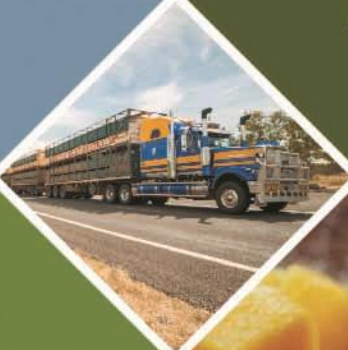

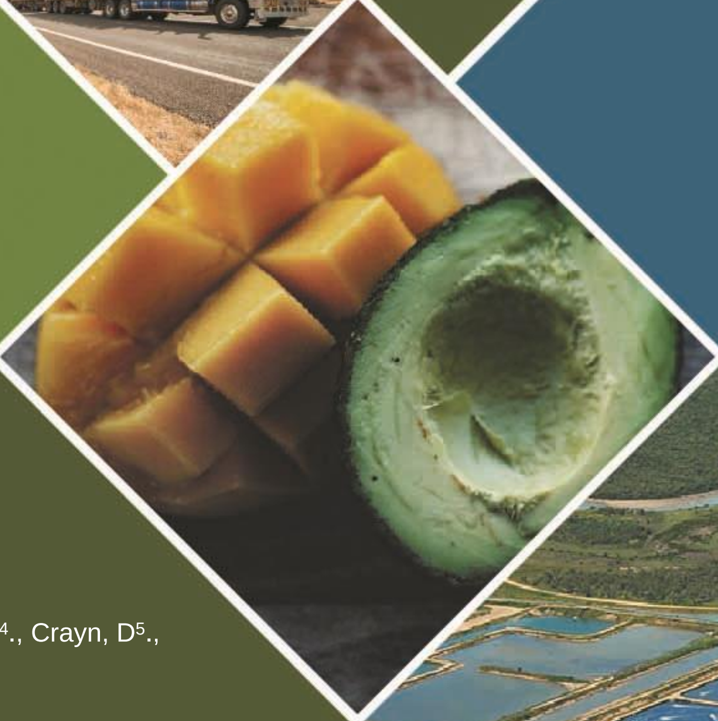

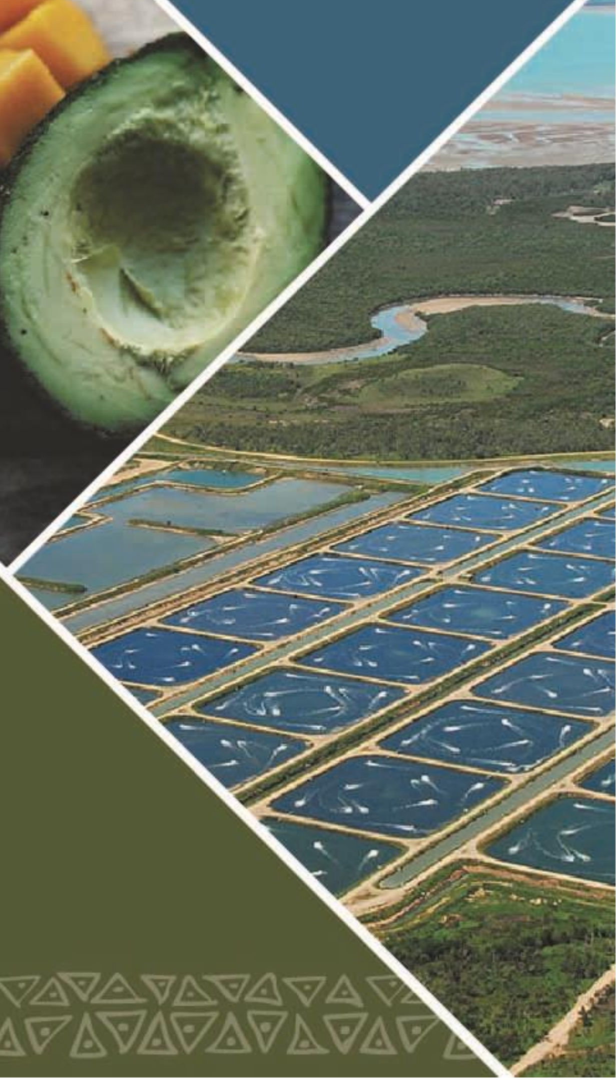

NORTHERN HEALTH SERVICE DELIVERY

TRADITIONAL OWNER-LED DEVELOPMENT

AGRICULTURE & FOOD

A situational analysis for developing a rice industry in Northern Australia

Project A.1.1718120

Chapman, B[1]., Henry, R[2]., Wurm, P[3]., Bellairs, S[4]., Crayn, D[5]., Smyth, H[6]., Furtado, A[7].

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CRCNA
DEVELOPING NORTHERN AUSTRALIA

Authorship

[1] Blake Chapman Communications, [2] The University of Queensland (project lead) ,[3] Charles Darwin University, [4] Charles Darwin Univerity, [5] James Cook University, [6] The University of Queensland, [7] The University of Queensland

Contributing participants

Industry

Russell Ford, *SunRice*Paul Ryan, *Olive Vale Pastoral*

Agronomy

Tony Matchett, *Savannah Ag Consulting*

Government

Siva Sivapalan, *WA Department of Primary Industries and Regional Development*

Greg Mason, *Queensland Department of Agriculture and Fisheries*

Research funding body (CRCNA)
Jed Matz, *Chief Executive Officer*, *CRCNA*
Allan Dale, *Chief Scientist, CRCNA*

Writing and report development

Blake Chapman, *Blake Chapman Communication*

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Project Participants

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The CRCNA recognises the value of knowledge exchange and the importance of objective peer review. It is committed to encouraging and supporting its research teams in this regard.

The authors confirm this document has been reviewed and approved by the project's steering committee and by its program leader. These reviewers evaluated its originality, methodology, rigour, compliance with ethical guidelines, conclusions against results, conformity with the principles of the Australian Code for the Responsible Conduct of Research (NHMRC 2018), and they provided constructive feedback which was considered and addressed by the authors.

List of Contributing Participants

Research

Robert Henry (Project Lead), *The University of Queensland*
Penny Wurm, *Charles Darwin University*
Sean Bellairs, *Charles Darwin University*
Darren Crayn, *James Cook University*
Heather Smyth, *The University of Queensland*
Agnelo Furtado, *The University of Queensland*

Industry

Russell Ford, *SunRice*Paul Ryan, *Olive Vale Pastoral*

Agronomy

Tony Matchett, *Savannah Ag Consulting*

Government

Siva Sivapalan, *WA Department of Primary Industries and Regional Development*
Greg Mason, *Queensland Department of Agriculture and Fisheries*

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Jed Matz, *Chief Executive Officer*, *CRCNA*
Allan Dale, *Chief Scientist, CRCNA*

Writing and report development

Blake Chapman, *Blake Chapman Communication*

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The CRCNA 'A Situational Analysis for Developing a Rice Industry in Northern Australia' Project team.

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Rice growing in a recently flooded field in Jerilderie, New South Wales.

List of Acronyms and Abbreviations

AWD	Alternate Wetting Drying
APSIM	Agricultural Production Systems sIMulator
CBD	Convention on Biological Diversity
CDU	Charles Darwin University
cm	Centimetre
CRCNA	Cooperative Research Centre for Developing Northern Australia
CRISPR	Clustered Regularly Interspaced Short Palindromic Repeats
CSIRO	Commonwealth Scientific and Industrial Research Organisation
FAO	Food and Agriculture Organization
FOB	Free on Board
FTE	Full Time Equivalent
GDP	Gross Domestic Product
GI	Glycaemic Index
GM	Genetically Modified
GRDC	Grains Research and Development Corporation
ha	Hectares
ILSMPs	Indigenous land and sea management programs
JCU	James Cook University
kg	Kilogram
km	Kilometres
l	Litres
m	Metres
mm	Millimetres
NSW DPI	New South Wales Department of Primary Industries
NT	Northern Territory
NT DTBI	Northern Territory Department of Trade Business and Innovation
NT DPIR	Northern Territory Department of Primary Industry and Resources
ORIA	Ord River Irrigation Area
QAAFI UQ	Queensland Alliance for Agriculture and Food Innovation, The University of Queensland

QDAF	Queensland Department of Agriculture and Fisheries
QLD	Queensland
R&D	Research and Development
RD&E	Research, Development and Extension
SE	Southeast
SME	Small and Medium Enterprises
SWOT	Strengths, Weaknesses, Opportunities and Threats
USD	United States Dollars
USA	United States of America
USQ	University of Southern Queensland
WA	Western Australia
WA DPIRD	Western Australia Department of Primary Industries and Regional Development

1 Executive Summary

The Situational Analysis for Developing a Rice Industry in Northern Australia was designed to (1) assess the current and projected industry need for Australian rice; (2) explore feasible options for rice production in northern Australia; (3) influence policy development to ease access to rice genetic resources and biodiscovery; and (4) develop strategic recommendations for the most critical next steps towards the development of a profitable, sustainable and socially beneficial northern Australian rice industry.

Around 500 million tonnes of milled rice are produced around the world each year and global rice consumption is expected to rise by 13% by 2027 (OECD/FAO 2018). Approximately 43 million tonnes is traded internationally (FAO 2018), but the number of countries that export rice is quite small. Due to decreasing availability of land and water for irrigated agriculture in many countries around the world, export capacity of many of these countries will also likely decrease in the foreseeable future. The market for Australian rice of approximately 1,700,000 tonnes for export and 130,000 tonnes for domestic consumption vastly exceeds the amount of rice that is currently produced in Australia (recent average of 600,000 – 800,000 tonnes, but less than 55,000 tonnes in 2019) (AgriFutures Australia 2017; SunRice 2019). Established export markets for Australian rice include 70 major international locations, including in the Middle East, Japan and Hong Kong (SunRice n.d.).

Northern Australia boasts a number of strong advantages in terms of producing rice. These include:

Suitable production temperature The current temperate rice industry in Australia produces rice in the summer, and even then is sometimes impacted by cool weather. Rice production in northern Australia may be possible all year round because of the higher temperatures.

Water availability The availability of irrigation water for rice in the Murray-Darling system has become more limited due to competition from perennial crops such as grapes and almonds. Climate change is predicted to make water supply even less reliable in this region. In contrast, the northern Australian wet season may support a rice crop in many areas of northern Australia.

Land availability Areas suitable for rice production are found in Queensland (e.g. Burdekin, Tully, Atherton Tableland, Cape York and the Gulf), the Northern Territory (e.g. Adelaide River floodplain and Katherine) and Western Australia (e.g. Ord River Irrigation Area).

Varieties High value aromatic rice varieties are attractive targets for production in northern Australia. Available varieties from Asia or southern Australia have been grown successfully in northern Australia in recent years. The selection or breeding of rice

Figure 1.1 Wild native Australian rice grows naturally in various locations across northern Australia. Photo: Blake Chapman

varieties more suited to northern Australia can be expected to result in significant increases in yields over the next 5-10 years. Native Australian rices also naturally grow in various locations across northern Australia (Figure 1.1).

Although the potential exists for northern Australia to become a ‘tropical rice powerhouse’ (SunRice 2019), notable challenges and threats to the progression of the industry in Northern Australia exist. These include navigating approval processes, sourcing the required capital investment needed to secure appropriate infrastructure, developing and breeding tailored rice varieties for northern Australia, and working within the valuable cultural, ecological and environmental lands in northern Australia. However, understanding and acknowledging that these potential challenges and threats exist means that risk management measures can be developed and implemented. The advanced knowledge and technology now available to breeders and growers, such as sophisticated modelling programs, better weather and climate forecasting, cutting-edge breeding tools, and enviable agronomic practices, also means that many mistakes of past production regimes may be better prepared for and minimised.

Large-scale industry developments such as this cannot evolve without significant cooperation, support and resourcing. This includes involvement from industry, growers, regional communities, researchers and government (at all tiers, across the north). The most direct pathway for the establishment of a northern Australian rice industry will involve government investment into infrastructure, economic policies and regulation that minimises costs on businesses, support of research that identifies and optimises opportunities for growing rice in the north, and approachable processes for navigating the regulatory landscape. It’s been repeatedly observed in northern Australia that private industrial schemes have far greater success when significant government investment is allocated to industry development (Ash and Watson 2018). Appropriate and direct governmental support will easily leverage industry and private sector investment, which is indeed already occurring (SunRice 2019).

Overall, this Situational Analysis has found that, with sufficient resourcing and guidance, a northern Australian rice industry has great potential to:

- ✓ Conservatively produce well over 100,000 metric tonnes of rice per year within 6 years
- ✓ Deliver $45 million to growers in north Queensland alone within 5-6 years (SunRice 2019), which is similarly scalable to other northern Australian regions
- ✓ Achieve yields of 10 tonnes/ha, or greater, through aerobic cropping, which would minimise water and nitrogen use
- ✓ Provide a unique and profitable rotation crop option for northern Australian farmers, which could support other agriculture industries, de-risk current rotations and provide additional income streams
- ✓ Achieve prices of up to $200/kg for wild harvested native rice (Wurm and Bellairs 2018)
- ✓ Create jobs in northern Australia (e.g. approximately 70 jobs at rice mills in north Queensland within 6 years; SunRice 2019)
- ✓ Create positive impact on community through capacity building and new regional opportunities.

The primary aim of this Situational Analysis was to investigate three potential rice industry development options for northern Australia. These include (1) growing existing domesticated rice cultivars (Figure 1.2); (2) developing and growing novel northern Australian rice varieties that combine the most beneficial traits of agronomically hardy domesticated varieties with the natural disease resistance and unique, high-value traits of Australian native rices; and (3) the cultivation or wild harvest of native Australian rices. A background review on the history of rice production in northern Australia was conducted to provide a foundation of past learnings, and a thorough market analysis of rice was conducted to gain a better understanding of the current and projected global market.

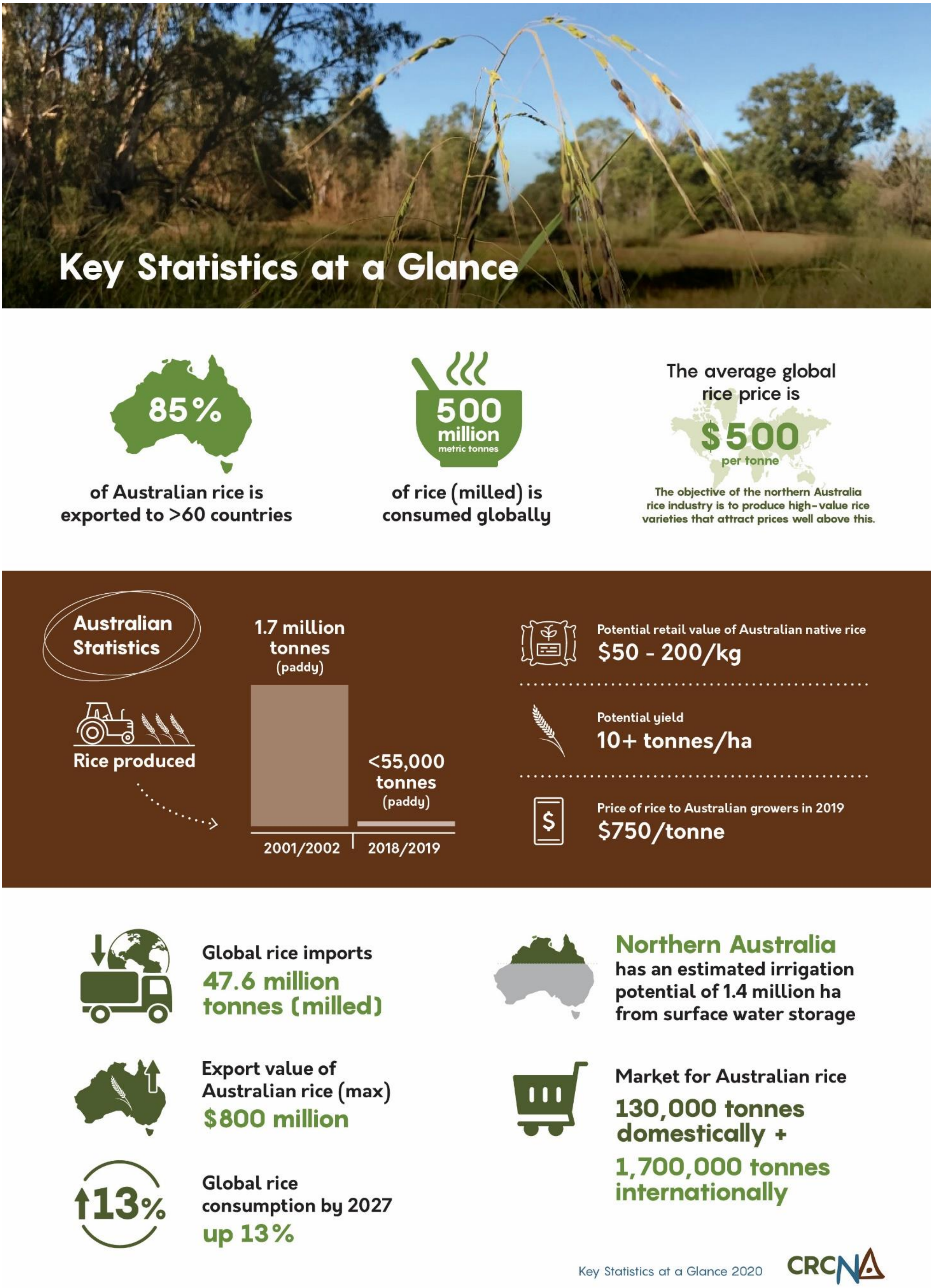
Figure 1.2 Project team members Robert Henry and Russell Ford examine new rice plants for growth characteristics in a field trial. Photo: Blake Chapman

Based on our analyses, each industry development option warrants further investigation and developmental trials. Ten recommendations were developed to outline the most critical next steps in developing a successful and sustainable industry.

