this is accompanied by extreme humidity and intense rain periods.

Protected cropping structures

Protected cropping structures provide various levels of protection from adverse climatic conditions such as temperature fluctuations, wind, precipitation and excessive radiation as well as providing protection from pest and disease pressures. Structures can range from simple low-tech polytunnels or shade houses, offering protection from solar radiation or simple rain exclusion, to fully automated high-tech greenhouse structures with computer-controlled decisions based on micrometeorological sensors to control opening/closing of vents and thermal screens, irrigation, fertigation, relative humidity and heating. Different structural forms and adopted technologies provide varying levels of potential yield increases related to the level of protection provided by the structure and the ability to control the growing climate.

Yield increases result from number of fruits per plant, quality and plant density and prolonged harvesting periods. Yield increases from protected cropping is much higher than is possible to achieve from normal outdoor production. Potential improvements are reported to range from 250 to 800% (graemesmithconsulting.com, 2017). Increases in yield potential are related to the level of sophistication of protected cropping practices during cultivation.

Low-tech structures consist of plastic covered polytunnels or simple shade-cloth (i.e. shadehouse) structures with minimal/passive ventilation and heating, if any. Medium-tech structures (or greenhouses) are more advanced incorporating computerised production systems such as automated screens, ventilation and heating systems. These are more sophisticated utilising multi-span greenhouses covered with various grades of plastic (i.e. polyethylene sheeting) or polycarbonate sheeting. High-tech greenhouses utilise more advanced computerised control systems for climate control mechanisms (e.g. heating, cooling, ventilation, light, CO_2 enrichment etc) with predominantly glass coverings. Any increase in the level of sophistication requires capital investment as a trade-off to achieve greater climate control and corresponding yield increases.

Shadehouses

Shadehouses protect cultivated plants from solar radiation (excessive heat and light) and can assist with protection from wind, frost, hail, birds and other pests. Shadehouses provide water-use efficiencies and increase relative humidity within the growing microclimate. The structures (either timber, iron, steel etc) are covered in shade net of various colours and percentages (or shade factors), protecting plants and providing passive environmental control. Various designs and quality of structural materials, cables and cloth affect shadehouse lifespans and maintenance/repair requirements. Shadehouses provide low level of protection and durability at relatively low cost of construction, maintenance and repair compared to other protected cropping structures.

Greenhouses

Greenhouse covers everything from plastic covered polytunnels to sophisticated glasshouses. Greenhouses differ from shadehouses in their covering which allow light and solar radiation to penetrate and be captured, heating plants, soil and air within the greenhouse, excluding precipitation. This gives the advantage of growing crops that are not suited to the local growing region and allow year-round cultivation. Low-tech polytunnels have roofs less than 3m high, no roof vents and small open areas for lateral ventilation. Similar to shadehouses, these are cheap to construct and repair, offering limited control over growing climate. As a result, temperatures under these structures frequently exceed optimal ranges for crop production. Effective natural ventilation limits the maximum length of these to 30-35m; by adding roof vents this can be increased three-fold (to 100m) and fans can also be added for forced ventilation (Arbel, 2017) (see venting for more detail).

In the tropics, tall passively-ventilated structures are often designed with a ‘sawtooth’ roof, created by roof vents (a series of vertical surfaces separated by a series of straight or curved sloping surfaces), which assist removing heat (Carruthers, 2015). In designs for warm environments, these roof vents can remain permanently open and can be screened with insect exclusion nets. Tall structures keep heat away from the crop and the slope of the roof reflects a high proportion of solar radiation away from the greenhouse (Carruthers, 2015). These taller designs adopt various levels of automation and technology to manipulate the growing microclimate, requiring increased level of capital investment for construction and maintenance, while offering improved durability and greater control over the climate.

High-tech greenhouses such as BW Global's Free Flow greenhouse provide 100% sealed, 3-story high, completely automated cyclone resistant structures with a hail guarantee (Kendrick, 2016). Achieving 100% enclosed growing structures provides even greater control over the growing process while saving energy and dramatically reducing water consumption by allowing recapture of transpired and evaporated water within the greenhouse. They provide ultra-high light diffusion, supplemental lighting and vertically pressurised bays for insect and disease control (Kendrick, 2016). While these offer the highest level of microclimate control, this is only achieved through significant capital investment.

Retractable roof structures

Retractable shadehouses (e.g. Cravo) are designed to provide protection against strong winds including hurricanes and cyclones, providing benefits for construction and durability in subtropical climates. Butler's Foliage in Florida invested in a five acre, Cravo fully automated retractable flat roof shadehouse following hurricane Katrina and cyclone Wilma (August and October 2005, respectively). The Cravo structure replaced shadehouses destroyed during the first storm event and is engineered to withstand winds of 130mph (210 kph) when closed (Butler, 2017) equating to a major Category 4 hurricane (nhc.noaa.gov 2017). At winds exceeding this speed the roof is opened to avoid capturing wind load, protecting the integrity of the structure (Butler, 2017).

Cravo shadehouses withstand extremely high wind loads when closed because of their unique fastening system. Strong, solid fabric strips are sown into the screens and hooks used to attach the cloth to the cables approximately every 40cm. Each hook supports two square feet (0.2 m^2) of screen. Significantly greater points of contact mean the cloth doesn't lift like a 'giant sail' like conventional shadehouses. If the roof needs to be retracted the plants may be destroyed but the structure will stand (Butler, 2017). Butler see this investment (which is significantly greater than the low-tech shadehouses it replaced) as part of their insurance policy (Butler, 2017). By comparison, conventional shadehouses are usually only attached on either side of a 25–30-foot (7.5 – 9m) span and are completely destroyed in winds over 90mph (145kph) (Butler, 2017).

Figure 2: Variety of protected cropping structures (clockwise from top left) low-tech timber and cable shade house (73% shade), Ronald Harris, Florida; Cravo retractable roof greenhouse, Butler's Foliage, Florida; medium-tech, semi-closed polycarbonate, saw-tooth design greenhouse, Gainesville, University of Florida; high-tech glasshouse Dushi-green, China.

Butler's five-acre Cravo is divided into four zones to provide different growing conditions (e.g. shade percentages) for different foliage crops. Two retractable screens are installed, one for shade and the other for heat retention. The system can be operated automatically based on time, wind speed and/or temperature. In warmer months, screens are opened in the morning to dry the foliage, increase air circulation, warm the plants and increase photosynthetic active radiation (PAR) and again in the afternoon to increase PAR, providing quicker grow times. The screens can also be partially opened (cracked) to release heat for ventilation (Butler, 2017). The 5.5m height of the structure helps regulate temperature during warmer months and the second layer of screens is closed to trap heat during cooler temperatures. The retractable screen design does not retain heat as well as a conventional system as it does not completely seal the growing microclimate, with small gaps on the edges and where pulley cables penetrate the screens (Butler, 2017).

Protected cropping coverings

A variety of different coverings are available to suit different climatic conditions and the variety of protected cropping structures, offering various levels of protection.

Polyethylene

Polyethylene is the least expensive option and includes product options from basic, single year use to sheeting with special additives such as UV extending the lifespan up to five years and protecting plants (and workers) from damage to UVA exposure. UV additives are also effective for controlling thrips but are not beneficial to bees (Wyse, 2017). Anti-condensation additives can also be added to reduce or eliminate condensation attached to the film which otherwise has the negative effects of reducing sunlight and dripping onto plants (Giménez, 2016 and Wyse, 2017). Various thicknesses and percentage shading of polyethylene sheeting can be selected to suit a variety of crops and offer diffused light options (Cretu, 2017). Double poly sheeting (3 to 4-year replacement) provides air space between layers for added insulation and fans are installed for improved insulation to reduce greenhouse temperatures (Butler, 2017).

While polyethylene is cheaper and easier to install, it requires replacement more regularly with the majority of growers replacing coverings every 2-3 years. A lifespan of 1-5 years is achievable depending on quality, climatic conditions and weather. Polyethylene is easily damaged by weather and may need to be replaced more regularly however repair and replacement are significantly less compared with alternative covering options. Tecnova based in Almeria, Spain, continue to develop new coverings and test for lifespan, light penetration, anti-condensation etc. Tecnova’s collaborative research projects with global partners are advancing protected cropping practices across a variety of aspects including coverings. As always it is a trade-off between potential benefits and increased capital investment (Giménez, 2016).

Polycarbonate

Polycarbonate sheeting is a very strong yet lightweight material and includes additives such as UV treatments to prevent yellowing and deterioration from sunlight. Polycarbonate coverings have an increased lifespan (warranty) of up to ten years but panels often require replacement every eight years in areas such as Almeria (Giménez, 2016). Similarly, Dynaglass panels with UV additives claim a lifespan up to 25 years but are reported to last 19 years under high UV conditions in Florida, USA (Mullins, 2017). Lexan panels can last up to 20 years however after the ten-year warranty they begin to break down becoming brittle and causing leaks (Strode, 2017). BioBee in Israel only recently replaced their polycarbonate sheeting with polyethylene to allow better light penetration (Wyse, 2017). This change to polyethylene also increased relative humidity and condensation (Wyse, 2017).

Extended covering lifespan is a benefit for installing polycarbonate sheeting, translating to less time required to purchase, transport and install compared with cheaper polyethylene that requires replacement every few years. Polycarbonate offers greater protection during weather. Repair to damaged sheets (e.g. hail damage) and replacement however is more complicated and requires increased capital investment.

Glass

Glass coverings are more durable than polyethylene and polycarbonate, however are less common in subtropical climates. Glass is the most expensive and heaviest covering requiring stronger supportive framework. Glass is effective at trapping heat however it is difficult to ventilate. As such, these structures are not commonly used but are better suited to cooler climates. Belgian owners of Deroose Plants in Florida and Dushi Green greenhouse construction company in China have both constructed Dutch-style glasshouses, the later has Dutch business partners (Deroose, 2017 and Wang, 2017). Plant producer Agristarts (located close to Deroose) expressed a desire to move from polycarbonate to glass if they were to expand (Strode, 2017) indicating glasshouse protected cropping designs do have a place in subtropical climates. Photovoltaic (PV) glass was installed at Dushi Green providing the added benefit of capturing electricity to offset some of the glasshouse energy requirements. The trade-off for energy production however is reduced light penetration resulting from the solar cells embedded into the glass (Wang, 2017). New research in Australia has developed clear PV glass embedded with nanoparticles to extract UV from the sun's rays, which are transferred to solar cells embedded on the edge of the panels (Stanley, 2017). This technology, developed by Edith Cowan University's Electron Science Research Institute, allows 70% of visible light to penetrate indicating a promising new technology for efficient PV glasshouse production.

Netting

Netting provides a simple economic covering for a basic level of protected cropping, reducing solar radiation and providing physical crop protection (e.g. hail, wind, pests). Insect netting excludes pests where greenhouses are covered hermetically. Hail netting can be used primarily for storm protection with the added benefit of reduced radiation intensity, increased vegetative growth, improved produce quality (including post-harvest) and pest exclusion; however reduced yields and quality have also been reported (Fadel, 2016 and Sivakumar, 2016).

Various coloured netting is available. Photo-selective netting aims to improve crop quality through modification of spectral light and microclimate under different shade cloths (Fadel, 2016 and Sivakumar, 2016). Black netting is cheapest and lasts longest (10-15 years) however this can be at the expense of reduced yields and reduced quality (e.g. pepper fruit colour affected on shaded side) (Fadel, 2016). In comparison, red and crystal shade netting increased yield and number of fruit per tree, however the lifespan of netting is reduced (4-5 years) and the red net fades to pink in 3-4 years. Most netting provides a minimum lifespan of 4-5 years. Black netting installed on conventional shadehouses should last 20 years however the reason they fail is during summer storms when wind speeds reach up to 120 – 130kph the cloth lifts and rubs on cables causing deterioration (Butler, 2017). If the cloth is hung by hooks (e.g. retractable Cravo structure) this removes deterioration caused by friction on the cables.

Nursery and foliage growers in Florida and Costa Rica use various percentages of black shade cloth on timber or steel cable structures ranging from 30% to 80% shade to provide optimum crop conditions. Foliage growers in Florida connect shade cloth with nails to allow flexibility during high winds and weather events (Hagstrom 2017 and Harris 2017). Other growers connect using clamp rings, ‘s’ hooks or grommets which can lead to damage to shadecloth in the event of strong winds (Harris, 2017 and McDonald, 2017)

Floating row covers

Floating row covers are a simpler form of protected cropping and very low cost as no structure is required. This method modifies the microclimate immediately surrounding the crop providing extended growing seasons by raising temperature, protecting from frost and providing shade to reduce sunburn. This also reduces water use and can exclude pests if using insect-proof netting (e.g. Queensland fruit fly). Examples of materials include fleece, a non-woven, spun bonded propylene for frost protection or netting (woven material, with variable mesh size) for insect exclusion. Netting is strong and reusable providing 10% shading, whereas fleece is easily torn, providing single use only and shading from 10-25%. Floating row covers increase marketable yield and increased daily maximum temperatures (but not night temperatures) providing a simple cost-effective form of protected cropping.

Chapter 3: Controlling the Microclimate

Temperature control

Temperature control is paramount for protected cropping in subtropical climates. Cooling is required in summer and heating in winter to improve yield and crop quality.

Height

Increasing the roof height is the simplest form of passive temperature control, providing a larger volume of air and more constant temperatures while reducing humidity within the greenhouse. Minimum gutter height observed in medium and high-tech greenhouses was generally 5m with the tallest gutter height observed at 7m; with BW Global now designing greenhouses up to three stories in height (Kendrick, 2016). Low-tech structures have significantly reduced roof heights which is a trade-off for ease of repair and maintenance (Butler, 2017). Taller (well ventilated) structures are preferred to allow crops to be trellised to higher levels while avoiding extreme high temperatures in the crop canopies, increasing yield and allowing more harvests throughout the season (Giménez, 2016).

Venting

Passive and forced venting can be effective cooling for low and medium to high-tech greenhouses. Passive (natural) ventilation can be achieved with sidewall vents, single or double roof vents or in designs that have retractable roofs. Ventilation is more effective when roof vents face away from the wind making dual butterfly roof vent structures more versatile for effective venting (Giménez, 2016). Airflow over the roof causes negative pressure that extracts warm air out of the greenhouse, causing outside air to be drawn in via the sidewalls, removing excess humidity (Arbel, 2017).

Greenhouses designed with forced ventilation are significantly more effective in controlling temperature compared to natural ventilation, increasing yields and cultivation windows. Air circulation fans can be added to assist with ventilation or when airflow is insufficient (Arbel, 2017). Knox Nursery in Florida has both naturally and forced ventilation Nexus greenhouses. A naturally ventilated greenhouse is significantly less effective in controlling summer temperatures, particularly when outside temperatures reach 43°C with indoor temperatures reported at 40-43°C limiting cultivation during summer months (Mullens, 2017). Systems that rely on venting do not provide uniform climate instead there is a gradient of heat (and relative humidity) within the greenhouse (Arbel, 2017).