1.1 Strategic recommendations

The strategic recommendations stemming from this project fall into five overarching categories, including:

- Guidance
    - Establish a Standing Industry Steering Committee
- Targeted Research into Growing Rice in Northern Australia
    - Develop a Tropical Rice Breeding and Varietal Development Program for North Australia (Domesticated Rice)
    - Develop an 'Industry Research and Development Coordinator' Role
    - Develop Varietal Simulation Modelling and Evaluation platforms
    - Develop Crop Management and Protection Strategies
- Communication and Stakeholder Engagement
    - Develop a 'Sector Development Officer' Role (Communications and Engagement)
    - Further Engagement with Indigenous Groups
- Advocacy
    - Create a Work Program to Establish a Sound Legal Framework and Improve Access and Benefit Sharing of Northern Australian Rice
    - Develop a Management/Conservation Plan for Australian Native Rices
- Targeted Research into Technology/Infrastructure Constraints
    - Review Options for Storage and Drying Infrastructure


Key Statistics at a Glance
85%
of Australian rice is exported to >60 countries
500 million metric tonnes
of rice (milled) is consumed globally
The average global rice price is
$500 per tonne
The objective of the northern Australia rice industry is to produce high-value rice varieties that attract prices well above this.
Australian Statistics
Rice produced
1.7 million tonnes (paddy)
<55,000 tonnes (paddy)
2001/2002
2018/2019
Potential retail value of Australian native rice
$50 - 200/kg
Potential yield
10+ tonnes/ha
Price of rice to Australian growers in 2019
$750/tonne
Global rice imports
47.6 million tonnes (milled)
Export value of Australian rice (max)
$800 million
13%
Global rice consumption by 2027
up 13%
Northern Australia
has an estimated irrigation potential of 1.4 million ha from surface water storage
Market for Australian rice
130,000 tonnes domestically +
1,700,000 tonnes internationally
Key Statistics at a Glance 2020
CRCNA

2 Introduction

Rice is one of the world's most significant food crops, and more than half of the world's population eats rice at least once a day (RGA 2019a). While rice is grown widely across the globe, significant demand still exists for Australian-grown rice. Australia only dedicates a very small area of land to rice (52,000 ha) and produces a very minor percentage of rice on the global scale (~1%) (Bajwa and Chauhan 2017). Yet, Australian rice is held in high regard within both domestic and export markets. Rice production in Australia has enjoyed many successes and, under certain conditions and with the right support, it has proven to be a profitable agro-based industry.

The vast majority of the rice produced in Australia is presently grown in the irrigation regions of the Murrumbidgee and Murray valleys of southern New South Wales. The industry contains around 1500 farm businesses that produce rice, often in rotation with other summer and winter crops (AgriFutures Australia 2017). Australian rice growers are world leaders in production efficiency (producing around 10 tonnes per hectare), water-use efficiency (tonnes produced per megalitre used; Australian farmers use around 50% less water per kilogram of rice compared to the world average), and environmental management (AgriFutures Australia 2017). Annual Australian production averages 600,000–800,000 tonnes per year, but in years of high water availability, this value can reach 1.2 million tonnes, or more. This, however, is countered by increasingly frequent years of drought, when production can drop to less than 20,000 tonnes (e.g. in 2007-2008) (AgriFutures Australia 2017). The Australian rice industry employs up to 8,000 people across growing, milling and transporting the product, with a further 37,000 jobs created in flow-on activities (AgriFutures Australia 2017). Australian rice is known for its high quality and generally achieves premium prices in global medium-grain markets.

Despite a century of effort and learning in southern Australia, it now appears that the most reliable and sustainable location, and indeed critical location, for Australian rice production may be northern Australia. In fact, great potential exists for northern Australia to become a major tropical rice production hub (SunRice 2019). The region's secure and reliable access to agriculture land and water, experienced farmers and a climate ideal for growing high-value rice varieties puts northern Australia in a prime position for the industry. A large-scale tropical rice industry in northern Australia would create significant economic activity and jobs, support current farmers and provide new, unique, high-value agriculture products for key strategic markets.

In response to this opportunity, a situational analysis has been conducted to evaluate the potential for a rice industry in northern Australia and the best approach for how to initiate the development of a successful, sustainable industry. The aims of this project were to:

- Evaluate the three main options for northern Australian rice production: wild rice, unique 'Northern Australian Rice', and domesticated rice;
- Predict challenges that may arise with growing, harvesting, processing and marketing of northern Australian rice, and develop strategies for how to mitigate these risks through future research and development activities;
- Develop an industry support group to drive the advancement of the industry after the completion of this Project; and
- Provide strategic recommendations for the Cooperative Research Centre for Developing Northern Australia (CRCNA) on the ongoing RD&E support and investment needed to achieve the vision of a productive, profitable and sustainable rice industry in northern Australia.

2.1 Rice

Rice is one of the three most important grain crops in the world and contributes significantly to fulfilling global food needs. In fact, rice is the most important grain in terms of nutrition and calorie consumption (AgriFutures Australia 2017). Rice contributes around 21% of world per capita caloric intake, and 27% in developing countries (Rosentrater and Evers 2018a). In certain locations, such as Vietnam, Cambodia and Myanmar, rice provides up to 80% of calories. Consequently, rice is also one of the most heavily domesticated species. Food and Agriculture Organization (FAO) statistics show that milled rice consistently makes up around 20% of the total global cereal production (which is currently estimated to be around 2,719 million tonnes) (FAO 2020). The forecast for rice utilisation in 2019/20 was a 1.0% year-on-year increase to reach an all-time high of 514 million tonnes (FAO 2020). Although other uses exist, rice is predominantly grown for human consumption. Around 80% of produced rice is consumed by humans; this is in contrast to 70% of wheat and just 15% of maize (Rosentrater and Evers 2018b).

2.1.1 The rice gene pool

Rice is grown in many regions across the world, with diverse production methods. Surprisingly, though, despite the fact that the rice genus (*Oryza*) is comprised of 27 species (Stein et al. 2018), we are heavily reliant on just a very small fraction of the potential *Oryza* gene pool.

Only two domesticated species (different to all wild species) are grown around the world: these are colloquially known as Asian rice and African rice. Asian rice (*Oryza sativa* L.) was domesticated from the wild rice species *Oryza rufipogon* Griff. approximately 9000 years ago (Molina et al. 2011), while African rice (*Oryza glaberrima* Steud) was domesticated approximately 3000 years ago from *Oryza barthii* A. Chev. (Meyer et al. 2016). Nearly all of the 40,000+ varieties of rice currently grown around the world (AgriFutures 2017) are varieties of Asian rice. In contrast, *Oryza glaberrima* is only grown over small areas in a few African countries due to its poor yield in comparison to *Oryza sativa* and its incompatibility with mechanical milling (Veltman et al. 2019). *Oryza sativa* is made up of two main types: indica, which grows in tropical and sub-tropical regions and is generally long grained; and japonica, which is a more temperate and subtropical type with short–medium, broad, round grains. Each individual rice variety within these two types has distinct agronomic requirements and unique cooking and taste characteristics. As a result of their isolated domestication, japonica and indica rices are more closely related to wild varieties than they are to each other (Gross and Zhao 2014).

Of the wild *Oryza* species, four are native to Australia. *Oryza rufipogon*, *Oryza meridionalis* and *Oryza australiensis* are widespread across northern Australia, while *Oryza officinalis* is known from only two localities. Interestingly, hybrids of these wild rices have now also been found in northern Australia (R. Henry, personal communication). *Oryza meridionalis* is an annual species that grows in wet areas and survives as seed in the dry season (Henry et al. 2010). Australian *Oryza rufipogon* (which is genetically distinct from Asian populations of *Oryza rufipogon*; Waters et al. 2012) is a native perennial found in wet or swampy areas. Two additional undescribed taxa of Australian perennial wild rice have also been identified; these are informally classified as wild rice 'Taxon A' and 'Taxon B', which correspond to populations of *Oryza rufipogon*-like (r-type) and *Oryza meridionalis*-like (m-type), respectively (Sotowa et al. 2013; Brozynska et al. 2017). The two species, which grow in close proximity to each other, are primarily distinguished by anther size (Brozynska et al. 2014). Interestingly, the nuclear genome sequence of Taxon A is much closer to domesticated rice (*Oryza sativa*) than to other Australian wild rices (Brozynska et al. 2017).

The *Oryza* genus has six diploid genomes, AA, BB, CC, DD, EE and GG, and four allotetraploid genomes, BBCC, CCDD, HHKK and HHJJ (Khush 1997; Ge et al. 1999; Lu et al. 2009; Wambugu et al. 2015). The AA genome is of greatest interest to the commercial industry, as it contains the cultivated rices. Notably, some wild rice species also fall within the

AA genome, including Australian endemic *Oryza rufipogon* and *Oryza meridionalis*. As such, wild Australian rices are of great interest and importance since they contain a broad gene pool of potentially useful, currently untapped genetic resources that can be easily crossed with commercial rice cultivars (Henry et al. 2010). *Oryza officinalis* and *Oryza australiensis* are representatives of the CC and EE genome types, respectively (Ammiraju et al. 2008; Brozynska et al. 2016). The CC genome may also provide important resources, as it is close to the AA genome (Brozynska et al. 2016).

2.2 Growing rice

Rice *(Oryza sativa*) is a warm-season grain, typically grown in tropical and subtropical climates (Figure 2.1). It is generally grown as a semiaquatic annual grass; however, it can survive as a perennial producing new tillers from nodes in the tropics (Rosentrater and Evers 2018a). Rice can be grown in a variety of ways. Most high-yielding rice varieties have been bred for anaerobic lowland flooded conditions. Paddy, or irrigated rice, is grown in enclosures that become flooded through irrigation so that plants are in standing water. In these systems, water depth can be controlled to best accommodate the different growth stages. Rice can also be grown aerobically, or in dryland or upland conditions. The varieties grown in these conditions generally exhibit some degree of drought tolerance. The major benefit to aerobic rice is that it does not need to be permanently flooded, so requires less water for production. However, it does still require a significant water investment, and may still require irrigation water. Rain-fed rice relies solely on natural rainfall. Flood-prone rice is grown in river basins, or other areas that become uncontrollably flooded. Water depth in these areas often reaches 1.5 m during the rainy season.

Figure 2.1 Domesticated Asian rice growing in Jerilderie, New South Wales. Photo: Blake Chapman

The greatest percentage of rice is grown with irrigation. Consequently, an estimated 34–43% of the world's total irrigation water - or about 24–30% of the entire world's developed freshwater resources – goes to irrigating rice (RKB 2015, in Prasad et al. 2017). Irrigation water is becoming scarcer overall and global water scarcity has threatened the productivity and sustainability of rice production worldwide. It is thought that several rice-growing Asian countries are likely to face ~30% shortages in water availability by 2025 (Prasad et al. 2017). This is especially concerning, given that nearly all (~95%) of the rice grown in China relies on irrigation. Less than half of the rice grown in India is irrigated; however, rice production there still requires 2500-3500 l/kg (Ricepedia n.d.).

While rice is grown in Asia, North and South America, Australia, Europe and Africa, Asia dominates the world rice economy, and this trend is expected to continue. A total of 90% of the world's rice growing area is in Asia, and 80% comes from just eight Asian countries: China, India, Indonesia, Bangladesh, the Philippines, Vietnam, Thailand and Myanmar (Prasad et al. 2017). These countries have further notable significance, as they alone also hold 46.6% of the world's population (Prasad et al. 2017). Africa grows rice over approximately 10 million ha (Zenna et al. 2017), Latin America and the Caribbean have about 6.0 million ha (Zorrilla et al. 2013) and around 1.5 million ha is used for rice production in North America (Ricepedia n.d.). In terms of total rice production, Asia contributes 90% of the 700 million tonnes of rice (470 million tonnes milled) globally produced per annum (Ricepedia n.d.). Again, China contributes the largest share (30.1%), followed by India (21.5%) (Wailes and Chavez 2012).

Although Australia contributes only a minor percentage of rice on the global scale (as little as 0.1%; Figure 2.2), Australian rice has an excellent reputation for quality and world-leading production methods. Australia is also one of the few countries that exports rice.

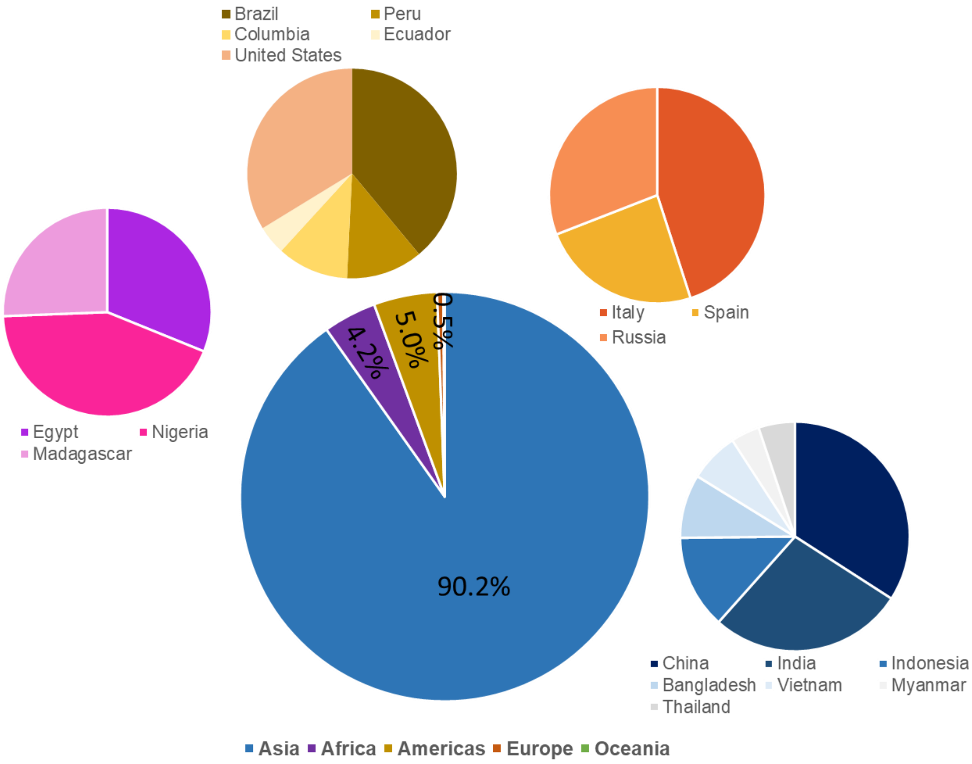


Figure 2.2 Global rice production per region. Rice is a major global crop and Australia contributes just 0.1% to the world's rice production. Data source: FAO (n.d.).

2.2.1 Opportunities for rice production in Australia

In order to meet both national and international demand for rice, especially in the context of a changing climate, Australia needs to explore new options to supplement rice production in the south. One of the most exciting and promising options being explored is the commercial growth of rice in northern Australia. While there are many benefits and advantages for this direction, past efforts have shown that rice production in the north needs to be approached and implemented with great caution and consideration. A successful rice industry for northern Australia will only succeed on a foundation of extensive planning, the development of specialised agronomic practices dedicated solely to the northern environment, careful monitoring of industry strengths, weaknesses, opportunities and threats, and the ability to integrate and react to new knowledge. The industry will need to be reliant on rice varieties that are resistant to diseases, climate change-ready and distinguishable as specialty types unique to northern Australia. Prior research has shown that there is potential in the north for the growth of high-value fragrant rices, specialty and coloured varieties, and even native wild rice (Wurm et al. 2012; Zhao et al. 2016; Tikapunya et al. 2018).

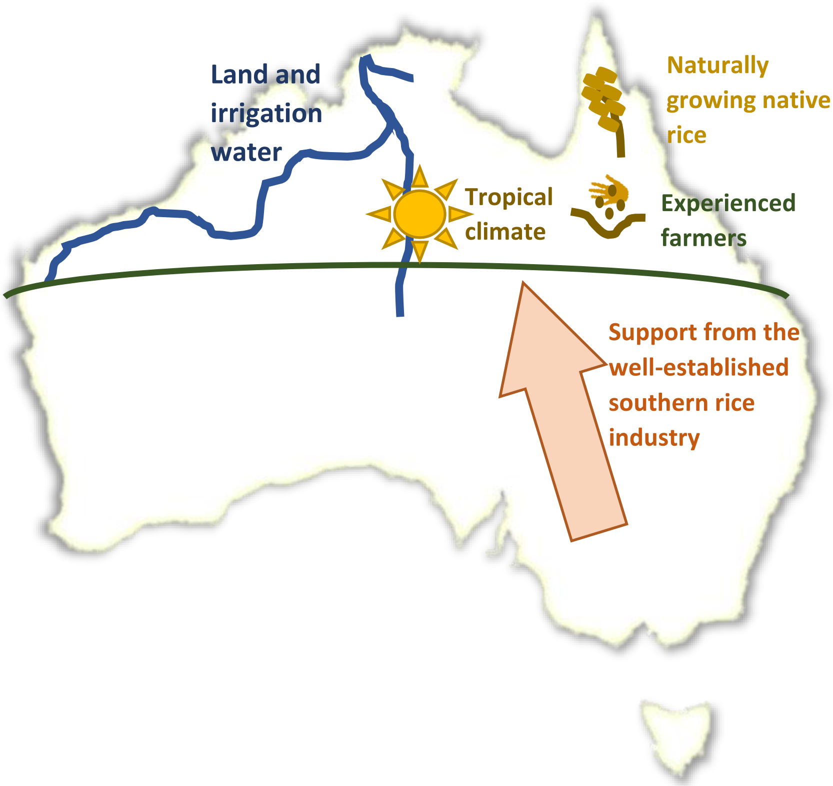


Figure 2.3 Key competitive advantages for growing rice in northern Australia.