Figure 3: Controlling the microclimate in protected cropping facilities in subtropical climates (clockwise from top left) extraction fans; and cooling pads installed in medium-tech greenhouse for hydroponic lettuce production (Mavor Hydroponic Lettuce, Israel); butterfly vents, retractable thermal screens and circulation fans in vegetative cutting production facility, TicoPlant, Costa Rica; retractable screens and HPS lamps for increased day length (Gafni Farms, Israel)

Evaporative cooling

Pad and fan evaporative cooling is a common form of greenhouse temperature control in the subtropics. Pad and fan cooling utilise a wet wall opposing a wall of giant fans to draw air through the centre of the greenhouse (See Figure 3). This method limits length of the structure between pad and fans, to 40m for effective cooling and does not provide uniform cooling throughout the greenhouse (variation of approx. 5°C between pad and fan) and is not as effective in regions with high humidity (Arbel, 2017). Agirstarts and Knox Nursery in Central Florida use wet pads on both ends of the greenhouse with fans mounted up in the centre of the roof to provide more consistent cooling throughout their greenhouses

(Mullens, 2017 and Strode, 2017). Internal high pressure fogging systems can also be installed for evaporative cooling using less water and power than pad and fan systems (Mazor, 2017).

Screens

Reflective thermal screens or shade netting can be utilised both inside and/or outside the greenhouse to decrease heat loads and prevent energy loss for heating and cooling. Retractable screens in medium to high-tech greenhouses operate automatically and are controlled according to light intensity and/or desired internal temperatures. The practice of internal thermal screens was common in the majority of greenhouses visited. Svensson Harmony screens were the most widely used, with Svensson Aluminet used in regions requiring effective heating in cooler months (Mullens, 2017). Multiple screens were used to increase temperature and light control as single screens allow radiation to penetrate while some heat is reflected (Arbel, 2017). Strode (2017) uses double thermal screens in their greenhouse furthest from their boiler which resulted in the most efficient house for heating because of the extra layer of energy curtain.

External screens stop/reduce the heat entering the greenhouse but are more susceptible to wind damage and require repair and replacement more regularly than internal screens (Qiang, 2017). In low-tech greenhouses, some growers apply the thermal screen directly on the polytunnels for cooling (Strode, 2017) or plastic sheeting directly over the top of shade houses to contain heat in winter months (Butler, 2017). In China, one grower combined external shade screens with external sprinklers installed above the multispan polytunnel greenhouses for cooling (Shi, 2017).

Heating

Limited heating is required in subtropical climates compared to temperate regions however many growers use some form of heating during winter to provide optimum conditions. Thermal screens installed inside the greenhouse significantly reduce the need for heating, conserving energy needs required for supplemental heating. The addition of two (or more) screens further reduces the need for heating, increasing the energy efficiency of the greenhouse (Arbel, 2017 and Strode, 2017).

In addition to passive heating, growers heat air inside the greenhouse using generators or hot water systems fuelled by coal, woodchips, oil or gas (propane). There is a shift away from non-renewable heating fuelled systems because of government regulations (e.g. China) and/or through encouragement by assistance programs (e.g. USA, Italy) (Qiang 2017, and McDonald, 2017 Quilici, 2017 respectively). Forced air heating uses large, plastic tubing through the greenhouse, installed under raised beds (Giménez, 2016 and Cretu, 2017) or above crops in the soil. Hot water systems circulate heated water through aluminium/poly pipes directly below/adjacent to the crop, embedded in soil or directly under heated benches to provide year-round optimum temperatures. In subtropical climates these systems are only run for a few weeks or months of the year depending on the geographic location. Some growers in Florida did not require any additional heating in winter of 2016/17 due to warmer than usual temperatures averaging 22-23°C (Cretu 2017). Propane fuelled under bench heating is common for young plant producers (in plugs and liner trays) to maintain temperature between 22 and 25°C for consistent year round production (Cretu, 2017 and Strode, 2017).

Closed (high-tech) greenhouse systems are more efficient to heat (as venting is not used) as they retain solar and/or direct heat inside the growing microclimate. Improved thermal insulation also provides significant reductions in heating (and cooling) costs by limiting direct or conductive heat gain/loss by thermally isolating the greenhouse' structural elements from the outside environment (Kendrick, 2017). Resulting operational cost savings can range from 40-60% depending on location (Kendrick, 2016). Increasing R&D into high-tech protected cropping means heating and optimum climate control is becoming more energy and emissions efficient.

Manipulating soil temperature

Soil temperature affects root development and in turn affects crop production. Israeli group RootsSAT (http://rootssat.com/) have developed an alternative solution for climate control using Root Zone Temperature Optimization (ROOTS) technology. The system offers cost-effective, sustainable microclimate control utilising proprietary ground source heat exchange (GSHE) technology for optimised root zone temperatures. GSHE principles are used for both heating and cooling the root zone to produce relatively stable root zone temperature (15-30°C) by reducing extreme fluctuations (Wachtel, 2017). Soil temperature below 3m is relatively stable year-round compared to fluctuations in top soil temperature. The ROOTS system uses GSHE coils inserted into the earth (depth greater than 4m), connected to a circulation pump to discharge water from coils into lateral pipes installed near the roots, distributing stable underground temperatures to the root zone (Figure 4). The closed-cycle system, filled with water once, can maintain an optimum or semi-optimum range of root zone temperatures. The only energy used is for operating a water circulation pump, although heat pumps may be used with hybrid systems as needed for greater temperature control. The technology is suitable for application in soil, elevated growing gutters and grow bags.

Figure 4: ROOTS being installed at Jordan Valley Herbs, Israel (clockwise from top left) digging and installing GSHE coils for root zone heating and cooling; coil ready to be installed in pits; covering the root zone growing area; coils installed in pits (Photos courtesy RootsSAT) Jordan Valley Herbs

The ROOTS system provides cost-effective, temperature control for year-round production with significant improvements to yield and quality allowing for early/late planting and early/extended harvest through mitigation of extreme heat and cold stress. In summer the GSHE system reduces, and in the winter, raises the root zone temperature by up to 11°C with reported yield increases ranging from 20-45 % and 10-140% for cooling and heating the root zone, respectively (Wachtel, 2017). Increases to product size, quality and reduced time to harvest were also reported.

The ROOTS system is able to sustain and maintain stable root zone temperatures year-round in most moderate climates, at 20% of the operating cost of conventional air heating systems. Conventional air-heating methods (e.g. using water from a boiler circulated in above ground pipes) lead to significant losses in energy. GSHE root zone heating targets the root zone with pipes imbedded in the soil heating the root zone only. If combined with a solar pump the system is 100% environmentally friendly. This new innovative technology is currently in commercialisation phase and shows promise for a sustainable, cost-effective climate control solution for crop production (Wachtel, 2017).

Humidity Control

Humidity control is of high importance within subtropical protected cropping systems to prevent humidity disease (e.g. botrytis) and reduce pesticide use. Pathogen problems begin when relative humidity levels exceed 80%, which impacts crop health and yields (Kendrick, 2016 and Arbel, 2017). Dry disease problems occur when relative humidity drops below 60% (Arbel, 2017).

Most greenhouses try to avoid excessive humidity by relying on direct venting with some regions and designs using heating as warm air has a greater moisture-holding capacity, reducing the relative humidity (Panakeet, 2017). Protected cropping structures with high roofs allow for greater humidity and temperature control (min height 5m) by increasing area of air inside the structure. Airflow serves to remove excess humidity through venting where humid air is extracted at the top of the greenhouse via automatic blinds/vents. Extraction fans set into the walls also reduce humidity through forced venting. Venting can be an effective method to remove excessive vapour however, heat (during cool evenings) and CO_2 may also be unnecessarily removed (Arbel, 2017). Different roof vents are available some are fixed (open), others provide the ability to manipulate the amount of ventilation and direction depending on weather and wind direction (e.g. butterfly design), the preferred method for more control (Giménez, 2016). Vents can operate manually or automated depending on investment. High-tech greenhouses can directly control relative humidity levels in finite increments through atmospheric water collection to optimize growing conditions. All this is achieved without losing water, which is recycled and used for irrigation (Kendrick, 2016)

A new technology developed by researchers at the Volcani Research Center in Israel, DryGair is an efficient solution for humidity control in greenhouse production while keeping the structure closed. This provides significant energy savings, limits pesticide use and prevents loss of CO_2 (Arbel, 2017). DryGair units can be connected to existing climate control system or ‘standalone’. They can be positioned along aisles or rows or on the side of the greenhouse on the ground or above the gutter; DryGair also offer split units for greenhouses without aisles. A standard unit can remove 45L/h of water in a 1,400 m^2 – 4,000 m^2 greenhouse (depending on the crop at a temperature operation range of 10-25°C). Small units are also available for 500-2,000m^2 greenhouse condensing 25L/h of water (Arbel, 2017). A combined dehumidifier and heating unit to control temperature and humidity inside the greenhouse is also available. This unit distributes warm air above the crop, enabling control of plant temperature. Incorporating this system allows for removal of heat pipes to reduce energy consumption and clutter within the greenhouse; combined with a reduction in the number and quality of thermal screens required (e.g. from three to one) (Arbel, 2017). Savings for installing DryGair system in exchange for a heated and vented system are calculated at 1:8.5 (Arbel, 2017).

Irrigation

Agricultural water sources vary from wells/underground aquifers, dams/above ground reservoirs, rainwater capture, recycled municipal wastewater and desalination. Water scarcity, drought and irregular rainfall patterns are becoming more commonplace due to increasing climate variability. The range of protected cropping practices allows for various levels of improved, water-use efficiencies by controlling the microclimate.

High-tech greenhouses provide ideal climatic conditions to optimise plant water use and offer optimum technology for water delivery. Closed loop hydroponic systems provide highly efficient water use through recycling of irrigation water and nutrients, significantly reducing water use by up to 90% (Giménez, 2016). Overhead irrigation delivered by moving overhead booms allow efficient water delivery with reduced spray drift and can be tailored to plant species and life stages within the same greenhouse (Strode, 2017). This technology can also efficiently apply chemicals and fertiliser supplied by the same boom (Deroose, 2017 and Strode, 2017). Combining this system (and other forms of irrigation) with ebb and flood benches provides a closed loop system where irrigation water and nutrients can be recycled, reducing wastage (Deroose, 2017 and Strode, 2017).

The ability of protected cropping practices to minimise water use allows for expansion into arid areas. Countries such as Israel continue to be at the forefront of innovative irrigation technologies such as the invention of drip irrigation. Rainfall in Israel is unevenly distributed averaging less than 100mm per annum (pa) in the south, to excess of 1,000mm pa in the north; one-third of the country receives a minimum of 300mm (Metz, 1998). Water for agricultural production is predominantly supplied (70%) from desalination and recycled municipal waste water (Giménez, 2016). Efficient water use in Israeli agricultural production is paramount. A promising new irrigation technology being developed by RootsSAT is investigating irrigation by condensation (IBC). The system irrigates by condensing water from humidity/moisture in the air/soil onto the external surface of pipes. IBC is a standalone closed loop system that circulates chilled water through pipes installed on the soil surface and/or in the soil at average root depth; humidity condenses on pipes and irrigates the crop (additional irrigation sources may be required). The water produced (and energy required to run the system) is directly related to relative humidity, air temperature, surface area of pipes and temperature of water being circulated (Wachtel, 2017). The IBC tank is filled once and continually cooled to below dewpoint and can be powered by solar. This new technology is currently in the R&D phase.

Increasingly, more greenhouse operations are capturing their own rainwater for irrigation. With many countries having perceivably reliable and readily available water sources, investment in rainwater capture is minimal. In Florida, the aquifers/ground water are of high quality and easily accessible providing an easy and economical option compared to significant capital investment required to construct rainwater reservoirs for storage (Strode, 2017). In South Florida, aquifers are only 6-7 feet below ground level, in summer this rises to 3 feet (Abreu, 2017). Two high-tech greenhouse growers in Florida have proactively chosen to invest in rainwater capture (Strode, 2017 and Deroose, 2017) to prepare for the future when they believe there will be stricter regulations regarding ground water use (Strode, 2017). In Almeria, Spain the EC of aquifers is too high so many growers invest in rainwater capture and/or buy water from waste treatment plants or desalination (Giménez, 2016). Greenhouse production in Almeria is reported to requires 800-1,000mm of rainfall per year however the region average is 200mm (Geographyfieldwork.com, 2016). Similar to Israel, water efficiency has improved rapidly with the use of drip irrigation and use of desalination, reducing reliance and overuse of natural aquifers (Giménez, 2016). More efficient water use including rainwater capture is paramount for sustainable crop production.

Pest and disease control

Protected cropping significantly lowers pest and disease pressures within the growing environment. This reduces the need to use environmentally harmful chemicals to control pests and weeds, assisting in relieving concerns regarding increasing resistance (Cretu, 2017). The ability to reduce pest and disease pressures is directly related to the level of technology incorporated into protected cropping practices and corresponding ability to manipulate the microclimate to provide optimum growing conditions. For example, pathogen problems begin when relative humidity levels exceed 80%, which impacts crop health and yields (Kendrick, 2016). The ability to effectively control relative humidity levels significantly reduces risk of fungal disease outbreaks such as botrytis.

Physical Exclusion

Physical exclusion of pests from the growing environment is the most efficient way to deal with insect pest pressures in protected cropping (Kendrick, 2016). Insect exclusion can be achieved by using semi-closed structures utilising insect proof netting on vents and sidewalls. Special netting is required to exclude thrips which can be achieved through correct netting choices and maintenance (Hernandez, 2017). Maintenance of semi-closed structures to ensure insect exclusion is difficult as netting can tear, and roof vents provide potential areas to penetrate the structure. In addition to insect proof netting, sticky traps can be placed as a plastic skirt around the greenhouse to reduce potential entry (Gafni, 2017). Sticky traps are also useful for monitoring and capturing pests inside the greenhouse. Investment in fully closed, high-tech greenhouse systems can provide complete exclusion to insects by removing any opportunity for pests to invade the greenhouse structure (Kendrick, 2016). Low to medium-tech structure coverings containing UV additives can be effective against deterring thrips (Wyse, 2017). Low-tech, open protected cropping structures provide challenges for insect control as pests are unable to be excluded.

Hygiene

Good hygiene practices are a highly effective, proactive measure to reduce contamination and pests and diseases entering protected cropping facilities. Greenhouses and shadehouses in high humidity climates displayed the highest level of hygiene protocols and procedures for production of vegetative cutting materials (Hernandez, 2017), seed (Barillas, 2017) and cut flowers (Uribe, 2017) in Costa Rica. Strict hygiene protocols enforced in these facilities include, prior to entry: hand washing facilities, lab coats and aprons (for each greenhouse/facility), hair nets, disposable gloves and disinfecting foot baths and boot scrubbers often supplied in positive pressure entrance rooms; some facilities combined this with ethanol hand spray (between touching each plant) and regular disinfecting of tools. Strict hygiene protocols significantly reduce introduction and cross contamination into and between greenhouses (Barillas, 2017; Hernandez, 2017 and Uribe, 2017).

Biological control

Control over the microclimate climate and reductions in pest and disease pressures can eliminate need for pesticides and fungicides allowing efficient and effective use of biological controls (Nichols, 2016). Increased sophistication in protected cropping is accompanied by higher degrees of integrated pest management (IPM). Natural enemies used in protected cropping included beneficials from suppliers such as Koppert, BioBee, Syngenta, Certic, and BioBest; examples include *Swirskii* mite (whitefly, thryp and mite control), *Orius* pirate bugs (thryp control) (Giménez, 2016) (Figure 5) and beneficial nematodes (fungus gnat and thryp control) (Hernandez, 2017).