Opportunities in northern Australia abound from regions with secure and reliable access to land and water, expert farmers and the ideal climate for growing high-value tropical rices (Figure 2.3).

While encouraging and supportive background research and industry development initiatives have already been made in northern Australia, the inception of a sustainable rice industry in northern Australia will require a coordinated, cross-jurisdictional effort between industry (across the supply chain), farmers, government bodies and researchers. Given the appropriate support and resources, it is projected that a successful northern Australian rice industry would offer significant economic and community benefits through the diversification of opportunities to not only farmers, but also to the business and rural and remote communities that support rice farming, processing, transport and marketing.

2.3 Project scope

The development of northern Australia has been a focal point for more than a century and the desire continues unabated (Ash and Watson 2018). Agricultural development has often been a leading aim, and in line with increasing global demand for food, northern Australia's close proximity to expanding Asian markets and political ambition to economically and socially support stable rural and regional communities, there is renewed interest in expanding agricultural initiatives in the north (Ash et al. 2017).

This report is part of the CRCNA's investment into supporting industry operations in northern Australia through industry-led research collaborations. *The focus of this Situational Analysis was to utilise past learnings in conjunction with current research and marketing expertise to analyse three options for developing a northern Australian rice industry.* The Project recommends necessary research, development and extension activities and the most strategic areas for future investment in an effort to ensure that forward progress is industry-focused, goal-oriented and complimentary.

The report is structured to present the detailed SWOT Analysis [Section 4.0], market analysis of rice [Section 5.0], projected industry opportunities around producing domesticated, distinctly northern Australian, and native Australian rices [Section 6.0], the key challenges facing the development of a profitable, socially and culturally beneficial, and sustainable industry [Section 7.0], results of scoping studies on producing northern Australian rice [Section 8.0], and recommendations for the industry moving forward [Section 9.0]. A background review of the rice industry in Australia, with a focus on northern Australia, is provided in Appendix 1.

3 Approach and Methodology

To address the objectives of the Project, the following activities were carried out:

1. Evaluation of the current needs, opportunities and challenges for a northern Australian rice industry through thorough SWOT analysis;

2. Background literature review of rice production in northern Australia;

3. Assessment of the current rice industry;

4. Scoping studies to identify more detailed needs, opportunities and challenges for northern Australian rice production;

5. Development of strategic recommendations for industry development.

3.1 Multidisciplinary SWOT analysis of the best pathways for the development of a rice industry in northern Australia

Three different categories of rice were considered to be feasible options for growth in northern Australia, each with different advantages and challenges: wild rice, domesticated rice, and the intermediate option that combines the most valuable traits of both into new intermediate 'distinctly northern Australian' rice varieties. In order to organise the most important industry concerns, and how the different options would be expected to perform against those criteria, a team-wide analysis of the strengths, weaknesses, opportunities and threats (SWOT Analysis) was developed. The analysis was developed based on extensive insight and discussion among team members, who stemmed from across the growing and production supply chain, in addition to rice researchers and variety developers [see List of Contributing Participants].

The SWOT analysis identified and explored potential technical and commercial risks, as well as knowledge, agronomic and infrastructural gaps. It also forecasted market demand and production value. The analysis identified and highlighted opportunities for the industry to distinguish and differentiate itself for improved market position, and so as not to compete but instead align with the southern Australian rice industry. The analysis was used as a foundation for developing the strategic recommendations for the industry.

3.2 Background literature report on the history of rice growing in northern Australia

A literature review [Appendix 1] was conducted to summarise previous attempts at growing rice in Australia and forecast the sectoral climate that the new northern industry would be entering into. The review covered certain global and Australia-wide considerations, but maintained a predominant focus on northern Australia. The substantial review included information gained from over 100 peer-reviewed journal articles, scientific books, industry development reports, governmental publications, grey literature and national and international industry/organisation websites.

The review was used to mine information and gather useful insight from previous attempts and experiences at growing, processing and marketing wild and domesticated rices in Australia. The literature review highlighted numerous challenges that previously affected or halted rice production in regional northern Australian locations. This historical background information was considered and utilised for the development of strategic recommendations for the forward progress of the industry.

3.3 Market analysis

Although it has been a focal area for decades, many initiatives for developing the north have failed. One of the common factors that was identified across unsuccessful initiatives was that market analyses were insufficient for truly identifying and understanding industry needs and demand (Ash and Watson 2018). Therefore, market analysis was a major consideration in this project. The market analysis included a literature review and consultation of statistics and documents from international specialised food and agriculture agencies (e.g. Food and Agriculture Organization of the United Nations). SunRice, one of Australia's largest branded food companies with an established network of rice distributors across Australia, New Zealand, the Pacific, SE Asia and the Middle East, was also heavily consulted.

Market analyses of rice are highly complicated because of the vast array of rice varieties (which are generally not separated for analysis) and the various processing and packaging methods (e.g. paddy, brown, husked, milled, parboiled or broken rice). Furthermore, the end weight of rice products varies according to variety, cropping area and the type of machinery utilised during the harvesting, processing and packaging stages along the commodity chain, with losses of as much as 37% observed (Bhattacharjee et al. 2002). Difference in rice producing seasons across the globe also complicate comparisons; the first month for recording the rice campaign in Thailand is January, April in India, and July in Pakistan (Giraud 2013). This analysis concurs with Giraud (2013) in that comparison between market values — especially between public and private sources for the same year and same country —presents significant discrepancies in values, and there is a substantial paucity in detail from recent data.

3.4 Native Australian rice scoping trials

Several scoping trials for native Australian rice were conducted for the purpose of this project. This included testing of collection and biodiscovery processes, planting small plots to test cultivation methods for native Australian rice in northern Australia; and harvesting and processing wild rices. The timeframe and resources of this situational analysis project meant that small-scale growing/harvesting trials were only possible over a single growing season.

3.4.1 Testing the regulatory framework

The complexity and challenges of working within state/territory, Commonwealth and international access and biodiscovery frameworks has been identified as a significant hurdle to biodiscovery and the integration of beneficial new traits and characteristics into agriculture practice. This project aimed to develop permits and test access and benefit sharing frameworks in the context of native rices. Directed effort were put towards advancing organisational (e.g. The University of Queensland, Charles Darwin University), state/territory and federal Australian legislation in line with global biodiscovery laws.

3.4.2 Wild harvest

Queensland:

Collection: Populations of wild rice (Taxon B) were naturally growing in wetlands, creeks, lagoons and dams at Olive Vale Station (Figure 3.1). Samples of this rice were collected by hand in late April/early May 2019.

Milling: A sample of the hand-collected wild rice (Taxon B) was sent to SunRice's mill in the Burdekin (Brandon, QLD). The sample was put through a laboratory-scale replica of a standard commercial mill, which utilised the same technology as other Australian commercial rice mills.

Figure 3.1 Searching for wild native Australian rice in north Queensland. Photo: Heather Smyth

3.4.3 Northern Australia rice trials

Planted wild rice: In order to test the commercial potential of growing wild rice, a small plot of native Australian rice (Taxon B) seed that had been collected previously from north Queensland was planted at Olive Vale Station (Laura, QLD). The seed was spread on 16 January 2019 into a 3 m^2 plot that had been set up formerly for domesticated paddy-based rice varietal trials. Approximately 30 g of seed was sown at a rate equivalent to 100 kg/ha. The plot allowed for a degree of ponding in a controlled area and the rice was initially spread in 150mm of pooled water. The seed was spread in a way that was intended to mimic wild growth, where rice sits in the low-lying areas that pool water and hold it for longer after rainfall events.

3.4.4 Sensory studies of northern Australian rice

Before use in rice breeding, it is essential to first understand the eating and cooking properties of Australian wild rice, as these are key factors in determining rice quality and consumer acceptance. Samples of Australian wild rice (Taxon B) were evaluated alongside a commercial Canadian wild rice (*Zizania aquatic* L), *Oryza sativa* L.cv. Nipponbare, and seven other commercial rices including long grain, medium grain, basmati, red basmati, and red rice. The cooking profiles were established, physical traits (grain size and shape) were measured and conventional descriptive analysis techniques were used to compare the sensory properties of unpolished ('brown') rices. Twenty-six descriptors, such as aroma, flavour, texture and aftertaste, together with definitions, were developed and assessed with a panel of 12 experienced assessors. The full methodology and results can be found in Tikapunya et al. (2018).

Comparative analysis of polished ('white') Australian native Oryza Taxon B samples were scheduled for assessment in early 2020. However, due to uncontrollable circumstances associated with the COVID-19 pandemic, these trials had to be postponed. The results, when available, will be added as a supplementary document to this report.

3.5 Development of recommendations

A set of recommendations were developed to aid the continuing progress towards a commercial rice industry in northern Australia. These recommendations were designed to consider economic growth opportunities for the north, encourage Indigenous enterprise and training, and the sustainability of a new industry that would meet future market demands and trends. Based on the findings from the background research, SWOT Analysis and scoping trials, as well as team discussions of potential opportunities for growth, which included market analysis, resource status and logistic supply chain, recommendations for immediate and long-term industry development projects were developed. Recommended high priority policy, financial investment and research and development issues facing the industry were identified for all stakeholders with an interest in progressing a northern Australia rice industry.

4 SWOT Analysis of Rices for Commercial Growth in Northern Australia

SWOT analyses of four potential options for rice production in northern Australia (wild harvest of native rices, cultivation of native rice, the development of intermediate ‘novel northern Australian varieties, and growing existing domesticated Asian varieties) were conducted (Tables 4.1 – 4.4). As an established northern Australian rice industry does not presently exist, all strengths, weaknesses, opportunities and threats are projected based on current understanding and past learnings of producing rice products in Australia, and around the world.

Table 4.1 SWOT analysis of harvesting wild native Australian rice for commercial production in northern Australia.

S STRENGTHS	W WEAKNESSES	O OPPORTUNITIES	T THREATS
• Uniquely northern Australian • Strong market differentiation (ancient wild grain; exceptional consumer appeal; highly discriminated attributes among other rices, e.g. colour, taste, starch properties) • High market value for wild rices in other global regions (e.g. *Zizania* produced in North America) • Authenticity as a product • Resistant to local pathogens • Organic	• Very low relative market size • Supply volumes small and vulnerable to seasonal impacts • High cost of harvest • Difficult to process • Product to supply a niche market • Presently reliant on harvesting by hand	• Very high relative product value • Indigenous employment and enterprises options • Ethical branding through compliance with the most stringent international access and biodiscovery frameworks • Unsaturated market • Value-add through Indigenous connection to product • Increased attention and social/economic benefits of harvesting native rice could lead to biodiversity and environmental awareness and greater conservation action • Food tourism opportunities • Public awareness of Australian native rices and their value • Rural development through a new industry	• Access restrictions (land and legislative, e.g. under the Biodiversity Act) • Government/Indigenous regulation/compliance regulations • Easy release of seed (shattering) causing difficulty in collection and loss in yield • Natural predation by floodplain vertebrates could potentially affect supply • Depletion of wild stocks • Variation in when the seed is ready to harvest between plants in an area (asynchronous maturation) • Potential environmental impact of removing an important food source that underpins the floodplain food chain • Potential market resistance/ market unpredictability • Biosecurity risk in moving parts of the plant/farming/harvesting equipment between rice growing regions (which could facilitate the transfer of diseases or weeds) • Habitat variability (seasonality)

Table 4.2 SWOT analysis of cultivating native Australian rice for commercial production in northern Australia. NR, unmodified native rice; NSNR, introgressed non-shattering native rice.

S STRENGTHS	W WEAKNESSES	O OPPORTUNITIES	T THREATS
• Uniquely northern Australian • Strong market differentiation (ancient wild grain; exceptional consumer appeal; highly discriminated attributes among other rices, e.g. colour, taste, starch properties) • High market value for wild rices in other global regions (e.g. *Zizania* produced in North America) • Resistant to indigenous pathogens • Greater consistency in product quality • Greater consistency in supply • Can be protected from predators through standard crop protection practices • Reduced logistics (compared to wild harvest) • Reduced pressure on wild rice resource and natural environments • Non-shattering (NSNR) • Higher yield (NSNR) compared to unmodified native rice	• Low (NR) to medium (NSNR) relative market size • Germination difficulty (possible) • Increased agronomic costs from growing a new, non-domesticated species (NR, NSNR), and because of the potential for high grain loss to lose grain (shattering) (NR) • Difficult to sow, harvest (NR) and process • Not organic (possibly) • Lower genetic base	• High relative product value • Indigenous employment and enterprises options • Ethical branding through compliance with the most stringent international access and biodiscovery frameworks • Unsaturated market • Value-add through Indigenous connection to product • Broader markets from extended growing regions and potentially less expensive product due to reduced costs throughout the supply chain (compared to wild harvest) • Rural development through a new industry • IP/Plant Breeders Rights revenues (NSNR)	• Potential market resistance/ market unpredictability • Difficulty in finding and transferring the desirable non-shattering trait (NSNR) • Government/Indigenous regulation/compliance regulations • Biosecurity risk in moving parts of the plant/farming/harvesting equipment between rice growing regions (which could facilitate the transfer of diseases or weeds) • Natural predation affecting supply (possibly manageable) • Easy release of seed (shattering) causing difficulty in collection and loss in yield (NR) • Variation in when the seed is ready to harvest between plants in a single region (asynchronous maturation) (NR, in particular) • Disease susceptibility • Potential loss of Indigenous participation (NSNR)

Table 4.3 SWOT analysis of developing and growing novel disease resistant and 'distinctly northern Australian' rice varieties for commercial production in northern Australia. NNAR [novel northern Australian rice], domesticated Asian rice varieties crossed with native Australian rice to combine the traits of interest [see Table 6.1] from both types, creating highly desirable, uniquely northern Australian rice varieties; DRR, domesticated Asian rice varieties crossed with native Australian rice for disease resistance traits only.

S STRENGTHS	W WEAKNESSES	O OPPORTUNITIES	T THREATS
• High (DRR) to very high (NNAR) relative market size • Desirable agronomic traits (NNAR) • Designer rice/brand discrimination (NNAR) • Uniquely northern Australian • De-risked production (DRR) • Maximised agronomic attributes	• Time required for breeding • Few discriminating characteristics to other rices already produced around the world (DRR)	• IP/Plant Breeders Rights revenues • Unsaturated market • Rural development through a new industry • Broader markets from extended growing regions and potentially less expensive product due to reduced costs throughout the supply chain (compared to wild harvest) • Potential for multiple growing seasons per year and within existing crop rotations	• Low (DRR) to medium (NNAR) relative product value • Attributes not found desirable in end product (NNAR) • Unknown market • Government/Indigenous regulation/compliance regulations • Biosecurity risk in moving parts of the plant/farming/harvesting equipment between rice growing regions (which could facilitate the transfer of diseases or weeds) • Climate variability • Potential competition with southern Australia industry (DRR) • Global competition (DDR)

Table 4.4 SWOT analysis for growing established, unmodified domesticated Asian rice varieties for commercial production in northern Australia.

S STRENGTHS	W WEAKNESSES	O OPPORTUNITIES	T THREATS
• High relative market size • Available and ready to grow now • Already has market acceptance/demand • Diversification of existing Australian production systems • Potential to be a premium tropical Australian product	• Few discriminating characteristics to other rices already produced around the world	• Risk mitigation for Australian rice production due to recent impacts of water security and drought on southern Australian production • Rural development through a new industry • Potential for multiple growing seasons per year and within existing crop rotations	• Very low relative product value • Disease susceptibility • Potential for competition (or perception of competition) with the southern Australia industry • Government regulation/compliance regulations • Biosecurity risk in moving parts of the plant/farming/harvesting equipment between rice growing regions (which could facilitate the transfer of diseases or weeds) • Global competition • Climate variability

5 Market Analysis

5.1 Rice market

Rice is produced and consumed in large quantities worldwide (more than 700 million tonnes of paddy rice, or 500 million tonnes of milled rice, per year) (Muthayya et al. 2014). Around 80% of the rice produced, and sometimes more, is utilised for human consumption (FAO 2018). Rice consumption in Australian has risen with increasing globalisation of diets and has reached 13 kg per person per year (Samal and Babu 2018) (Figure 5.1). Considering the growth of the Australian population, this indicates a domestic demand of only around 350,000 tonnes per year. This analysis suggests that the domestic market, although important, is very small relative to the potential export market.

43 **million tonnes** of milled rice is ***imported*** globally per year

The Australian rice industry instead has a strong export focus with 80-90% of production exported in years when larger crops have been produced. Exports have largely gone to Asia and the Pacific.