Figure 5: Beneficial insects used in protected cropping (from left): Biobest Eretmocerus, parasitic wasp, Koppert bumble bees and Swiski mites

Subtropical climates are effective for beneficial insect IPM strategies as cooler climates can slow development, activity and affect reproduction; extreme temperatures need to be controlled for optimum efficacy (Cohen 2017). Supplementing bees in protected cropping is essential for pollination as pest excluding structures also exclude pollinators required for crop production (Giménez, 2016, and Barillas 2016). TicoPlant in Costa Rica use 15 beneficial insects and biological controls in their IPM program (Hernandez, 2017). Access to beneficial insects can be a problem in some countries due to biosecurity legislations restricting imports of insects (e.g. China) (Cohen, 2017; Qiang, 2017 and Wang, 2017). More R&D is needed to identify and develop native species as beneficial predators to remove barriers to successful use of beneficial insects in IPM.

Common soil pathogens (such as pythium, phytophera) and plant diseases (e.g. botrytus) can be controlled by inoculating growing media or plant material with preventative biological agents. Plant producers in Florida use media (e.g. plugs, elle pots) pre-inoculated with a patented *Bacillus* bacterium, broad-spectrum biofungicide (Double Nickel 55), as a preventative for the control and suppression of fungal and bacterial plant disease (Strode, 2017). Similarly, patented *Trichoderma* strains (e.g. RootShield® Plus WP) are applied to propagative material (including seeds and transplants) or media to prevent against plant root pathogens (such as *Pythium*) and other root disease (e.g. *Phytophthora, Rhizoctonia, Fusarium, Cylindrocladium* and *Thielaviopsis*) (Mullins, 2017).

Foliar diseases can also be controlled using contact biological fungicides (e.g. Cease) which uses patented strain of the bacterium *Bacillus subtilis* biological fungicide (Strode, 2017). Agristarts nursery (Florida) use contact biofungicides to control botrytis immediately prior to shipping as soft leaves of greenhouse produced plants are susceptible to botrytis during shipping (Strode, 2017). Application of foliar biofungicides combined with hardening off treatments prior to shipping is effective in reducing outbreaks during transit (Strode, 2017). Foliar biofungicides target common fungal diseases (e.g. *Botrytis*, powdery mildew, Anthracnose), several leaf spot diseases (e.g. *Alternaria* and *Entomosporium*) and controls bacterial diseases (e.g. *Pseudomonas, Erwinia,* and *Xanthomonas* spp.), as well as soil diseases (e.g. *Rhizoctonia, Pythium, Fusarium* and *Phytophthora*) (Arbico-organics.com, 2017).

Integrated Pest Management

IPM is becoming popular across farming practices, particularly within closed or semi-closed environment of protected cropping. These systems rely less on chemicals and more on beneficial insects and biological controls for pest and disease management. Higher levels of protected cropping sophistication and technology correlate with lower chemical applications and greater incorporation of IPM including beneficial and biological agents.

Light

Subtropical climates require reductions in light penetration (solar radiation) in protected cropping practices. This is achieved through various coverings as outlined previously. Retractable screens are the preferred choice to have greater control over optimum light penetration. Most medium and all high-tech protected cropping structures utilised retractable screens. Low- to medium-tech greenhouses in Almeria still use whitewashing to control light penetration during summer months to protect crops against burning, as greenhouse temperatures can reach 45°C. Whitewashing does not provide flexibility for optimum light manipulation and is not suitable in areas with high rainfall as the paint is washed off (Giménez, 2016).

Supplemental lighting is required to optimise photoperiods in subtropical climates, promoting growth by increasing the growing season or to initiate/delay particular plant life stages. Overhead high-pressure sodium (HPS) lamps are common to increase light hours in low- to high-tech structures observed in all countries across all levels of technology. HPS lamps are cheap to install but have high energy cost for operation. LEDs (light emitting diodes) are more energy efficient they cannot be installed in low- to medium-tech structures where they will be exposed to the elements (Cretu, 2017). Investment in LEDs is currently considered too expensive for the amount of supplemental lighting used in protected cropping in subtropical climates, however rising energy prices are leading proactive growers to investigate cost benefit analyses of installing/replacing HPS with LEDs (Giménez, 2016 and Cretu, 2017).

In greenhouses where multiple crops are grown (or crops at various life stages) supplemental lighting can be applied to the required plants by attaching light sources (e.g. LEDs, fluorescent tubes) onto automated irrigation booms and operated at different speeds for optimum light delivery. This method delivers efficient and cost-effective supplemental lighting directly to the crop required without affecting or interfering with other crops (Strode, 2017).

Efficient photoperiod response can be achieved using Beamflicker™ lights as an alternative to HPS where supplemental lighting needs for increased growth is not required. It uses an oscillating parabolic reflector with a high-intensity sodium lamp that broadcasts beams of light over a large footprint, providing intermittent light across the greenhouse (Cretu, 2017). Beamflicker™ can manipulate day length using fewer lights compared to HPS (six lights verse 100 respectively); the lights are cheaper to install and use significantly less power than HPS to achieve photoperiod response in plants (e.g. delay flowering in poinsettias) (Cretu, 2017)

Growing media

Methods of protected cropping are experiencing a shift from soil grown crops to soilless mediums. Soilless media removes reliance on local soil properties, is less weather dependant and does not require soil sterilisation techniques. Soil disease problems are common from repeat crop cycles requiring diverse crop rotations, fallow years and/or fumigation to remove or suppress soil borne disease pressures. In areas of high rainfall soil disease can move through the soil profile or be transported in overland flow to non-diseased areas during high rainfall events (Uribe, 2017). Using soilless substrates physically separated from the ground reduces transference of soil borne diseases in growing media and removes the potential for water logging from rainfall events (Uribe, 2017).

Soilless media

Soilless substrate (e.g. grow bags/pots, closed- loop hydroponics) reduces disease pressure from within the growing medium, removes the concern of water logging from increased precipitation and allows optimum nutrition and irrigation management during cultivation (Uribe, 2017). Many traditional soilless substrates utilised in protected cropping are non-renewable such as rockwool or peat, however there is a shift towards sustainable substrates.

Renewable and sustainable soilless substrates are becoming more favourable to growers across the world for environmental and economic reasons without compromising cultivation. For example, fruit and vegetable, nursery, young plant, seed producers and foliage growers in Spain, USA, Costa Rica and China are moving away from non-renewable mediums such as peat moss and substituting for coco fibre or coir. Coir media has high water-holding capacity, resulting in reduced irrigation requirements coupled with reduced media cost compared to rising peat prices (Barillas, 2017, Cretu, 2017, Hernandez, 2017 and Qiang, 2017). A seed producer in Costa Rica has migrated from a variety of non-renewable mediums to coir for its sustainability and water holding properties, leading to reduced irrigation requirements and equal or higher yields across plant lines. In the past, the producer used 46 types of media (including mixes with topsoil, pumice, volcanic rock) then moved to a single media consisting of peatmoss and now uses only coir, the last change reduced media costs by more than 50% per square metre. The predominant mix comprises a ratio of 70:30 coco fines to chips, however they continue to experiment with various blends for optimum aeration and water-holding capacity for different crop lines (Barillas, 2017). A key note to remember if using coir is to check the quality of supply and check sodium levels in the media before use (Barillas, 2017).

A new renewable soilless media recently released in the USA is Hydrafiber™ Advanced Substrate, made from southern pine. Hydrafiber™ is produced through a patented, thermally refined process to produce fibre strands with large surface areas providing significant water-holding and aeration capabilities essential to effective soilless media. The new media aims to reduce reliance on non-renewable substrates such as peat and pearlite. Hydrafiber™ was awarded a 2017 Cool Product Awards at the Tropical Plant Industry Expo (TPIE) in Florida, USA. Costa Farms nursery (Florida), who tailor their growing medium to over 300 different plant lines (currently utilising 67 different mediums), is trialling Hydrafiber™ with promising results (Cretu, 2017).

Soil grown crops

Low-tech protected cropping methods, where crops are grown directly in the soil pose significant risk from soil borne diseases (e.g. phytophthora and Pythium). Restrictions to soil fumigation methods as a result of environmental concerns (e.g. methyl bromide) are causing concern for effective sterilisation treatments and pose significant risks to crop production. Chemical fumigation replacements to methyl bromide are considered more harmful to humans and environment and are often not as effective (Dvir, 2017). Chemical soil fumigation methods are not sustainable soil health management practices. Other methods for soil disinfestation include solar radiation treatments where polyethylene sheeting is removed from low-tech polytunnels annually and laid over the soil in summer between growing seasons and crop rotations. This method is showing success for farmers in Israel (Foreiler, 2017) but requires removal and replacement of polyethylene sheeting each year for treatment. In areas where low-tech quality plastic sheeting is replaced every year this is acceptable however not in Almeria where plastic sheeting is replaced every 2-3 years. The economic benefit of solar radiation during summer, fallow periods needs to be compared with converting to above ground soilless media practices.

Growing crops directly in soil relies on the inherent quality of local soil properties and over time soil is depleted of nutrients which need to be replaced. This requires soil amendments to improve soil health for crop production. For example, Israeli farmers use volcanic rock additives, rich in iron and essential minerals called 'tuff' to supplement their poor soils (Foreiler, 2017). Greenhouse growers in Almeria use soil amendments to create an artificial soil called 'enarenado'. This method was designed in the 1970s to overcome their extremely poor indigenous soils and is still used by 80% of farmers in the Almeria region (Giménez, 2016). The artificial soil is applied on top of the original soil base and consists of partly clay (6cm), organic material (e.g. goat/sheep manure) (6cm) covered with sand (6-10cm) to reduce evaporation (Giménez, 2016). This amendment is removed and replaced every 3-4 years.

The remaining growers in Almeria are using soilless media such as coir, perlite or rockwool, with more growers moving towards soilless media cultivation. This shift is partially in response to Dutch producer influences utilising hydroponic systems with rockwool media and computerised chemical fertigation (Giménez, 2016). This method significantly reduces water needs. It is anticipated more growers will continue to move to soilless media for greater control of soil parameters and for reliable access to cost-effective, renewable growing media.

Chapter 4: Forest Farming

What is forest farming?

Forest farming is a form of agroforestry practice, a land management system that combines trees with crops and/or livestock in the same plot. The system combines agriculture and forestry techniques to create diverse, productive and profitable sustainable land-use systems (Nac.unl.edu, 2017). The principles of forest farming constitute an ecological approach to forest management. Forest farming more specifically is the cultivation of high-value specialty crops under the *protection* of a forest canopy that has been modified to provide the correct shade level, creating a zero-tech or natural form of protected cropping practice. Thinning, pruning, or adding trees manipulates the amount of light reaching the understorey. Existing stands of trees can be intercropped with desired crop species or canopy trees can be planted for the specific purpose of providing additional income, erosion control and/or as protection for understorey crops. This method of cultivation has been demonstrated to be more biologically productive, more profitable and more sustainable than forestry or agricultural monocultures (Agroforestry.co.uk, 2017) and contributes to carbon sequestration (Van Damme, 2016).

Forest farming provides income security through product diversification and asset building requiring minimal capital investment. Cultivation of high value, speciality crops in forest settings provides new sources of diversified annual (or periodic) income before tree crops (e.g. timber, fruit, nut products) reach maturity (Chamberlain et al. 2009; and Nac.unl.edu, 2017), increasing benefits to landowners with the additional benefit of maintaining forest integrity and environmental health (Nac.unl.edu, 2017).

Areas of land that have been cleared for mono-cropping can lead to substantial soil erosion. By introducing forest farming or agroforestry practices, soil erosion and runoff is reduced, reducing loss of water, soil, organic matter and nutrients. Forest farming improves soil physical properties by maintaining soil organic matter and biological activity and increasing soil fertility and allows for closed nutrient cycling within the forest ecosystem. The resulting intensively managed cultivation through forest farming provides an ecologically responsible contribution to significant rural economic stability and growth while biodiversity and wildlife habitats are conserved (Agroforestry.co.uk, 2017).

Crop compatibility

A variety of crops can be grown under forest farming conditions. Understory and canopy plant compatibility is essential for successful forest farming. Unfortunately, limited research is available due to the high number of companion crop combinations. Local biotic and abiotic conditions, such as tree cover, soil type, water supply, topography and other site characteristics, determine what species are suited for this farming practice. Biological and cultural requirements of each plant need to be taken into consideration when selecting suitable candidates for forest farming. Important considerations include how species interact including competition for resources resulting from companion plantings and potential damage from harvest mechanisms and crop management (Simone, 2016). A wide variety of crops can be cultivated under the canopy such as food (nuts and mushrooms), botanicals (herb and medicinals) and ornamental products. Some products especially botanicals have high economic value, while others provide a lower but steady supplemental income. Shade loving plants that are naturally adapted to understorey conditions are key candidates for forest farming cultivation. For this method to be profitable tree and crop species selections and combinations are critically important. Markets for products being produced also need to be considered.

Simone (2016) has created a pre-selection tool for multi-cropping systems for planting under coffee plantations. The aim is to diversify agricultural production for added value and balanced nutrition through fruit and vegetable multi-cropping in Africa. The tool uses multi criteria decision making to merge all influential criteria into one composite indicator (CI) to identify the top ten most suitable crops (Simone, 2016). The CI is calculated as the sum of all weighted and normalised criteria values. Criteria include risk of coffee root damage during harvest, ease of coffee harvest, canopy competition, tolerance to shade, farmer’s knowledge and opinion, and nutritional value (Simone, 2016). Similar tools can be developed for other potential, high-value forest farming canopy and/or tree crops. These tools can be combined with modern farm forestry practices designed to allow optimum light penetration to the understorey crop(s), These include modern ‘shade monocultures’, utilising a single canopy crop or commercial polycultures (with two or more canopy/sub-canopy crops) which provide greater light penetration below the canopy than rustic forest farming or traditional polyculture systems (Patrick Van Damme, 2016).

Successful understorey crops observed in Costa Rica and Florida include vanilla, turmeric, decorative ferns and other foliage crops that are harvested from the understorey and sold for medicinal, culinary, and ornamental uses. Over storey crops included native tree crops, cacao and a variety of other tree crops. For timber production and shade producing canopy crops selections of native trees is preferred (Karczynski 2017 and Uribe 2017).

Villa Vanilla Spice plantation in Costa Rica is a sustainable plantation using organic, biodynamic (certified 1992, 2000 respectively) and forest farming cultivation methods. The major crop under cultivation is vanilla, with other crops in the forest farming cultivation system including Ceylon (true) cinnamon, cacao, black pepper, allspice, cardamom, turmeric and a variety of exotic tropical fruits, essential oils and medicinal plants (Karczynski, 2017).