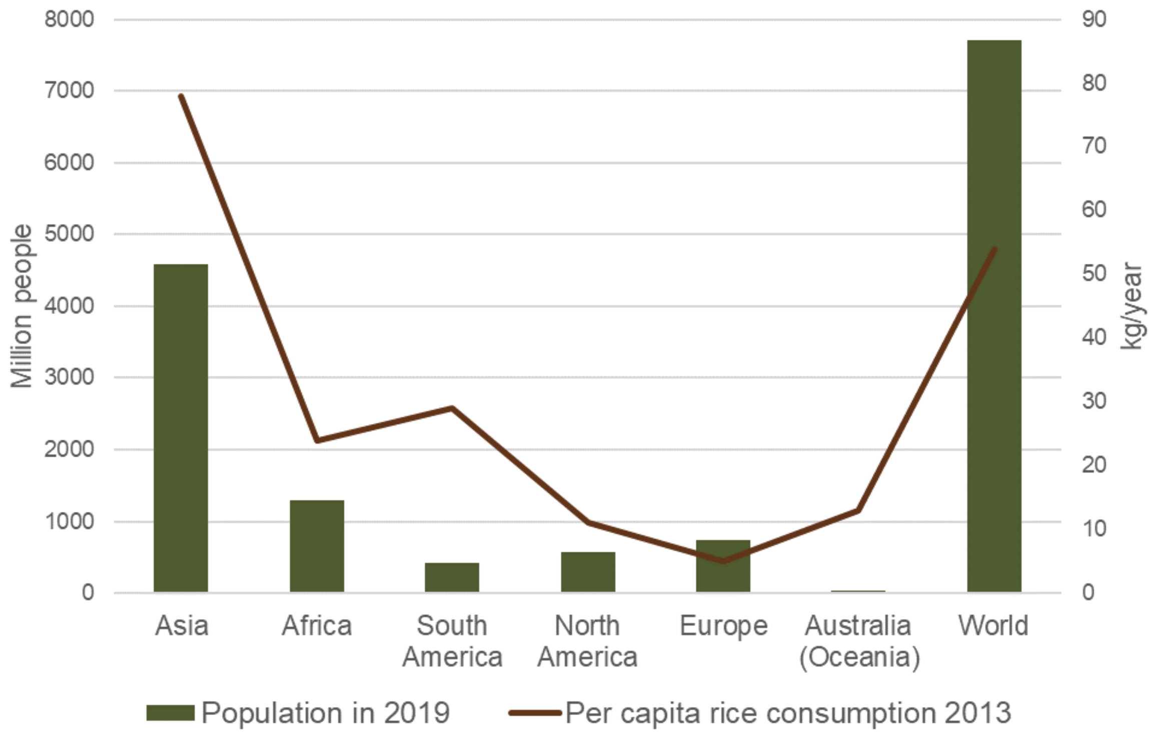


Figure 5.1 Population and rice consumption per capita. Sixty percent of the world's population lives in Asia. Rice consumption (per capita) is also more than 2.5x higher in Asia than in any other continent of the world. While a domestic market exists for Australian-grown rice, the greatest market potential lies in export production. Population data sourced from Kiprop 2019; rice consumption statistics sourced from the FAOSTAT database, as reported in Samal and Babu (2018).

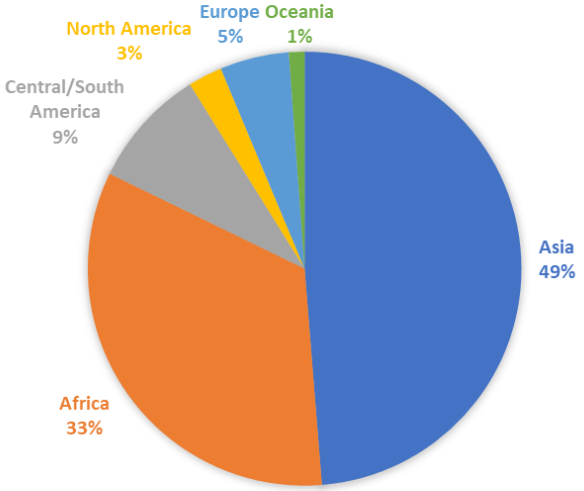


Figure 5.2 Percentage of the average (2013-2016) annual 43 million tonnes of milled rice imported per region. Data sourced from the FAO Rice Market Monitor (FAO 2018).

Top 10 Rice Importing Countries
(million tonnes of rice imported per year, milled)*

1. **China (6.4)**
2. **Nigeria (2.7)**
3. **European Union (1.7)**
4. **Iran (1.4)**
5. **Saudi Arabia (1.4)**
6. **Côte d'Ivoire (1.3)**
7. **Philippines (1.3)**
8. **Senegal (1.3)**
9. **Iraq (1.1)**
10. **Malaysia (1.0)**

* Annual average from 2013-2016. Data sourced from FAO 2018.

While Australian rice consumption is relatively low, people in Bangladesh, Lao People's Democratic Republic, Cambodia, Vietnam, Myanmar, Thailand, Indonesia and the Philippines consume more than 110 kg per capita annually (FAO 2013). Some African countries also report similar per capita quantities (Muthayya et al. 2012). An average of 43 million tonnes of milled rice is imported across the globe per year and China alone imports approximately 6.6 million tonnes (milled) annually (FAO 2018) (Figure 5.2). Global rice consumption is projected to increase 13% by 2027 (OECD/FAO 2018). Asian countries account for more than 70% of the projected increase in global consumption, primarily due to population growth, and African countries account for 23% of the increase due to income growth and urbanisation driving demand (OECD-FAO 2018).

Global rice consumption by 2027
↑13%

India, Thailand, Viet Nam, Pakistan, Myanmar and the United States are the largest rice exporting countries (FAO 2018). Australian export quantities mirror trends in domestic production. Years with higher production allow for larger quantities to be exported, with associated economic gains. Recent Australian rice production has averaged around 750,000 tonnes per year, and around 80% of that was exported with an economic value of nearly $800 million (Ford 2019).

Around 80% of the rice produced in Australia is medium grain japonica rice (Department of Agriculture, Water and the Environment n.d.). This is primarily due to the fact that the southern Australian climate has high summer temperatures without the humidity of tropical climates, which particularly suits these temperate-climate varieties. The remaining 20% is comprised of long grain indica type varieties (Department of Agriculture, Water and the Environment n.d.). However, long grain and jasmine indica rice varieties make up around 80% of global demand (SunRice 2019), presenting a potential market opportunity for northern Australian rice. In Australia, indica varieties comprise 58% of the Australasian Food Service market (which services restaurants and ethnic retail chains) (SunRice 2019). The demand for these products is increasing, and there is ample room in the market for significantly larger production volumes.

Overall, the market for Australian rice sits at around 130,000 tonnes of indica rice domestically and a further 1,700,000 tonnes internationally (SunRice 2019). In 2017, Australia produced 800,000 paddy tonnes of rice. However, this number was reduced to around 55,000 tonnes in 2019 due to drought and low water allocations in the Murrumbidgee, Murray and Coleambally Irrigation areas (New South Wales and Victoria) (RGA 2019b), clearly showing the potential opportunity for northern Australian rice.

In peak years, when water is plentiful, the southern rice industry (which is presently comprised of approximately 2000 farms with an average size of 400 hectares each; Department of Agriculture, Water and the Environment n.d.) is deemed to have the capacity to produce 1 million tonnes of rice per year (RGA n.d.). In these years, the rice industry generates around $800 million in revenue per annum, with around $500 million of this coming from value-added exports (RGA 2019b). It is widely accepted that the southern rice industry alone is not capable of keeping up with the demand for Australian rice, highlighting the need and market opportunity for sustainable, high-quality, tropical northern Australian rice.

5.2 The value of rice

Understanding the international rice market is complex and valuing products within the sector is difficult for a variety of reasons. These include (1) global trade accounts for less than 10% (48 million tonnes, milled) of total rice production; (2) variability and shortfalls in regional (often small-scale) production results in volatility in rice prices; (3) rice is one of the most protected food commodities in world trade, and as such is governed by various national and international regulations and treaties, and many countries have strict policies and restrictions on rice imports and exports to maximise domestic food security and protect producer prices and income, resulting in major distortions in trade; and (4) the rice trade is highly segmented by rice variety (indica, japonica, aromatic rice), the degree of processing (paddy, parboiled, brown, white rice) and the degree of milling (percentage of broken rice) (Muthayya et al. 2014). Predicting future prices and volumes is further complicated by climate change, water availability and rapidly evolving technology, which can greatly affect yield and supply. The most frequently used export price to represent the market is for Thai 5% broken, FOB Bangkok (Muthayya et al. 2014). The price of this rice has averaged around A$500 per tonne (FOB Bangkok)

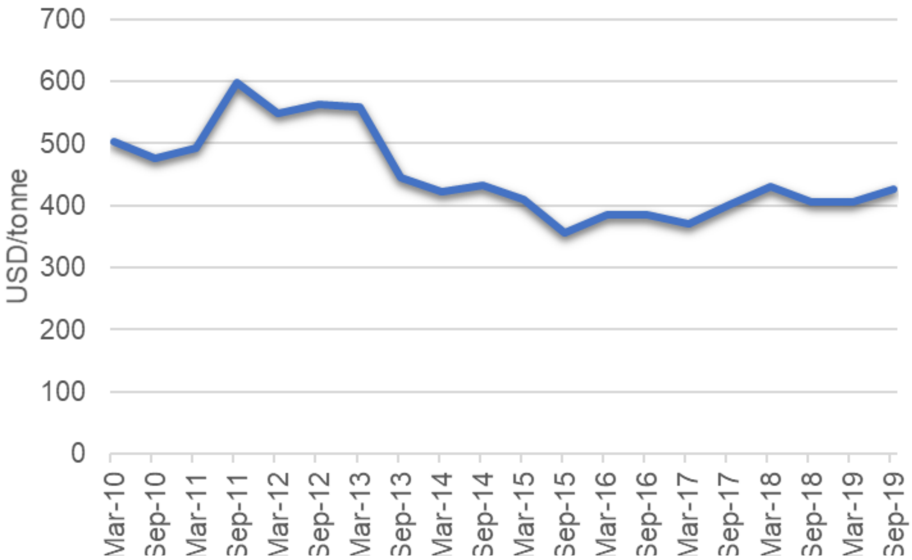


Figure 5.3 Trend in the price of rice over the past decade. Price (in US dollars, government standard, FOB Bangkok) based on Thai-grown 5% broken milled white rice. Data sourced from index mundi (n.d.).

over the past 10 years but rose to around A$800 per tonne in March 2020 (index mundi n.d.) (Figure 5.3).

5.3 Quality factors of rice

To be successful in current and future markets, new (and existing) rice varieties will require strategic breeding procedures that combine important agronomic features with the demands of target consumers for specific quality attributes and consumer acceptance (Calingacion et al 2014). Grain quality is the single most important factor in the determination of rice marketability (Fitzgerald et al. 2009; Concepcion et al. 2015), and grain quality is primarily measured by the percentage of broken grains (Giraud 2013). The average difference in Thai and Viet varieties of rice with <5% broken grains compared to <25% broken grains between 2013 and 2017 was US$18.60 and US$23.20, respectively, or 4.4% and 6.2% of the export price (Figure 5.4). Market acceptance is also determined by continued access to the product (Cardello 1995; Moskowitz 1995; Grunert 2005; Concepcion et al. 2015).

Aromatic rice cultivars, such as basmati and jasmine, constitute a small but special group of rice and are considered to be the best in terms of quality and aroma (Aljumaili et al. 2018). While the vast majority of rice is bought specifically as a food staple related to food security, fragrant rices are premium products for niche markets (Giraud 2013) (Figure 5.4). Price volatility (Figure 5.3) is intrinsic for course rice due to harvest variations and persistent high domestic demand in the main rice producing countries, but for fragrant rice, high price is more standard due to stable increase in demand from rich importing countries (Giraud 2013).

Organically grown rice typically attract prices up to 50% higher than conventionally produced products (CBI 2017).

Niche varieties, whether they revolve around aroma, health benefits, or simply that they contain something unique all provide a point of difference in the market.

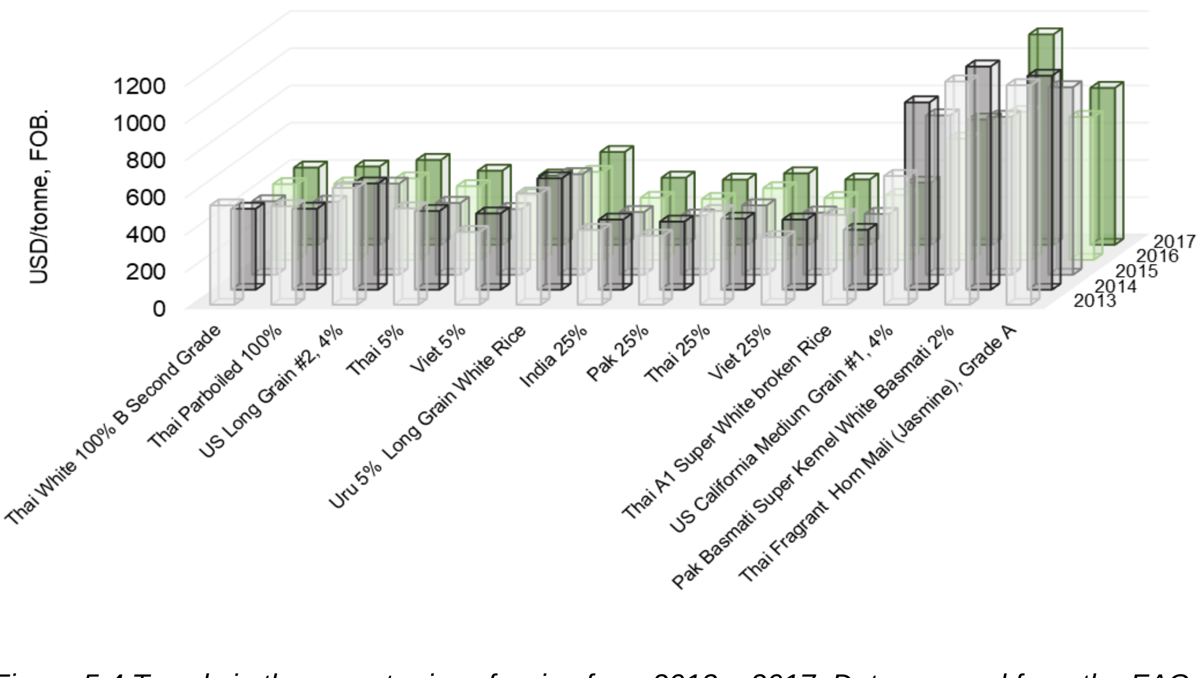


Figure 5.4 Trends in the export prices for rice from 2013 – 2017. Data sourced from the FAO Rice Market Monitor (FAO 2018).

5.4 Niche markets

5.4.1 Fragrant rices

Fragrant rices comprise just over 7% of global rice production and 15-18% of the global rice trade (Giraud 2013). Despite the variability in agricultural commodity prices over the past decade, fragrant rices have been reliably strong and are regularly the highest priced sector within the world rice market (Giraud 2013). Basmati trade peaked in 2008 with a record of 2.45 million tonnes (milled) (Giraud 2013). The value of fragrant rices on the world market are generally around double that of course rice. In 2012, fragrant rices were priced on the world trade market at USD $1,050 per metric tonne or more, while course white rice was USD $440-$580 per tonne (FAO 2012). Jasmine rice tends to attract higher prices than basmati, but it is heavily influenced by export market values, as ironically, it is not a staple of the local Thai diet (Giraud 2013). Due to their special niches and markets, jasmine and basmati rices are not considered to be direct competitors of each other, or of course rices (Giraud 2013).

To ensure premium value, fragrant rices must be characterised as superfine grain and have a pleasant but subtle aroma when raw and cooked (Giraud 2013). In basmati, this stems from the presence of 2-acetyl-1-pyrroline (2-AP) (Giraud 2013).

The high value of basmati rice has led to the incorporation of non-basmati rice as filler. In about 10% of cases, the non-basmati portion was more than 60% (Burns et al. 2004 in Giraud 2013). As such, authentication of fragrant rice has become a relevant topic and traceability of products throughout the supply chain is important (Giraud 2013). With crossbreeding and hybridisation of fragrant rices around the world, the questions of what constitutes true fragrant lineages (and what can be branded as 'fragrant') and the role of geographical indication (GI) are also becoming relevant (Giraud 2013). The gene for fragrance in rice was discovered and characterised in the Australian laboratory of Robert Henry (Bradbury et al. 2005). This discovery has allowed fragrance to be rapidly assessed in rice breeding and has significantly reduced the cost of breeding new fragrant varieties, saving around $1 million per variety. This innovation has also provided robust tests for fragrant rice adulteration.

5.4.2 Health foods

In general, milled domesticated rice is a poor source of vitamins and minerals (Muthayya et al. 2014). However, nutritional improvements in crops is an important goal in agriculture, broadly (Liu et al 2018) and health foods comprise an extremely high value market. The global health and wellness food market is projected to increase from US$707.12 billion in 2016 to US$811.82 billion in 2021 (Shahbandeh 2019). Increasing health challenges, such as diabetes, heart disease and obesity associated with a diet high in starch rich cereals such as rice, mean that added health benefits in rice (such as low amylose content) are also popular in more mainstream varieties. A variety of diverse measures have, and continue to be, developed and implemented across the rice production chain to improve the nutritional characteristics of rice products. These include strategies such as parboiling the rice, which involves soaking and partially steaming the grains before drying and milling to retain some of the B vitamins (Muthayya et al. 2014); increasing the number of aleurone cell layers to retain lipid, protein, vitamin, mineral and fibre content (Liu et al. 2018); and fortification during growing stages by adding bioavailable vitamins and minerals (Muthayya et al. 2014).

The utilisation of wild rice is gaining popularity among consumers, and North American native *Zizania* spp. are now grown and commonly available in the North American supermarkets and restaurants (Aladedunye et al. 2013). *Zizania* has a wealth of nutritional qualities. For example, general γ-oryzanol content was approximately double in *Zizania palustris* compared to regular brown *Oryza sativa* L. rice (Aladedunye et al 2013). γ-Oryzanol is the primary contributor of many of the observable health benefits of rice and rice products (Lerma-Garcia et al. 2009). It has been shown to possess antioxidant, anti-inflammatory, anti-tumor, and hypocholesterolemic activities (Yasukawa et al. 1998; Akihisa et al. 2000; Berger et al. 2005;

Juliano et al. 2005; Wilson et al. 2007). Market prices for *Zizania* couldn't be sourced; however, a retail price comparison via Amazon.com [16.04.2020] of United States cultivated wild rice and United States-grown brown rice indicated that wild rice sells for nearly five times that of brown rice.

Australian native rices are known to have unique starch properties including high amylose content, and more specifically, short chain amylose structure in *Oryza australiensis* (Henry 2019). High amylose rice contains slowly digestible starch, resulting in the potential for them to be marketed as low GI. Low GI branded rices (e.g. SunRice Low GI Clever Rice, long grain) retail for more than double that of standard long grain white rice (Figure 5.5). While the full suite of nutritional characteristics in the grain of Australian native rice species is not yet known, a similar elevated market spot is expected for these wild rices. Indeed, Australian wild rice has the potential to retail from at least $5.00/100 g to restaurants to up to $20.00/100 g in 'attractively labelled and culturally identified small sample packets' for tourism markets (Wurm and Bellairs 2018) (Figure 5.5).

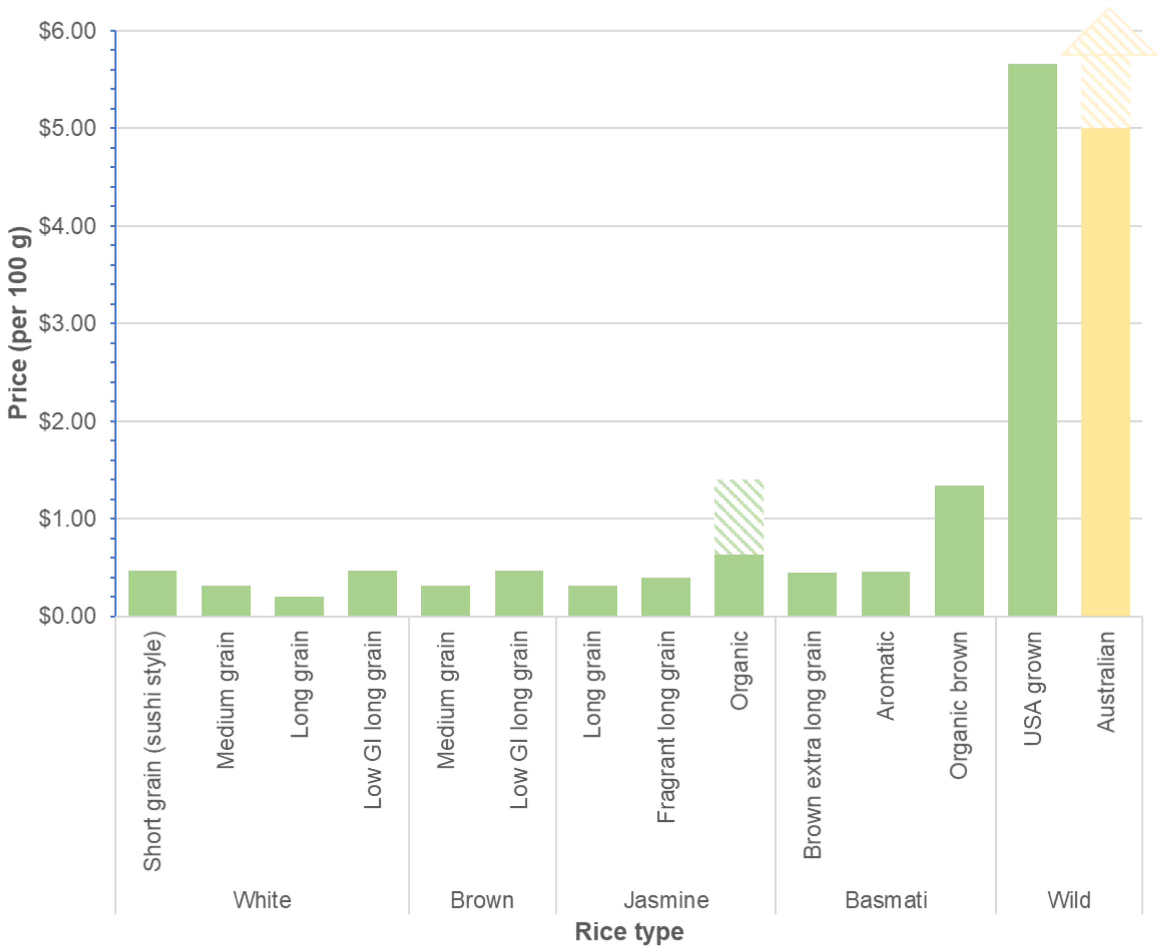


Figure 5.5 Current retail values of the different rice types commonly sold in Australia and the potential value of wild harvested native Australian wild rices. The range in value of organic jasmine rice stemmed from the difference between different suppliers (Woolworths versus Naked Foods Organic & Health Foods). The price range of Australian wild rice was sourced from Wurm and Bellairs (2018). Full details of the products used for this evaluation can be found in Appendix 2.

5.4.3 Coloured rices

Rices are typically 'coloured' by anthocyanin pigments in the bran layer of the grain, and these are rich in phytochemicals and antioxidants (Rathna Priya et al. 2019). The demand for brown and wholegrain rice has been increasing for several years and there is a growing opportunity for niche rice varieties, such as red and black rice (CBI 2017). Black and red rices are generally priced around 3-5 times higher (€ 3–5 per kg) than regular white rice (€ 1 per kg) and wild rice has an exceptional value in retail of 10-20 times that of white rice (€ 10–20 per kg) (CBI 2017).

6 Opportunities for Growing Rice in Northern Australia

Although limited rice production has been attempted in northern Australia, the Australina rice industry, including domestic and export markets, is well-established. The century of efforts made in southern Australia provide an excellent foundation for shifting production to the north. The north also boasts a range of notable advantages for growing rice.

Suitable production temperature The current temperate rice industry in Australia produces rice in the summer, and even then is sometimes impacted by cool weather. Rice production in northern Australia may be possible all year round because of the higher temperatures.

Water availability The availability of irrigation water for rice in the Murray-Darling system has become more limited due to competition from perennial crops such as grapes and almonds. Climate change is predicted to make water supply even less reliable in this region. In contrast, the northern Australian wet season may support a rice crop in many areas of northern Australia.

Land availability Areas suitable for rice production are found in Queensland (e.g. Burdekin, Tully, Atherton Tableland, Cape York and the Gulf), the Northern Territory (e.g. Adelaide River floodplain and Katherine) and Western Australia (e.g. Ord River Irrigation Area).

Varieties High value aromatic rice varieties are attractive targets for production in northern Australia. Available varieties from Asia or southern Australia have been grown successfully in northern Australia in recent years. The selection or breeding of rice varieties more suited to northern Australia can be expected to result in significant increases in yields over the next 5-10 years. Native Australian rices also naturally grow in various locations across northern Australia.

Three different options appear to be viable for growing rice in northern Australia: growing domesticated rice varieties; growing novel northern Australian rice varieties, and commercially cultivating or wild harvesting native Australian rices. Strategic opportunities exist for growing domesticated rices, including aromatics and soft cooking long grain rice, as well as producing rices targeted at health food markets, including coloured grains and crosses with wild-type, and organic products (see SWOT analysis). Jasmine rice is currently the only fragrant rice grown in Australia, but the tropical climate of the north may allow for other fragrant rices to be produced. Tropical regions of Australia are ideally suited to the production of high-quality speciality rices. Furthermore, the prospect of wild-harvesting and cultivating native rices boasts the potential for extremely high-value products for niche markets. The northern Australian rice market will likely blend a mix of rice types and varieties.

As global populations, and consequently the need for more food calories, continues to increase, so will the need for food staples, like rice. Additionally, economic growth in Asia is expected to lead to a greater demand for higher-value rice from western cultures. However, the land available for rice production is at a premium. The worlds growing population means that agricultural land is being lost to urbanisation and other human commodities. As an example, the increasing demand for food combined with the increasing scarcity of water means that Indian farmers may be forced to grow high yielding varieties across smaller areas instead of highly popular and high-value (but low-yielding) specialty basmati rice (Giraud 2013). In this regard, Australia has a distinct advantage. Already, Australia has the potential to produce enough rice annually to feed more than 20 million people, 365 days a year (RGA 2019a). Yet, the county still has ample area available for cropping, and parts of this area could be well-suited to rice production. Rice is native to northern Australia, and several distinct, wild rices naturally grow in the country's northern tropics. This, along with a variety of the region's other attributes, such as its close proximity to Asian markets, suggests that northern Australia has the potential to become a global tropical rice powerhouse (SunRice 2019) with the capacity to meet the desires of multiple global markets.

Australian rice already holds a number of accolades in productivity, efficiency and sustainability leading to a world-renowned 'clean, green' reputation. Rice that could also include a cultural and/or provenance 'story' to its development would add to these current market advantages. The development of a successful northern Australian rice industry would allow for ongoing supply to current key Australian and New Zealand markets, and potentially also Australia's established markets in the Pacific, SE Asia and the Middle East. Without the northern industry, and in the context of the environmental struggles currently faced in the southern regions, these markets will fall to overseas suppliers and Australia will be largely reliant on imported rice.

Past learnings around challenges and opportunities across the value chain for new irrigated agricultural developments in northern Australia have shown that, due to the large expanses and remoteness of much of the region, financial returns are generally only positive for high value/specialist niche crops or for industries that have local processing facilities (Ash et al. 2017). Thus, the opportunity for northern rice production revolves around high-value characteristics, or unique niche varieties, that can fetch premium prices in both domestic (including regional) and global markets. Opportunely, tropical regions of Australia are ideally suited for the production of high-quality speciality rices (Sivapalan 2016). Speciality attributes, such as aroma, grain appearance and flavour, are far superior when they are grown in tropical environments (Sivapalan 2016). Branding that accentuates that products have been grown in Australia, and potentially northern Australia specifically, will immediately add value in Asian markets. Other traits that may be targeted to improve value are grain size, colour and starch content: all of which may be derived from cross-breeding hardy domesticated varieties with native Australian rices. The key to achieving a place in high-value niche markets is through detailed understanding of what consumers really want, in terms of both sensory and health profiles.

Rice has the potential for high returns to northern Australian growers and significant additional rural employment opportunities (Sivapalan 2016). The social benefits of rice enterprises would also include opportunity for new Indigenous enterprises, capacity building that will flow throughout the industry and region, training and education opportunities, new infrastructure and the potential for increased food tourism opportunities.

Statistics from southern New South Wales show that, in terms of employment, for every person directly employed by the industry, four jobs are created through associated activities (Sivapalan 2016). Similarly, for every dollar earned by the industry, $6 is generated in associated activities (Sivapalan 2016). Rice also allows crop diversification, which means less financial risk to the farmers. These figures highlight the social benefits that could also be realised in the north through the establishment of a successful northern rice industry. The more growers who decide to adopt rice growing as part of their crop mixture, the better the chance for a rice industry in tropical northern Australia.

The development of a northern rice industry is expected to be able to contribute at least 100,000 metric tonnes of rice in Queensland, alone, per year within five years. This would equate to more than $85 million per annum into the north Queensland economy (SunRice

2019). Direct payments to growers are projected to reach $45 million over the same time period. The industry would create jobs for farmers, and an estimated 70 jobs at the Brandon Mill (SunRice 2019). Productivity increases are also expected, based on unique new rotational systems that would allow sugarcane and pulse crop farmers to integrate rice into their systems, offering growers an additional source of income throughout the year. Similar opportunities are expected in the Northern Territory and Western Australia.

The development of a northern Australian rice industry also presents an opportunity for greater advocacy for improved environmental awareness of Australian native plants and ecosystems, better management of flood plains and national parks, and greater focus on weed control. This could create important environmental, ecological and biodiversity outcomes for the region. Rice grown in raised-bed systems is expected to have minimal impact on ecological sustainability, in line with what has been seen in other field crops grown in the north (Sivapalan 2016). Interestingly, farmer adoption of rice production on the Adelaide River floodplains could present an economically feasible method for the control of mimosa (*Mimosa pigra*) (Sivapalan 2016). Mimosa is the major weed of northern Australian floodplains, and a 'Weed of National Significance' (WoNS). Also, rice under a flooded system could actually contribute to greater biodiversity of aquatic life. Hundreds of millions of spotted grass frogs (*Limnodynastes tasmaniensis*) were produced annually from rice bays in the Riverina Bioregion of New South Wales (Sivapalan 2016). Given that these frogs consume insects, they may control economically important pests of rice crops (Sivapalan 2016). While rice cultivation will inevitably lead to altered landscapes, irrigated systems will result in the seasonal availability of extensive aquatic habitats in previously drier landscapes (Sivapalan 2016).

6.1 Domesticated rices

Australia markets about 800,000 tonnes of milled (domesticated) rice, which is sourced from around the globe. Around 500,000 tonnes of this has been produced in southern Australia; however, Australian production dropped to just 55,000 tonnes in 2019. Northern Australia is currently seen as a support system for domesticated rice production in the south with valuable opportunities in the form of land and the production possibilities of rice varieties that require far less water.

Australians prefer to eat local rice, but there is not enough Australian rice produced to supply even the local market (R. Ford, personal communication). Strategically, continuing with the production of the same (or very similar) domesticated varieties that are currently grown in the south makes sense. The rice seed and market already exists for these products, and the transition for consumers would be seamless.

Trials on anaerobically grown rice in Kununurra (WA) in 2013 found gross margins to be in the range of -$902 to $3725 per hectare, depending on the price of rice per tonne (Sivapalan 2016). At a yield of 8 tonnes/ha, which was considered commercially achievable, the gross margin at $317/tonne was $298/ha. The highest yielding results came from the variety dubbed 'Viet 1', which delivered the equivalent of 14.3 tonnes/ha. At a farm gate price of $317/t, this generated a revenue of over $4533/ha. This revenue compared very favourably with many of the other field crops grown in the ORIA (Sivapalan 2016). Another variety, 'NTR 587', achieved an equivalent yield of 12.5 t/ha.

Domesticated rices, such as long grain and jasmine indica rices, could be an option for exploration, especially as these varieties make up around 80% of the global demand for rice (SunRice 2019). Tropical northern Australia is viewed as an ideal region for growing indica varieties, and regional production values in excess of 100,000 metric tonnes of paddy per year in the next 5–6 years are considered possible and sustainable (SunRice 2019).

6.2 New northern Australian varieties

Possibly the most attractive option for high-value, high-yielding rice production in northern Australia is the transfer (introgression) of genes of interest from native northern Australian rices into the most desirable genes from existing high-quality, agronomically strong and high-yielding Australian domesticated rices. Australian wild rices have evolved independently to all domesticated varieties due to geographic separation and have been exempt from the loss of diversity resulting from gene flow through the large populations of domesticated rices in Asia (Moner et al. 2018). Auspiciously, most of the important genes for commercial rice growth in northern Australia are already in Australian domesticated rice. However, southern varieties do not carry resistance to the, in some cases crippling, pests and diseases found in northern Australia, as they are not found in the south. Consequently, disease resistance is essential, whereas other traits from native rices would just be beneficial for product differentiation.

Fortunately, Australian native species have much to offer, not only in terms of diversity and points of differentiation for marketability, but also through genetic tolerance and resistance to many northern Australian biological threats of economic important (Henry et al. 2010; Waters et al. 2012; Khemmuk 2016). Two of Australia's wild rice species, *Oryza officinalis* and *Oryza australiensis*, have provided resistance genes for rice blast disease, *Pyricularia oryzae*, which is considered to be greatest threat to rice production worldwide (Jeung et al. 2007) [see Section 7.2.1]. *Oryza rufipogon* plants have remained disease-free when challenged with rice tungro disease (Khush et al. 2004; Shibata et al. 2007).

The opportunities for new products that combine traits from native Australian rices with domesticated rice varieties are extensive and could be tailored to meet market demand. The most reasonable starting point would be the introduction of the bare minimum number of native rice traits that would simply increase the survival potential (e.g. disease resistance) of established domesticated species. While the resistance genes for these diseases have not been characterised as yet, this is not seen as a major limitation to the transfer of this genetic material as the most direct way to transfer these traits is through phenotypic (as opposed to genetic) selection. The developmental process, which would be relatively quick and efficient in comparison to selecting for other genetic traits, would involve making crosses of wild and domesticated rice varieties, then exposing the resulting generations to fungal cultures or isolates obtained from specific growing regions in the north (see section 7.2.1). The plants that didn't contract the diseases would then be selected for future breeding programs. Combining desirable quality, yield and stress tolerance traits is complex; however, the availability of new genetic modification tools and strategies in breeding programs means that it is not inconceivable to utilise successful, well-accepted varieties as a platform for carrying new favourable genes (summarised in Concepcion et al. 2015) [Recommendation 1].

Major economic gains can be obtained from disease resistant crops. If pest and disease resistance can be maximised and crops can be grown organically, product value can easily triple and costs for pesticides are negated (R. Ford, personal communication). Even a reduction in pesticides relates strongly to economic gains through reduced production costs. Modelled evaluation of the impacts of successful development and deployment of blast (*Magnaporthe oryzae*)-resistant rice to just the mid-south of the United States showed that producers would gain USD $69.34 million annually and the supply from this region alone would feed an additional one million consumers (Nalley et al. 2016). This is especially significant, given that the United States only produces a small percentage of the total amount of rice produced globally (and generally experiences less loss from rice blast disease than other rice producing countries) (Nalley et al. 2016). Furthermore, disease resistant crops have lower environmental impacts than disease susceptible varieties, due to their reduced use of fossil fuels, potentially toxic/carcinogenic crop protection platforms, eutrophication, acidification, and other harmful side-effects (Nalley et al. 2016). Along with economic gains and farmer security, the development of high-yielding, sustainably produced, disease-resistant rice varieties could play a greater role in societal welfare through advanced measures towards global food security. Rice blast disease is a key concern for global food security since it, alone, accounts for approximately 30% of rice production losses globally; a value that translates to the nutritional needs of 60 million people.

With further effort, more unique and highly differentiated 'distinctly northern Australian' rice varieties could be developed [Recommendation 1]. These could introduce a wide range of the most appealing attributes of native rices into the hardier, more agronomically friendly foundation of domesticated varieties. Newly developed varieites would be expected to produce very high-value specialty rices for niche markets. Market analysis has suggested that the most desirable traits that could be obtained from native Australian rices would focus around grain and eating characteristics, such as grain colour and size and the health attributes of the rice (R. Ford, personal communication).