Karczynski (2017) began farming vanilla on his property near Quepos in 1987. His initial approach for cultivation was traditional monoculture, using conventional vanilla farming methods with a single host tree crop (coral tree) for support while maintaining a lawn approach for inter-row control. Karczynski (2017) describes unfavourable weather events that resulted in excessive water stress alongside degenerated planting material combined with 'unsound agricultural practices' which collectively brought vanilla production in Costa Rica to a halt in the 1990s. This adverse experience forced Karczynski to reflect on suitable farming methods for tropical regions and more sustainable farming practices. The new approach to farming focused on forest farming principles coupled with biodynamic farming practices; viewing and treating the farm as a single unit, to encourage biodiversity and practice holistic sustainable farming methods. Karczynski experimented with a diverse array of host trees including local flora and focused on creating a soil and plant environment that encouraged repopulation with beneficial microorganism through mulching (including large forest debris), beneficial microbial inoculations and compost tea applications for improved soil health. The result, a '180-degree-turnaround' – the farm is now easier to manage and more profitable with increases in yield and quality from improved soil and plant health in a diverse ecosystem producing crops for diversified security and income streams (Karczynski, 2017). The variety of canopy species are more suited to vanilla production and local climate.

Forest farming has the potential to restore ecological balance to fragmented forests as demonstrated at Finca Luna Nueva, a Demeter certified organic biodynamic 207-acre farm in Costa Rica. Established in 1994 to grow organic ginger and turmeric the farm also includes sustainable tourism practices teaching regenerative organic agriculture. The farm uses forest farming techniques to combine food production practices with methods that regenerate the soil and assist with reversing climate change and regenerative biodiversity (Ismael, 2017) This practice allows multiple sources of income, reduced pest and disease pressures and has allowed biodiversity to re-establish. This was demonstrated in February 2017 when the first puma was reported to have returned to the area (Ismael, 2017).

Figure 6: Forest farming protected cropping practices for cut foliage production (clockwise from top left) under live oaks at Ronald Harris Ferneries, Florida; including cyclone damage at Albin Hagstrom & Sons, Florida; and flower foliage farming under native Gallinazo (**Schizolobium parahyba*****) at Orocosta, Costa Rica.***

Foliage growers in Costa Rica and Florida use forest farming protected cropping practices for cultivation of decorative ferns and other high-value ornamental foliage products. Foliage farms in Florida use existing live-oak (non-deciduous) hammocks to provide shade and additional protection to ferns which are irrigated, fertilised and harvested for domestic and export floriculture markets. The live-oak hammocks are a native forest ecosystem, manipulated by thinning and planting additional oaks to provide optimum light penetration for the understorey crop (Hagstrom, 2017 and Harris 2017). The canopy crop is not harvested as additional income. The method of cultivation reduces capital investment required for shadehouse construction and conserves natural vegetation in the area. During storms and high winds limbs and trees may fall and need to be removed and replaced for optimum understorey growth. In Costa Rica foliage grower, Orocosta plant native succession species Gallinazo (*Schizolobium parahyba*) from the Fabácea family for its fast growth, low limb drop and small leaf. This canopy crop provides fast shade (under two years) without limb drop or large leaf debris damaging the understorey crop growth or quality (Figure 6).

All of the above demonstrate the successful use of forest farming as a natural, zero-tech form of protected cropping for subtropical climates. Benefits include reduced capital investment in protected cropping structures, diversified income streams and income security. Forest farming methods provide additional benefits of maintaining forest integrity, improving soil physical qualities, increasing biodiversity and improving overall environmental health. This zero-tech form protected cropping is particularly useful for developing countries and improving environmental health to damaged mono-cropping farming practices.

Chapter 5: Barriers to Adoption

Protected cropping structures and related technologies offer numerous benefits to the future of food security and adaptations to increasing climate variability and the unknown effects of climate change. Unfortunately, key barriers pose significant challenges to adoption across various levels of technology. These relate to economic, environmental and/or social challenges, including capital investment, significant operational costs, weather events, business structure and level of education.

Economic barriers

The highest level of benefit potential from protected cropping is high levels of capital to invest in medium to high-tech structures and associated technologies. Significant capital investment however, is a key barrier to adoption . Medium to high-tech structures require high energy-use for heating and cooling and high energy-inputs for greenhouse construction including manufacture of materials (Carruthers, 2015). Maintenance can also incur expenditure for repair and replacement of covering materials, automation and other climate control equipment. Considerable capital investment and operational costs can be offset by corresponding yield potential and continuity in supply offered by increasing investment in technology. It is important that the level of investment in protected cropping is economically justified and is designed to suit the local conditions (Arbel, 2017).

Australian industry

Despite considerable capital investment costs, the protected cropping industry is the fastest growing food producing sector in Australia (Smith, 2017). Peak industry body Protected Cropping Australia (2017) estimates investment in new protected cropping structures between $100 and $300 plus per square metre depending on the sophistication of the greenhouse and technology. Viable production units are considered a minimum of 1,500 square metres with an average return on investment between 5%-10% with high-tech greenhouses returning 20-25% (protectedcroppingaustralia.com, 2017). The investment value of expansion within the industry is calculated at approximately $50 million per year, 20% of the total value of vegetable and cut flower production in Australia (protectedcroppingaustralia.com, 2017). With current average protected cropping infrastructure value in Australia at $75/m^2 compared to the cost of building new structures (average $200/m^2) it is clear Australia’s rapidly growing protected cropping industry realise the benefits of investing in high-tech protected cropping (protectedcroppingaustralia.com, 2017). The Australian industry is keen to develop and utilise new technology to make further gains in quality, productivity and sustainability.

Global industry

Globally there is a trend towards high-tech computerised protected cropping technology as growers realise benefits of investing in the full suite of technologies available to control the climate and increase production (Yingkuan, 2016). In developing countries however, high-tech facilities are not practical due to significant costs associated with initial capital investment and operational costs. In this instance low-cost, low-tech protected cropping or forest farming can be a compromise for field crops to provide improved growing conditions with minimal levels of protection resulting in potential yield increases and protection from adverse environmental conditions. These simple, ‘traditional’ low-tech greenhouses while economically vulnerable, are practical for developing countries. Forest farming practices provide additional benefits in relation to crop diversification and income stability.

Any investment in protected cropping provides the potential to limit or mitigate the effects of seasonal fluctuations, extreme weather events and effects of climate change. Increased investment in protected cropping technologies allows for more sustainable and efficient production systems and increased yields to optimise plant growth conditions, reduce plant stress and disease pressures. With a growing global population and increased climate variability, control over the growing climate is essential to produce high yield quality products in the future. The level of technology adopted in each production system needs to be determined by cost benefit analyses.

Environmental barriers

Protected cropping offers a suitable adaptation strategy to increasing climate variability and unknown effects of climate change. The occurrence of extreme weather events is rising around the world. Various levels of protected cropping provide crop protection from adverse weather events such as strong winds, hail, hurricanes and cyclones.

Crop damage

Crop damage as a result of adverse environmental conditions and extreme weather events is a key determining factor to the adoption of various levels of protected cropping technology. The level of protection and investment is determined by the value of the crop and/or associated crop risk. Low-tech structures such as hail netting or polyethylene coverings can provide adequate crop protection during hailstorms or by excluding precipitation during long rainfall events but only if the integrity of the structure is not comprised (Cretu, 2017). Protection from storms and winds can be achieved by low to medium-tech structures however significant structural damage and/or removal of coverings exposes the crop below to the elements resulting in damage (e.g. sunburn) (Figure 7) (Cretu, 2017).

Structural damage

A second key environmental barrier to technology adoption is concern for structural damage resulting from extreme weather events (e.g. hurricane). Growers in hurricane/cyclone regions consider it more cost effective to repair low-cost structures where investment in hurricane or cyclone proof structures (e.g. Cravo) is economically unachievable.

The impact of catastrophic weather events can be minimised by increasing capital investment in high-tech facilities providing guaranteed hail protection and/or cyclone/hurricane proof structures. While investment is expensive, these provide growers with 'insurance' allowing consistent supply of quality produce. Butler (2017) is confident after more major hurricanes, more growers will consider investing in Cravo or equivalent systems. With more extreme weather events predicted across the globe growers will see the benefit of investing in these systems (Kendrick, 2016 and Butler, 2017).

Figure 7: Damage from strong winds during tornado event north of Florida (23, January 2017) Costa Farms, South Florida; major structural damage at Ronald Harris Ferneries following Hurricane Matthew; and Albin Hagstrom and Sons, causing millions of dollars of damage to shadehouses in Central Florida, August (2016) (bottom photo courtesy Albin Hagstron and Sons).

Insurance

Insurance of crops and protected cropping structures can offset the economic damage during adverse weather. Crop insurance is uncommon in protected cropping for subtropical climates as claims are only approved where the majority of the crop is lost or damaged (Strode, 2017). Because protected cropping practices provide some form of protection this outcome is rare. Some growers invest in insurance for structures or choose low levels of sophistication in areas where insurance is difficult because of high likelihood of storms, tornadoes. For many growers, insurance seems a waste of money until an extreme weather event occurs (Hagstrom, 2017). Significant weather e.g. hurricane Matthew, Florida, cause millions of dollars of damage. Insurance claim payouts to growers are resulting in growing concerns that insurance companies will back out of the market as a result of increasing claims and high pay-outs in an increasingly uncertain climate (Hagstrom, 2017).

Social barriers

Social barriers are another determining factor for technology adoption. Many operations which invest minimally in their protected cropping structures are often correlated to both size and ownership model of the farm. Small and/or family operated farms were observed to adopt the least amount of new technologies or invest in advance protected cropping structures. This was a result of the level of education within farm management or the family unit, the age of the farmer and/or the stage in succession planning combined with the financial position. There is a distinct trend of smaller, family farming operations merging or being absorbed by larger organisations. These have greater capital investment capabilities which in turn allow investment in more high-tech production systems. It is important to educate farmers to the many benefits and yield potential increases from increased investment and adoption of protected cropping practices. Iit is important to provide public investment and incentives for farmers to adopt more efficient and sustainable farming practices, removing barriers to the adoption of new technologies and improved protected cropping practices.

Chapter 6: Future Direction

The future of farming is faced with the unique challenge of being required to produce more food with less land and resources in the face of climate variability and the unknown effects of climate change. Through manipulation of the microclimate, protected cropping allows growers to no longer rely on Mother Nature for correct growing conditions. It offers various levels of potential for improving produce quality, increasing yield per square metre, and allows off-season and year-round production, even when confronted with adverse climatic conditions. In the words of Timothy Kendrick (2016) the future of protected cropping provides the potential to grow *"any crop, anywhere, anytime".*

The protected cropping industry is likely to be least affected by the physical impacts of climate change making this method a key adaptation strategy. Food production will become more vulnerable to extreme weather events and must adapt to projected global mean surface temperature increases from 1.8°C to 4.0°C by 2100 as a result of climate change (FAO, 2009). Crop production in subtropical regions will be affected by the projected increases to global temperatures and vulnerable to increasing extreme weather events. Increased adoption of efficient and sustainable protected cropping methods for cultivation will assist farmers to adapt to climate change reducing its impact on global food security.

Priority has to be given to protected cropping R&D in order to achieve yield and productivity gains required to feed the world. Increased R&D investment is required to improve protected cropping practices and lower the cost of technology. While high-tech protected cropping provides the greatest level of control over the growing climate and better protection from extreme weather events, capital investment and operational costs pose key economic barriers to adoption across the globe, particularly in developing countries. Increased R&D investments are required to provide advances in crop production for both developed and developing countries. Increased investment in R&D will continue to improve structural designs and related technologies for optimum climate control and protection from adverse weather events. R&D innovations need to focus on lowering initial capital investment and operation costs by developing energy and emissions-efficient protected cropping systems. This will ensure continuous innovations in sustainable and efficient production systems for global food security.

Conclusion

Protective cropping offers a viable, productive growing system that meets the financial, environmental and social requirements of the future. Growth in protected cropping and related technologies will continue to rise in response to climate risk and ensure continuity of quality supply. Promotion and development of new, innovative protected cropping technologies will ensure productivity growth continues to be accompanied by sustainable and efficient production systems with reduced inputs and emissions for successful protected cropping practices for the future.

Action is needed now to ensure the required 70% increase in food production is achieved by 2050. Opportunities offered by protective cropping systems are only just beginning to be realised and has huge potential to play a key role in the future of food security. Increasing uncertainty in climate variability is leading to increased R&D and adoption of protected cropping systems across the globe. Australian growers are rapidly embracing protected cropping methods to improve yield production and continuity of quality supply. Continued investment, adoption and promotion of protected cropping R&D and cultivation methods will lead to increasingly efficient and sustainable production systems for an increasingly productive future of cultivation in subtropical climates.

Recommendations

- Increase R&D investment across all levels of protected cropping technologies for subtropical climates to improve climate control, increase yield and optimise resource management while lowering capital investment and operating costs for more efficient, sustainable production.
- Provide incentives for farmers and the private sector to invest resources into the development and adoption of new, sustainable technologies to improve efficiencies in climate control, energy and water-use and pest and disease management within the industry.
- Promote new innovations through education and technology transfer to demonstrate potential gains from protected cropping practices.
- Increase R&D into forest farming as a form of zero-tech protected cropping with a strong focus on optimised production systems and crop compatibility.
- Medicinal cannabis was also identified as a highly valuable new crop species for production in the Australian subtropical climate. It is further recommended to investigate and determine optimum cultivation practices for cannabis production using protected cropping practices.

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Plain English Compendium Summary

Project Title:	Protected Cropping in Subtropical Climates
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Objectives	• Identify the variety of protected cropping structures and associated technologies being used for horticultural production in subtropical climates • Investigate the challenges for protected cropping in subtropical climates • Determine the barriers to adoption and investment in protected cropping technology for horticultural production in subtropical climates • Identify current and new technology being developed for more efficient and sustainable protected cropping in subtropical climates • Investigate forest farming practices and their potential as an effective form of 'low-tech' protected cropping • Identify potential new or under-utilised crop species suitable for protected cropping production in subtropical climates
Background	Protected cropping is an important method for horticultural production in Australia and around the globe. Protected cropping has gained increasing popularity because of the numerous advantages it offers over conventional farming practices, allowing for a more controlled, sustainable approach to crop management and production. Protected cropping practices are a sustainable adaptation strategy for crop production in an increasingly uncertain climate as crops grown using this method are less affected by climate variability and weather extremes. Sustainable food production is an imperative for the future of food production and protected cropping has the potential to play a significant role in the future of food security.
Research	This report aims to provide an overview of the protected cropping methods currently utilised in subtropical climates around the globe, including forest farming practices. Potential new and emerging technologies are covered as well as barriers and challenges to the adoption of more sophisticated protected cropping technologies in the future. The unknown effects of climate change and increasing climate variability are also considered to ensure protected cropping practices can provide food security for our rapidly expanding global population into the future.
Outcomes	Protective cropping offers a viable, productive growing system that meets the financial, environmental and social requirements of the future. Significant capital investment is a key barrier to adoption of protected cropping practices where construction, maintenance and operating costs can provide a significant challenge to technology adoption. Continued investment, adoption and promotion of protected cropping R&D and cultivation methods will lead to increasingly efficient and sustainable production systems for an increasingly productive future of cultivation in subtropical climates across all levels of protected cropping.
Implications	Increased adoption of efficient and sustainable protected cropping methods for cultivation will assist farmers to adapt to climate change reducing its impact on global food security. Protected cropping offer an intensively managed cultivation practice to achieve increases in food production to supply growing global populations.
Publications	Nuffield National Conference, verbal presentation, Darwin, September 2017