An assessment of germplasm needs was conducted to consider the traits that could be incorporated and estimate the feasibility of transfer and the likely added value in production (Table 6.1).

Table 6.1 Traits that could be incorporated into novel northern Australian rice varieties, the genes responsible (where known), the feasibility of successful transfer, and the likely added value to production and/or marketing.

Challenge	Trait	Gene responsible (if known)	Feasibility of successful transfer	Benefit to production/ marketing	Key references
Disease resistance	Resistance to the most important potential rice diseases found in northern Australia	Multiple	Moderate–high	Very high — this will prevent major losses due to endemic diseases	Khemmuk et al. 2016
Market appeal (taste)	Eating characteristics	Multiple	Low–moderate	Moderate–high — attractive to consumers	Tikapunya et al. 2018
Market appeal (health)	Health attributes (e.g. starch properties)	Starch metabolism genes	Moderate	High — appeals to consumers	Tikapunya et al. 2017
Market distinction (appearance /colour)	Highly distinguishable visual appeal	Easily screened as phenotype	High	Moderate — appeals to specific consumers	Tikapunya et al. 2016

Furthermore, certain other traits or native Australian rices may present beneficial agronomic opportunities for northern Australian rices. For example, *Oryza australiensis* has the unique characteristic of being able to survive the dry season as a rhizome; whereas other perennial species are only able to survive in areas that are permanently wet (Henry et al. 2010). Adapting rice cultivation to a wider range of environments may be possible with greater utilisation of these Australian wild genetic resources (Henry et al. 2016; Khemmuk et al. 2016).

Figure 6.1 Australian native rice, 'Taxon B'. Photo: Robert Henry

6.3 Australian indigenous rices

There are at least four species of native wild rices in Australia, *Oryza australiensis*, *Oryza meridionalis*, *Oryza rufipogon* and *Oryza officinalis*. As these species are so distinct from commercially cultivated rices, Australian wild rices could present entirely new opportunities for unique and distinct food products (Figure 6.1). Market analysis suggests that wild-harvested native Australian rices could attract values of up to $200/kg (Figure 6.2) (Wurm and Bellairs 2018).

Oryza australiensis is found across northern Australia, as far south as Rockhampton. This species appears to be very divergent from other rices. It grows the furthest from water, even on banks during the wet season, then dies back during the dry season. The grains, which are quite short, also appear to be quite different to other species.

Oryza meridionalis is an annual species that grows in wet areas and survives as seeds during the dry season (Henry et al. 2010). It is the most wide-spread species, existing across northern Australia from The Kimberley to the tip of Cape York. It is high-yielding, naturally producing a lot of grain. It also has a high amylose content, and sensory evaluations suggest it is an attractive product for eating.

Australian *Oryza rufipogon* is morphologically very similar to Asian rices, but quite different genetically. This species is much rarer, but is still found in diverse wet or swampy locations around northern Australia. Little is also known about *Oryza officinalis*, as it has only been found in two remote locations in the north of Queensland and the Northern Territory.

Figure 6.2 Styled native Australian rice. Photo: Jason Wilks

Harvesting wild native Australian rices could provide unique, highly differentiated local products for regional operations. Native rices also present an opportunity for cultivation in new northern Australia environments, which could add additional scope for the marketability of new traits with unique, traceable provenance. Furthermore, as coloured rices, northern Australian wild rices would likely carry desirable health benefits, potentially including compounds that help to counteract obesity and act to supress cancer cells (AgriFutures Australia 2018, p. 50).

Compared to indica and japonica rices, the Australian native rices *Oryza australiensis*, wild rice Taxon A and wild rice Taxon B had higher amylose content, a larger proportion of shorter amylose chains and a lower proportion of amylopectin chains, which resulted in high gelatinisation temperature. This also suggests that products from these species could be marketed as high-value, low-GI foods. *Oryza australiensis* flour exhibited the lowest pasting properties. Taxon A exhibited a lower pasting viscosity, while taxon B exhibited a similar pasting viscosity but lower final viscosity. The significantly different molecular structure to domesticated rices, and concomitant different cooking, nutritional and sensory properties, suggest potentially advantageous uses of native Australian rices for certain processing purposes in value-added products, such as rice crackers and rice pudding. Functionally, these wild rices may provide a good source of slowly digestible starch.

In terms of taste, unpolished ('brown') Australian wild rice (Taxon B) has a mild aroma and flavour similar to that of red rice and red basmati, but without a lingering aftertaste (Tikapunya et al. 2018). Australian native rice is firmer, and somewhat crunchy and chewy, rather than soft and fluffy, despite requiring a longer cooking time. It has a distinct mid-red colour. Overall, the sensory, physical and cooking profiles indicate that Australian native rice has a high potential for commercialisation in itself, particularly in the coloured rice market (Figure 6.3).

Figure 6.3 Rice samples prepared for sensory evaluation. Photo: Heather Smyth

The concept of commercially producing low-volume, high-value, culturally identified wild rices is not new. Enterprises in both Canada and the United States exist for *Zizania* spp. The United States has also developed higher-volume, lower-value options for these varieties. Consultation with these industries could provide valuable lessons for commercial Australian native rice opportunities.

6.4 Industry opportunities and value-adding

Growing, harvesting, processing and marketing rice has the potential to open up myriad jobs in rural and remote northern Australia. Australia is an established producer of rice with well-recognised, world-leading methods. The foundations and support for the industry are already in place; what is now needed is a broadening of growing regions and the recruitment of rice farmers in the north [Recommendations 3, 2].

The development of a productive, high-value, globally reputed northern Australian rice industry is projected to provide substantial benefit to the prosperity of northern Australia, including the generation of wealth, a driver of economic growth and the creation of jobs, wages and support for the livelihood of many across the supply chain. As with other northern Australian agriculture industries (QEAS 2019), this relates broadly to both upstream and downstream jobs, including mill and transport operators; ports; planting and harvesting contractors; fuel distributors; fertiliser and chemical retailers; farm machinery retailers; irrigation equipment suppliers; and accountants and insurance brokers.

Indigenous communities living on the floodplains of Australia's north have limited options for economic activities. The development of a wild rice industry for high-end bush tucker or gourmet products could provide significant economic, cultural and social opportunities and benefits for these communities (Wurm et al. 2012) [Recommendation 9]. Work within these niche markets could incorporate traditional collection and processing methods, and utilise various parts of the rice plant in different ways for the creation of different products. This sort of creative enterprise within a socio-cultural environment is beneficial for business development and long-term progress (Jarvis et al 2018). If well structured, the opportunities for improved and diversified livelihoods for Indigenous communities may extend beyond jobs within existing communities to potentially also allow for the resettlement of depopulated traditional lands (Barber 2018).

And notably, because these food resources have been exploited by Indigenous communities for thousands of years, traditional methods exist for managing floodplains, collecting and preparing native rices for food. This strong cultural link and long history of attachment to northern land and waterscapes (Barber 2018) will not only help to ensure the sustainability of these (and related) important Australian biodiversity resources, but the story and provenance of the products will increase marketability and product value. Industry raised awareness of native Australian rice resources could also provide additional opportunities for Indigenous communities through employment and contributions to natural resource management (Jarvis et al. 2018). Indigenous land and sea management programs (ILSMPs) are dually beneficial, as they generate both environmental benefits and economic benefits that support Indigenous aspirations and contribute towards the delivery of multiple government objectives (Jarvis et al. 2018).

During an exploration of Australian native rice as a new wild food enterprise, Wurm et al. (2012) received 'expressions of support for future projects and interest in results' from Northern Territory Government (Regional & Indigenous Economic Development unit), North Australia Land and Sea Mangers Alliance (NAILSMA), Tropical Rivers and Coastal Knowledge consortium (TRaCK), an individual Indigenous family and the Northern Land Council (NLC). Opportunities for Indigenous enterprises and engagement with Indigenous communities and regional/state governments will be further explored by the proposed Standing Industry Steering Committee [see Recommendations 2 and 9].

One of the most immediate opportunities for rice production in the north is as an appealing crop option for established farmers who may be looking to diversify, reduce risk and/or improve farm profitability through a cropping option for sugarcane fallow (uncultivated) periods. Many north Queensland communities are reliant on sugarcane production for wealth, jobs and the livelihoods of community members (QEAS 2019). However, the sugar industry is facing major threats due to decreasing values in sugar products. Over the past five years alone, the gross value of sugarcane at the mill door dropped 17% (State of Queensland 2018). Global sugar prices are now 'well below' the cost of production, even for producers that utilise the most efficient methods (Pietsch 2019), and continued decreases in sugar value are forecast based on projected surplus production in India and Pakistan (State of Queensland 2018). In line with reduced value, sugar production has shown a net decrease over the past decade (State of Queensland 2018).

Tropical climates can support one, two, or sometimes even three, rice crops per year, depending on rainfall and the availability of irrigation water (Prasad et al. 2017). Rice can also be grown in a cropping cycle, with certain other rotational crops, providing advantages in soil fertility, other environmental benefits, and greater profit margins. For example, in north Queensland, it is recommended that rice be grown in rotation with sugarcane and pulses (e.g. soy bean, mung bean), among other potential crops (SunRice 2019). Adding rice to a sugarcane rotation cycle in Florida (USA) showed that standard sugarcane plantings following a rice crop benefitted through reduced pest management costs, carryover effects to the sugarcane from the silicon used to boost rice yields, and overall, significantly improved sugarcane yields (Schueneman et al. 2001). Rice can also provide farmers with a use for fallow land that generates significant profit and may also improve soil condition and break disease cycles through crop rotation.

Rice is put through a series of processing steps such as drying, milling, and packaging after harvest to be sold for human consumption. The first step of the milling process removes the husk from the whole rice grain or paddy, leaving the whole brown rice grain with an outer (typically brown) bran layer. The second step removes the outer bran layer to give polished or white rice. The bran layers consist of pericarp, aleurone, subaleurone layer, and germ, which contain large amounts of nutrients and bioactive compounds (Saleh et al 2019). The recovery of these by-products can present additional value-added revenue opportunities. The approximate 12 tonnes/ha of rice hay produced as a by-product provides an opportunity for baling rice stubble as cattle feed, which has brought additional income to the value of $150/ha to growers in the Ord Valley (Sivapalan 2016). De-hulling rice on site can also provide a mulch product (rice hulls) for use on horticulture crops. Furthermore, processing the grain on-site, or nearby, can reduce the cost of freight by an estimated 25%.

Rice is also considered a preferred source of grain for intensive cattle feed-lotting, or to use in livestock pellets/cubes. In 2009, $200/tonne was offered for local Western Australia rice grain for stockfeed and $300/tonne for local grain in the Northern Territory (Sivapalan 2016).

6.5 Growing regions

Northern Australia contains many attractive areas for commercial rice production; including wild harvest/cultivation of native wild rice species and growing domesticated rices. While northern Australia has a total estimated irrigation potential of 1.4 million ha from surface water storage (Petheram et al. 2014), the actual established area for irrigated agriculture in northern Australia is just ~150,000 ha (see Ash et al. 2017). This is comprised from approximately 119,000 ha in Queensland (mostly from large dams in the Burdekin and Mareeba-Dimbulah Irrigation Areas), 5000 ha in the Top End of the Northern Territory mostly from groundwater sources and 30,000 ha in Western Australia predominantly from the Ord River Irrigation Area and Lake Argyle and, to a lesser extent, groundwater based irrigation in the West Kimberly region (Ash et al. 2017).

> Northern Australia has a total estimated irrigation potential of
> **1.4 million ha**
> from surface water storage.

Historically, a major hurdle to large-scale agriculture developments in the north has been failure to appropriately manage, plan and finance operations, with a recurring issue of attempting to rapidly grow operations in new environments where there was a lack of experience in climate, soil and agronomy and how these factors would affect farm operations (Ash and Watson 2018). Fortunately, there is now far greater understanding of much of the land in northern Australia, as well as an understanding of this restriction to past progress. Various agricultural developments have occurred – and continue to occur – across the north. This is matched with excellent knowledge of the agronomic needs of successfully growing rice. While caution in developmental strategies and expectations is still needed, current and historical knowledge and understanding can be combined to form a much better prediction of the likelihood of successful scenarios. Furthermore, cropping system models (e.g. APSIM) can capture interactions between different environmental, climactic and management variables to provide rigorous predictive evaluation of different scenarios prior to field testing and the introduction of expensive infrastructure (Gaydon et al. 2012).

6.5.1 Wild harvest

Fogg Dam on the Adelaide River floodplain in the Northern Territory could present a suitable site for wild harvest rice. Abundant amounts of both *Oryza meridionalis* and *Oryza rufipogon* grow naturally in this environment (Wurm and Bellairs 2018), and it is believed that enough rice grows naturally here to meet demand. A wild rice enterprise in this region could supplement other ongoing economic and cultural activities on these lands and could be run congruently with other endeavours associated with using and managing floodplains (Wurm and Bellairs 2018). However, challenges around difficulties and variability in accessing and collecting rice on the floodplains would need to be considered and addressed. In order to collect the rice (by airboat) there needs to be enough water available for boat access, and the opportunity for collecting rice is only a few weeks of the year. *Oryza meridionalis* has been observed to produce between 26-265 kg/ha under wild conditions (Wurm 1998). If optimally timed, approximately 40 kg of *Oryza meridionalis* can be collected in 2 hours; *Oryza rufipogon* yield may be slightly less (Wurm and Bellairs 2018).

6.5.2 Domesticated (and newly developed) varieties

Zhao et al. (2016) evaluated 203 local and introduced rice varieties across 28 trials, mostly in northern Australia. The study had some very promising results, with yields of up to 10 tonnes/ha reached in all of the northern states (Zhao et al. 2016). However, the challenge remains to develop better agronomic packages and rice varieties to match potential pests and diseases and the climatic and environmental conditions of northern Australia. Each region has a unique growing season ideal for the local environment, and varieties perform differently in different environments across each state, territory, and indeed region (Zhao et al. 2016). This presents both unique regional opportunities, but also unique regional challenges.

Ash et al. (2017) assessed two scenarios involving rice in cropping cycles in the Ord (WA) and the Flinders-Gilbert region of Queensland. They found that the examined cropping cycles could be profitable; however, profitability could be challenged when returns were weighed up against high production costs, marketing and transport from more remote parts of northern Australia. It appears that it will be imperative for profitability that crops can be grown in both the wet and dry seasons through rotational cropping systems (Ash et al. 2017).

Queensland:

North Queensland presents an attractive region for growing rice based on available land, water and infrastructure. The climate conditions are most suited towards higher-value specialty rices, such as fragrant indica and long grain rice types (SunRice 2019). North Queensland also has a secure water supply from a combination of irrigation schemes and areas with high and relatively reliable seasonal rainfall. Within Queensland, the areas that are considered suitable for growing rice (and have land availability), are Burdekin, Lakeland, Atherton Tablelands, Innisfail, Tully, Ingham, Proserpine and Mackay (SunRice 2019).

The Lower Burdekin is considered to be one of the most attractive places in the north for the production of domesticated rice varieties. The 80,000 ha of land in the Lower Burdekin is northern Australia's largest irrigation area (Petheram et al. 2008). The area can be broken down into the groundwater-dominated 'Delta' region on the Burdekin River Delta, and the Burdekin Haughton Water Supply Scheme (BHWSS), a surface water-dominated scheme on the alluvial floodplains of the Burdekin River (below the Burdekin Falls Dam) (Petheram et al. 2008).

The Burdekin ranges from tropical sub-humid on the coastal plains, to semi-arid in the west. Rainfall in the region is highly variable, with annual totals ranging from 250 mm to 2000 mm (avg. in the Delta is 1000 mm) (Petheram et al. 2008). Generally, two-thirds of the annual rainfall is received between January and March, but some winter rainfall is common. Maximum air temperatures average 32°C in December and January, while the minimum temperature in July is 11.6°C.

Burdekin is a strategic location for the central point of north Queensland rice production because there is an existing mill in Brandon (owned by SunRice). This is currently the only operational rice mill in Queensland. However, the mill is only small; funding contributions are currently being sought to increase the capacity of the mill over 5-10 years to achieve a processing capacity of 100,000 tonnes per annum (SunRice 2019). The upgraded capacity of this mill will be essential to the development of a successful commercial rice industry in north Queensland, as profitability can't be maintained when run as a small-scale operation.

Rice growing was trialled in Mackay during both wet (December to May) and dry (July to December) seasons (Zhao et al. 2016). These trials were done using alternate wetting drying (AWD) irrigation techniques on reasonably flat beds and yields reached 12.5 tonnes/ha for multiple varieties. The loamy soil of the area was highly supportive of rice, providing excellent structure and fertility. Outcomes were extremely promising and suggested excellent economic opportunities for farmers.

Western Australia:

Rice has been grown for both commercial and research purposes in the Ord River Irrigation Area (ORIA), and this still appears to be the most sensible place for rice production in Western

Australia. About 15,000 hectares of land suitable for irrigated agriculture became available in the Ord Valley (Stage II) in November 2011 (Sivapalan 2016). The two major soil types present in the Ord Valley, Cununurra Clays and Aquitaine Soils, have high clay content (49–57%) and are ideally suited to rice cultivation (Sivapalan 2016).

It was found that rice grows best in the ORIA with reduced chances of pest and disease infection during the dry season (May to September). However, this means that the crop may be susceptible to severe cold damage as minimum air temperatures in the region can fall below 15°C during cold sensitive growth stages (tillering, panicle initiation, early pollen microspore and flowering) (Sivapalan 2016). Thus, cold tolerant varieties, such as 'Yunlu 29', are essential for this region.

Both permanent flood culture and aerobic AWD culture of growing during the dry season could prove successful for the ORIA (Zhao et al. 2016). Furthermore, if management practices can be developed that allow rice to be a viable option for the wet season, this could generate a second income for growers. Of the 880 mm of annual rainfall in the ORIA, more than 500 mm is available for wet season cropping. This 'free water' would contribute half of the rice crop's water requirement, and some tropical rice varieties may be more suited to wet season cropping than to dry season cropping (Sivapalan 2016). The longer day length during the summer months has the potential to greatly enhance rice growth and its yield potential compared to a dry season crop in the region (Sivapalan 2016).

A rotation system between rice and a legume crop appears highly suitable and profitable for the soil types in this region (as well as the Katherine and Tortilla Flats regions of the Northern Territory) and permanent raised-beds may provide a viable production system (Sivapalan 2016).

While some farmers did choose to grow rice in the ORIA, the occurrence of rice blast disease in the Ord Valley from 2010 collapsed the fledgling industry. Research trials, however, continued through 2015. There is some evidence that rice varieties with tropical origin may naturally have some tolerance to rice blast disease (Sivapalan 2016).

Northern Territory:

The Northern Territory presents several locations with promise for commercial rice growing. These include Tortilla Flats on the Adelaide River, Katherine and the coastal plains. The Adelaide River area boasts large amounts of space with suitable topography and soil types for growing rice (Zhao et al. 2016). Rice growing trials in the Northern Territory have achieved yields of 11.5 tonnes/ha (Zhao et al. 2016). The potential area for rice growing on the Adelaide River floodplains has been estimated to be 5,000 ha in the Upper Adelaide River and 40,000 ha in the Lower Adelaide River regions (Airey et al. 1981). The major market targeted in the Northern Territory is likely to be the export market for Papua New Guinea, in conjunction with SunRice's marketing strategies for northern Australia (Sivapalan 2016).

One of the main advantages with Katherine is the availability of a reliable source of underground water. Katherine and the coastal plains may also provide opportunities for wet season rice crops, although several challenges around environmental pressures, rice blast disease *(Magnaporthe grisea)* and herbicide residues will first need to be addressed (Zhao et al. 2016).

6.6 Logistic synergies with other existing industries

Freight costs can be a significantly large and even prohibitive component of overall production costs for many crops in northern Australia (Ash et al. 2017). Ash et al. (2017) analysed the gross profit margins and freight percentage of value for various crops over four regions in northern Australia. This included rice in the Flinders and Gilbert region of Queensland and the Ord (WA) region. Based on estimated yields of 8.3-10.7 tonnes/ha and a price of $350/tonne, the gross margin would equate to -$780 to $1150/ha. Freight costs were calculated to comprise 18-58% of the total cost of production.

There are a variety of opportunities for improved gross margins through the development of more cost-effective supply chains. Growing regions that were closer to markets or ports (e.g. the distance between the Flinders-Gilbert region and major Australian east coast markets) had substantially reduced transport costs, and, consequently, greater gross profit margins (Ash et al. 2017). Paddy rice typically produces 25% husk, 10% bran and germ, and 65% white rice (Chen et al. 1998). Local processing facilities significantly reduce transport costs, as non-saleable parts of the product can be removed and eliminated to maximise transport capacity. However, processing facilities require substantial financial investment and there needs to be a sufficient crop grown in a region for processing facilities to be viable. This means that regional development needs to be coordinated appropriately, well-resourced and done with an expectation that it may take some time to broadly realise profit (Ash et al. 2017; Ash and Watson 2018).

The large capital investment needed for certain supply chain constraints (such as reliable roads and port facilities) are only justifiable for multi-industry product volumes, or through deliberate and strategic government investment (Ash and Watson 2018). Commercial rice production in northern Australia is expected to benefit from existing infrastructure and supply chains from other industries. For example, rice is proposed as a seasonal crop within sugarcane farming rotations in the Burdekin (Queensland) region. While not specific to rice, the area is well-established for mass sugar production, so transport networks and agriculture infrastructure are already in place (Ash and Watson 2018). There is also already support and services for sugarcane farmers, which would still be available to farmers who gradually introduce rice into their practices. Other potential rice growing regions may benefit from infrastructure in place for various other northern Australian broadacre, horticulture and animal agriculture commodities.

The opportunity for coordination and logistical synergies between crop industries could lead to overall cost savings and better regulation and investment into infrastructure. This is important, as Australian supply chains have been found to be costlier than for competing grain producing countries (AEGIC 2018). Greater collaboration and networking between industries could also buffer some of the infrastructure and supply cost burden of large annual variation in yields (due to seasonality and the continuously changing climate) and greater competition. Added efficiencies throughout the supply chain would make Australian agriculture products more competitive in the global market.

Possibly most importantly, due to the relatively small scale of rice production in northern regions (in comparison, Australia produced approximately 20.9 million tonnes of wheat, 9.2 million tonnes of barley and 1.3 million tonnes of sorghum in 2018/19, ABARES 2019), collaboration with other grain or legume industries in terms of developing commercial storage networks would present a huge advantage to the fledgling industry. This is especially relevant, as the rice industry has the potential to grow quickly, so a fluid model of storage would provide clear advantages. The Australian grain industry has identified that technical barriers to post-farm gate costs need to be addressed, and specifically, the reliability and cost effectiveness of on-farm grain storage needs improvement in order to reduce handling costs and gain better market opportunities (GRDC 2018) [Recommendation 8].

Certain growing regions, producing specialty or niche rice products, may also only exist to service local markets. This could include unique, high-value products sold through tourism operations. Other more regional production areas may be best suited to supplying just the Australian domestic market. Significant added cost accompanies products for export, as they need to be shipped through specific export facilities that have quarantine capabilities. Although northern Australia is closest to Asian markets, proximity to these ports will still need to be a major consideration when deciding what varieties of rice to grow in specific areas.

7 Key Challenges Facing the Sector

Ash and Watson (2018) explored past agriculture developments in northern Australia to tease out factors that could prove critical to success or failure in future endeavours. The two common factors that emerged across unsuccessful initiatives were (1) an underestimation of the time required to build an industry to full scale and insufficient allowance of time to understand new environments and adapt farming practices; and (2) insufficient market analysis for understanding industry need and demand. These two concerns have been heavily considered; however, while a commercial rice industry would be relatively new for north Australia, Australia as a whole has an extensive and successful history with producing high quality rice (Figure 7.1). SunRice, which is owned by Australian ricegrowers, is one of the largest branded rice food companies in the world (SunRice n.d._2)). The company has extensive experience in developing not only Australia's rice industry, but also rice regions in Vietnam (with the company now being one of the country's largest exporters) and tropical Papua New Guinea (including opening the country's first hulling mill). This expertise and existing place in the sector mean that the northern rice industry will have a very effective platform to base itself.

Nonetheless, the present Situational Analysis identified a number of other important threats that could challenge the success of a rice industry in the north (Figure 7.2)

Figure 7.1 High quality domesticated rice growing in New South Wales. Photo: Blake Chapman

Historically, rice yields in the north have been lower than those in the south, yet costs to producers are similar (Burt 2002). Previous industry projections have suggested that rice farms in the Ord, for example, would not be profitable (Burt 2002). However, this assessment was based on the same Asian varieties of rice being grown in the north as the south. Instead, it is now believed that the Ord could contribute to a northern rice industry once varieties are developed to match the climate and disease pressures (R. Ford, personal communication). These assumptions will need to be tested with willing growers to assess the viability of new varieties.

Another key challenge to rice production in the north is pests, diseases and weeds. Northern Australia presents a range of pests and diseases (see Table 7.1) that are not found in the south. As a result, it is likely that crops of the most successful rice varieties grown in the south could easily falter, or even be decimated by novel diseases found in the north. The potential to transfer genes from the naturally disease and pest-resistant native rices found across northern Australia holds great potential as a solution to this issue [Recommendation 1].

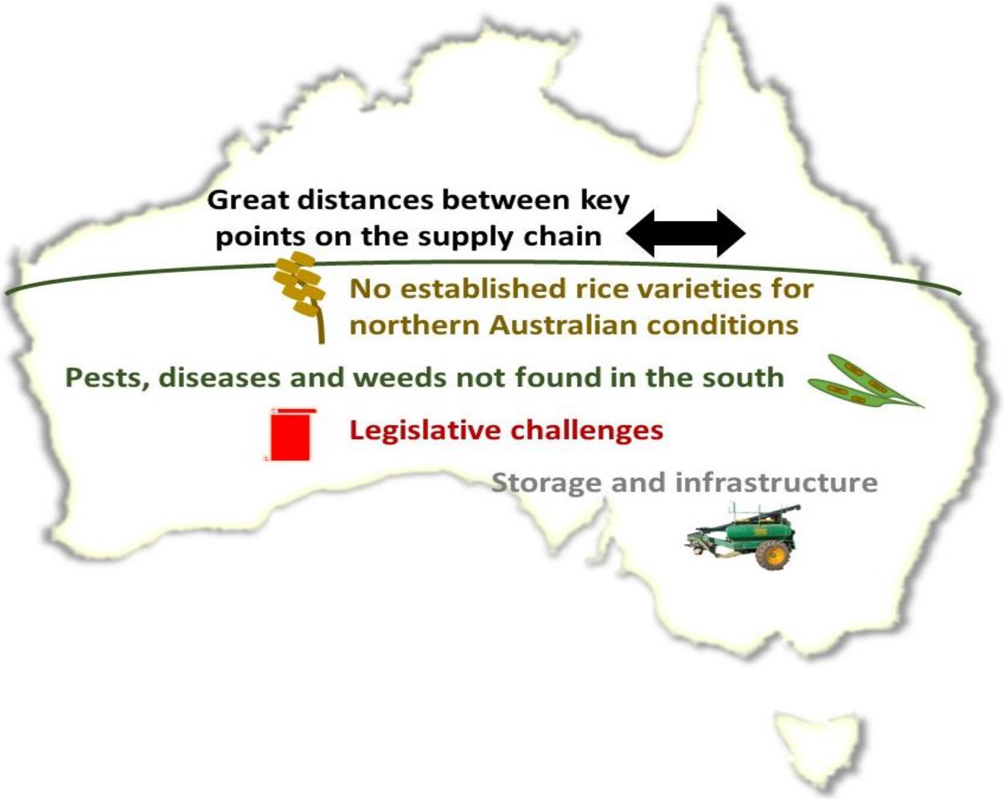


Figure 7.2 Key challenges facing the development of a successful rice industry in northern Australia.

Domesticated rices grown in the north will also need to be adapted to tropical conditions [Recommendations 4, 1]. The temperatures in the north are more stable than in the south (not reaching the minimum extremes, in particular), but they are generally much warmer and there is higher humidity. The optimal temperature for growing rice is 22–28°C (night–day) (AgriFutures Australia 2018, p. 40-41); this is commonly exceeded in north Australia. As a result, current rice varieties may prove to be susceptible to heat stress, especially at flowering. This, in turn, can cause spikelet sterility and significant yield losses that could make rice production commercially unviable (AgriFutures Australia 2018, p. 40-41). Selection of varieties with physiological, morphological and biochemical traits for heat tolerance and other tropical climactic qualities may successfully alleviate this risk (AgriFutures Australia 2018, p. 40-41).

Furthermore, rices grown in the north will need to be adapted to the different agronomic processes that will be sustainable for northern rice production [Recommendation 4]. For example, as rice is likely to be grown under an aerobic AWD system across the north of Australia, developing and understanding root characteristics for each variety will be extremely important. The root and osmotic system of the plant will require certain traits that are not presently found in many domesticated rice types. Various loci and their candidate causal genes that may provide a foundation for the genetic improvement of root traits and drought resistance have been identified (Li et al. 2017). Novel genes from Australian wild relatives may also provide answers for improved function under new growing systems.

Legislation, policy and biosecurity additionally pose risk to progress in developing a successful and sustainable northern Australian rice industry [Recommendations 5, 2]. Quarantine restrictions have previously presented a major obstacle in getting seed to Western Australia, since the required methyl-bromide fumigation is cost-prohibitive and has restricted varietal exchange (ACIAR 2016). The ecological risks of agriculture also need to be considered and addressed [Recommendations 6, 4]. This is of particular importance when watershed areas are within areas of national and international importance and significance, such as the Great Barrier Reef (Thorburn et al. 2013; Carlson et al. 2019) or when drainage or conversion of wetlands may disturb ecosystem functionality of Ramsar listed wetlands.

Considerations must also be given to how changes to land and aquatic resources may affect the well-being and social systems of Indigenous communities (Stoeckl et al. 2013) [Recommendation 9]. Caution and attention need to be afforded to new agricultural developments, in particular, as their impact on the environment can have increased impact on downstream social and economic systems, especially in rural communities (Dasgupta 2007; Stoeckl et al. 2013). Changes to the land and waterways through intensive irrigated agriculture practices may impact Indigenous peoples' culture, identity, land, diet, resources and livelihoods (Asafu-Adjaye 1996; Gray et al. 2005; Stoeckl et al. 2013).

7.1 Storage

While challenges around varietal selection and agronomic practices will certainly be present and require attention, possibly the greatest challenge for the developing industry is the lack of existing (effective) regional infrastructure – and storage capacity, most specifically [Recommendation 8]. Grain storage facilities need to provide safe conditions to prevent product loss from adverse weather, moisture, rodents, birds, insects and micro-organisms, like fungi. Storage systems also need to provide an ease of loading and unloading, efficient use of space, ease of maintenance and management and prevention of moisture re-entering after drying. It is recommended that food rice is stored in paddy form, rather than milled, as the husk provides some protection against insects and helps prevent quality deterioration (IRRI n.d.). Brown rice only has a very short shelf-life of approximately two weeks under tropical conditions (IRRI n.d.). However, storing paddy rice takes up 20% more space than brown rice (IRRI n.d.).

The key challenge for storing rice in northern Australian agriculture regions (and the main notable factor that sets it apart from southern regions) is the humidity. While humidity has minimal impact on rice growing, it poses a significant challenge to drying and storage processes and infrastructure. Rice in Australia is generally harvested at 18–22% moisture (although this could be higher in tropical, rainy seasons) to achieve the highest quality grain; however, seed needs to be stored at a moisture content of at or below 14%. The equilibrium moisture content of many tropical countries exceeds safe storage moisture levels. If not managed appropriately, the high humidity and temperatures in tropical climates can easily lead to improperly stored grains absorbing water and an unacceptable high final moisture content.

Paddy rice is hygroscopic, meaning that in open storage systems the grain moisture content will equilibrate with the surrounding air's moisture content. As a living biological material that absorbs and gives off moisture, the grain quality is heavily influenced by the relative humidity of the air and the temperature of the surrounding atmosphere (Mejía 2003). The respiration of paddy rice can be seen through decreases in dry matter weight, the utilisation of oxygen, evolution of carbon dioxide, and the release of energy in the form of heat; however, respiration is negligible when the moisture content is controlled to remain between 12% and 14% (Mejía 2003).

At higher moisture contents, rice is particularly susceptible to attacks by micro-organisms, insects and other pests. The heat released during respiration is retained in the grain and bulk due to the insulating effect of the rice husk, which quickly results in losses in terms of both quantity and quality (Mejía 2003). In these conditions, mould growth is encouraged, viability rapidly decreases and eating quality is reduced. On-farm drying is discouraged if the moisture content is >20% because grain quality deteriorates with inefficient drying. A temperature of 40–43°C is ideal for drying rice seeds, and in some climates, this can be achieved with shade drying. Higher temperatures can lead to physicochemical disorders in the grain (Zheng and Lan 2007) and exceeding 54.4°C diminishes the rice aroma principle 2-acetyl-1-pyrroline (Itani and Fushimi 1996). To best preserve quantity and quality, paddy rice should be dried within 24 hours of harvest (Mejía 2003).

Hermetic storage, where grain is stored in airtight containers, provides a solution where the moisture content of stored grain will remain the same as when it was sealed. Hermetic storage has proven to be very successful in providing a safe, more environmentally friendly (through negated need for chemical treatments), pesticide-free storage option for hot, humid climates (Villers et al. 2006). It works through gas impermeability and oxygen levels that effectively act as insecticides (Orge and Abon 2014). This storage strategy can extend the germination life of seeds, control insect grain pests and improve head rice recovery. The strategy has been utilised in the Philippines, Bangladesh, Ghana, Sri Lanka, Rwanda, Costa Rica, Indonesia and India for rice, coffee, cocoa, corn, peanuts and spices (Villers et al. 2006). This may be an option for rice storage in northern Australia, but the grain will still need to be dried first. Hermetic storage can also be expensive, depending on the technology used and the quantity of product needing to be stored (Orge and Abon 2014).

Drying will be very expensive if gas or electricity is required to fuel the process, but solar power may be an option. It will be imperative that the most efficient technology for cost-effective deployment is determined early on. In terms of temperature and humidity, northern Australia has more in common with tropical Asia than southern Australia. In Vietnam, rice hulls are burnt to dry the rice and this option could be explored for northern Australia.

A storage control method called 'adaptive discounting' was developed at the Stored Grain Research Laboratory, CSIRO Entomology (Darby 2000). It can achieve drying, cooling and maintenance actions, and targets specific grain moisture and temperature conditions. The ‘adaptive’ component refers to set points being adapted during the control process and ‘discounting’ refers to the discounting of aeration work quantities. The technology was trialled in the field in Dalby, Queensland with 71 t of wheat in a self-loading silo with a target moisture of 11.5% and target temperature 16°C (in-loaded moisture 14%, in-loaded temperature 30°C). The final moisture content was measured to be within a 0.75% band centred at 11.5%. To be effective, the fan rating must be known when installing or commissioning these systems.

Establishing and financing effective infrastructure and storage procedures is expected to be one of the most significant hurdles for success in the northern Australian rice industry. Yet, it is critical for minimising post-harvest losses during storage, transportation, distribution and processing [Recommendation 8]. The determination of the most effective drying system needs to consider projected drying capacity requirements, cost, ease of installation and operation, the range it will need to service and heating/drying method. Integrated drying and storage facilities at specific locations shared between rice and other grain/pulse commodities should be explored, as this may present the most efficient and effective way of overcoming this challenge. Drying regimes and infrastructure that has proven to be successful in other tropical rice growing regions should also be assessed.

While storage is considered to be the main challenge, an array of other infrastructure and machinery will be needed on-farm, or at least within access, and at the time needed for the region. This includes tractors, cultivation equipment, seeder/disc drills (Figure 7.3), boom sprayers, combine harvesters (headers), chaser bins and grain trucks (AgriFutures Australia 2017). Some of this can be shared and sourced/carried out by contractors, which could ease some of the capital investment burden. Aerial contractors could also be required if the crop is to be aerially sown, or for the application of pesticides and herbicides (AgriFutures Australia 2017), depending on the scale of the operation.

Figure 7.3 An air seeder. Photo: Blake Chapman

Disease, pests and weeds

Diseases and pests severely threaten agriculture crops. Major epidemics can severely reduce, or even decimate yields. Disease events have major societal and economic ramifications, including food shortages, increased global rice prices and economic losses for farmers through reduced yields. Many of the major rice pests and diseases, including rice blast disease, do not exist in the southern Australian growing regions. As such, introducing resistance to these pathogens has not been a focus in Australian rice breeding and development programs. Australian domesticated rice varieties introduced into the north, however, would be exposed to some of these serious rice pest and disease threats, as they are known to be present in the north.

7.1.1 Diseases

Diseases in rice crops can be caused by fungi, bacteria, viruses or nematodes. While most attention in Australia has been given to diseases present in the southern region, a significant number have also been identified in the north (Table 7.1).

7.1.1.1 Fungi

Pyricularia oryzae: The greatest threat to rice production worldwide is rice blast disease, which is caused by the fungus *Pyricularia oryzae* Cavara (syn. *Magnaporthe oryzae* Hebert). Rice blast disease is present in all continents where rice is grown, and is a notable problem in over 85 countries (Khemmuk 2016). Rice blast epidemics can cause yield losses of up to 100%

and significant economic losses. *Pyricularia* is capable of causing infection on some Australian native wild rices, as well as all domesticated cultivars, including Doongara, Langi, Kyeema, Illabong, Sherpa, Reiziq, Koshi, Opus and Quest (Khemmuk 2016).

Pyricularia oryzae can infect any aerial parts of host plants, although it particularly affects the leaves and panicles. The fungus prefers long periods of plant surface wetness, high humidity, little wind at night, temperatures of 17-28°C and high nitrogen supply (Greer and Webster 2001; Ballini et al. 2013). However, a greater temperature range is tolerable and high temperatures around 32°C can increase lesion expansion (Khemmuk 2016). Disease symptoms include visible lesions or spots of varying colour, shape and size on the infected area; however, they are often reddish-brown with grey centres, elliptical or diamond shaped and 1–1.5 cm long and 0.3–0.5 cm wide (Khemmuk 2016). The fungus is most often spread through the air, but it can also be spread via infected seed, straw and irrigation water (Ou 1972). *Pyricularia oryzae* can remain viable at 18–32°C for up to three years (Kato 2001).

Pyricularia oryzae has been found at a variety of sites across northern Australia (Table 7.1). The discovery of *Pyricularia oryzae* on wild rice species introduces the possibility that the fungus is native to Australia (Khemmuk 2016).

Magnaporthe grisea is the telemorph (sexual reproductive stage) of *Pyricularia oryzae* (which is the anamorph, or asexual reproductive stage of the fungus). *Magnaporthe grisea* has been found on both *Oryza meridionalis* and *Oryza rufipogon* collected at various sites along the floodplains of the East and South Alligator River and Mary River (Cother 2006). The disease showed regionality; some sites were diseases-free, while others, sometimes just a few hundred metres away, had high incidence of the disease.

Magnaporthe grisea has not been reported on domesticated rice varieties in Australia. However, predictive modelling (CLIMEX and DYMEX) has indicated that many sites in New South Wales are suitable for the fungus, suggesting that a potential outbreak of this devastating disease is possible (Lanoiselet et al. 2002; Bajwa and Chauhan 2017). It is likely that southern rice varieties brought into northern Australia for cultivation would be susceptible.

Bipolaria oryzae: Brown spot disease is caused by *Bipolaria oryzae* (syn. *Cochliobolus miyabeanus*). Brown spot disease has been described as the most common plant pathogenic fungus on wild rices and it is likely that *Bipolaris oryzae* is an indigenous Australian pathogen (Khemmuk 2016). It, too, is a major concern for domesticated rices, as it can cause severe yield losses (Matsumoto et al. 2017). Brown spot disease is characterised by dark brown small to larger elongate spots on plant leaves. Major infection can cause blight of seedlings. The disease can also reduce the number of grains per panicle and kernel weight (Anon. 2014 in Khemmuk 2016). Brown spot disease is associated with soil nutrient deficiency.

Bipolaris oryzae may be mitigated through optimising growing conditions, as it is predominantly a threat to rice production in regions with nutrient poor soils. Severe epidemics of brown spot disease on cultivated rice appear to be correlated to above average temperatures, so it is not surprising that incidence is increasing (Matsumoto et al. 2017). Due to the tropical conditions, commonality of drought and poor soils in parts of northern Australia, *Bipolaris oryzae* could pose a serious risk to rice production in the north. The major genes for brown spot disease resistance are not known; however, loci conferring partial resistance have been identified (reviewed by Mizobuchi et al. 2016; Matsumoto et al. 2017).

Tilletia horrida: Rice kernel smut (*Tilletia horrida*) is a soil-borne fungus that affects both yield and grain quality of cultivated rice. The disease infects rice floral organs. While the disease was previously considered of minor importance globally, the push to produce higher yielding hybrid rice varieties has led to greater incidence of rice kernel smut (up to 100% in some fields) (Wang et al. 2018). The early stages of *Tilletia horrida* are asymptomatic, so the disease only becomes noticeable at crop maturity (Khemmuk 2016; Wang et al. 2018). The fungus' teliospores can survive for three years or more on grains and even through the digestive track of animals (Ou 1985). Rice kernel smut has been found on rice at Mareeba, Ayr and Brandon (Tonello 1980). The import of used farm equipment from overseas, transport of rice material and farmers travelling to other rice growing areas present the greatest risks in spreading rice kernel smut (Khemmuk 2016).

Other fungal diseases that have been isolated from wild and cultivated rices in northern Australia, and that could potentially cause harm to commercial production in the north are *Curvularia spp*., *Rhizoctonia oryzae-sativae* (aggregate sheath blight) and *Waitea circinata* (sheath spot) (Khemmuk 2016).

7.1.1.2 Bacteria

Xanthomonas oryzae pv. *oryzae*: Leaf blight is caused by the bacterium *Xanthomonas oryzae* pv. *oryzae*. It is an important rice disease globally, and has severely damaged cultivated and wild rice species, including *Oryza rufipogon* and *Oryza australiensis* in the Northern Territory (Aldrick et al. 1973). The pathotype recovered in the Northern Territory in the early 1970s was likely indigenous to northern Australia and was distinctly different in virulence, and virulence pattern to Asian strains of the bacteria (Aldrick et al. 1973).

7.1.1.3 Viruses

Rice production can also be severely threatened by more than 15 different viruses (Chen et al. 2019). The majority of these require tropical insect vectors (Khemmuk 2016). The most important virus is rice tungro, which is caused by a mixed infection of *Rice tungro bacilliform virus* and *Rice tungro spherical virus* (Hibino 1996). Both of these viruses are considered to be 'High Priority Pests' to the rice industry, so biosecurity plans are in place (Plant Health Australia 2017). The Northern Territory has been declared free of the virus (DPIR 2018).

7.1.1.4 Disease prevalence and infectivity in northern Australia

Foliar disease surveys of wild and cultivated rices were completed in 2014 and 2015 in northern Queensland by Khemmuk (2016). The study recovered a total of 109 fungal isolates, which were classified into seven genera: *Bipolaris*, *Colletotrichum*, *Curvularia*, *Nigrospora*, *Phoma*, *Pestalotiopsis* and *Pyricularia*. These included the rice blast pathogen, *Pyricularia oryzae*, brown spot pathogen, *Bipolaris oryzae* and numerous *Curvularia* species. *Bipolaris oryzae* was the most commonly found fungus, accounting for 16.5% of the isolates. It was found on *Oryza australiensis*, *Oryza rufipogon*-like and *Oryza rufipogon meridionalis*-like. *Pyricularia oryzae* was the second-most frequently recovered fungus, accounting for 10.1% of the isolates. It was found on *Oryza sativa*, *Oryza* Taxon A and *Oryza* Taxon B.

The pathogenicity and cross-infectivity of *Pyricularia* species were further investigated. Isolates of *Pyricularia oryzae* recovered from Australian domesticated and wild rice were tested on the commercial cultivars Doongara, Langi, Kyeema, Illabong, Sherpa, Reiziq, Koshi, Opus and Quest. Infection occurred on all varieties. Quest was the most susceptible, while Sherpa was the least susceptible.

It is particularly important to note that the native rices *Oryza officinalis* and *Oryza australiensis* have natural resistance to *Pyricularia oryzae* (Jeung et al. 2007), bacterial blight (*Xanthomonas oryzae*), whitebacked planthopper (*Sogatella furcifera*), and brown planthopper (*Nilaparvata lugens*) (Brar and Khush 1997). This resistance can be transferred through introgression into rice cultivars (Jena et al. 2006). *Oryza rufipogon* has been used as a source of genetic tolerance to rice tungro disease (Brar and Khush 1997). Sivapalan (2016) also found some evidence that rice varieties with tropical origin may naturally have some tolerance to rice blast disease.

7.1.1.5

Table 7.1 Diseases that have been found on rice in northern Australia. Greyscale shading, fungus; Blue shading, bacteria; Yellow shading, virus.

Pathogen	Location found	Notes	Mode of transfer	Reference
Rice kernel smut (*Tilletia horrida*)	Mareeba, Ayr and Brendon, QLD	Affects yield and grain quality	Farm equipment, farmers and infected rice products	Tonello 1980
Smut (*Tilletia australiensis*)	Fogg Dam, NT	Affects seeds	Highly localised	Wurm and Bellairs 2018
Brown spot disease (*Bipolaris oryzae*)	Abattoir Swamp and Clancy's Lagoon, North QLD (but not observed on Doongara within a radius of 50–100 km)	Found on *Oryza australiensis*, *Oryza rufipogon*-like and *Oryza rufipogon meridionalis*-like		Khemmuk et al. 2016
Curvularia spp., incl. *C. aeria*, *C. alcornii*, *C. asianensis*, *C. clavata*, *C. lunata* and *C. muehlenbeckiae*	Fogg Dam, NT; north QLD	Isolated from rice leaf samples collected		Khemmuk et al. 2016; Wurm and Bellairs 2018
Pantoea ananas	Fogg Dam, NT	Isolated from rice leaf samples collected		Wurm and Bellairs 2018
Drechsler sp.	Fogg Dam, NT	Isolated from rice leaf samples collected		Wurm and Bellairs 2018
Rice blast disease *(Pyricularia oryzae, syn. Magnaporthe oryzae, telemorph* with *Pyricularia/Magnaporthe grisea)*	3 isolated north QLD locations	Found on *Oryza* AA genome-type plants		Khemmuk et al. 2016
Nigrospora sp.	Fogg Dam, NT; north QLD	Isolated from rice leaf samples collected		Khemmuk et al. 2016; Wurm and Bellairs 2018
Rice bacterial blight (*Xanthomonas oryzae* pv. *Oryzae)*		Affects cultivated rice, *Oryza rufipogon* and *Oryza australiensis*		Aldrick et al. 1973

Rice tungro (mixed infection from *Rice tungro bacilliform virus* and *Rice tungro spherical virus*)	Tropical and sub-tropical northern Australia	Typically requires tropical insect vectors		Hibino 1996

7.1.2 Weeds

The possibility of cross-infection is an important consideration from the perspective of disease scouting and management. Many common weedy grasses in rice fields could potentially act as alternative hosts and provide green bridges between rice crops [Recommendation 10]. For example, *Pyricularia oryzae* (the rice blast pathogen) can also infect cereal crops and grass weeds, including wild oats (*Avena fatua*), ryegrass (*Lolium rigidum*) and Phalaris (*Phalaris aquatica*) (Lanoiselet 2016). *Pyricularia oryzae* has been recorded in Queensland from *Brachiaria mutica*, *Hordeum vulgare*, *Pennisetum clandestinum*, *Phalaris canariensis*, *Rhynchelytrum repens* and *Setaria italica*, all of which are introduced grasses (Khemmuk 2016).

Invasive grasses, such as exotic para grass, *Urochloa mutica*, are also a threat to wild rice populations, and biodiversity more broadly (Boyden et al. 2018). These grasses have the potential to out-compete native flora, including wild rices, and can have negative ecological and economic impacts (Williams et al. 2011).

7.1.3 Pests

Various vertebrate species may be pests of cultivated rice at different crop stages. Seed-eating ducks, geese, and to a lesser degree, black swans, are considered common pests to aerial sown crops during their establishment phase, having the potential to completely decimate a field worth of crop (AgriFutures Australia 2017). Grazing ducks, members of the cockatoo family, finch, ibis, emus, kangaroos, mice and grasshoppers may also eat or damage rice crops (AgriFutures Australia 2017; Sivapalan 2016) [Recommendation 6].

Uniformly sown, large areas of quick-growing crops is considered to be the best defence against bird pests. In some cases, decoys or scaring devices, such as gas guns and flashing lights appear to be effective in deterring vertebrate pests (AgriFutures Australia 2017). The use of AWD strategies has also been shown to convey some resilience to bird pressure (Zhao et al. 2016).

Wild populations of native Australian rices would undoubtedly be predated on by a variety of vertebrate species as well. Trials of *Oryza meridionalis* seed were 'set' in different zones of the floodplains of the South Alligator River (Kakadu National Park) (Wurm 1998). The seed was heavily predated (at least 75%). Vertebrate predators were most heavily implicated, with the most likely pest being the dusky plains rat *(Rattus colletti).* Magpie geese *(Anseranus semipalmata)* have previously been considered a major pest in northern Australia, but the extent of the damage they have, or may, cause to rice crops is unclear (Mollah 1982). Seed broadcasting and rapid water inundation may afford some protection from predation (Wurm 1998).

7.2 Harvesting and cultivating wild rice

Although there are very clear benefits to commercialising Australian native rices, there are significant potential limitations to wild-harvesting native rices (Table 7.2) and also cultivating native rices (Table 7.3).

7.2.1 Key challenges that will need to be addressed for commercial wild harvest of native rices

Access to wild populations of native rice is limited by legislative and physical restrictions to accessing land. With forward planning, the legislative restrictions can be addressed through consultation with land owners and discussion of benefit sharing as appropriate

[Recommendations 2, 3, 5]. However, unpredictable and variable floodplain water levels restrict access by airboat. This can be addressed by mapping of accessible populations and being able to source grain from numerous sites. Modelling and remote sensing options should be assessed to identify populations that can be reached by airboat or other means. Use of remote sensing to identify flowering stands should also be assessed. If the size of flowering stands can be assessed, this would aid the efficient harvesting of wild populations and assist in reducing costs and variability in grain volumes from wild harvest. The ability to identify multiple accessible populations will reduce variability in supply due to loss of populations by weed invasion, disease or seed predation by vertebrates.

Access to wild populations would also be enhanced by developing collection techniques suited to a wider range of environmental conditions. Currently, the harvest of potentially commercial volumes has relied on the use of an airboat. This requires sufficient water levels to operate and launch. Dryland harvest techniques should be investigated if mapping of wild rice populations shows that this is warranted as a potential source of commercial supply. Regardless, crocodile risk must be accounted for during wild harvesting.

Application of research knowledge to weed invasion threats is necessary for the conservation of wild rice populations [Recommendation 7]. Weed control and rehabilitation of weed infested floodplains to regenerate wild populations of native rice should also be investigated. Invasive grassy weeds are the most significant current threat to diverse populations of Australian native rice. However, inundation of floodplains by marine waters, due to predicted sea level rise resulting from climate change, also poses a devastating threat to native rice and other plant and animal species.

To ensure conservation of the genetic diversity of wild rice populations, seed banks should be established to ensure native rice genetic material from across northern Australia is preserved. The genetic structure of wild populations should be investigated to identify the desired collection strategy to maximise diversity of the collection. This information will also inform strategic management for floodplain conservation planning.

If large-scale native rice collection for commercial purposes occurs from wild populations, then it is essential that environmental impacts are assessed. The native rices underly the vertebrate food chain of the floodplains, including the reproduction of the iconic magpie geese. Before large-scale wild harvest occurs, an evaluation of the baseline native rice resource across the floodplain should be implemented, so that the impacts of collecting can be assessed.

Efficient threshing, milling and processing techniques for native rice need to be investigated. Identifying populations that can be easily harvested and improving threshing, milling and processing will reduce the costs of wild harvested native rice (Figure 7.4).

Figure 7.4 Cleaning wild harvested native Australian rice grain. Photo: Penny Wurm

Table 7.2 Assessment of the major barriers to commercial production from wild populations of native rices.

Barrier	Risk level (high, medium, low) and explanation of risk	Impact	Control options
Production of wild populations is variable	Medium – *Oryza meridionalis* has been observed to produce between 26–265 kg/ha under wild conditions (Wurm 1998).	Cannot meet market demand; irregular supply; potential loss of buyers when product not available.	• Manage water and nutrients in certain locations to improve consistency of yield
Access restrictions (land)	Medium – In order to collect the rice (by airboat) there needs to be enough water available for boat access, and the opportunity for collecting rice is only a few weeks of the year; high or very low seasonal rainfall can limit or prevent collection (Wurm and Bellairs 2018).	Limited access to sites resulting in low harvest volumes or complete inability to collect wild rice.	• Collaborate with local Indigenous groups to locate additional collection areas [Recommendation 9] • Develop remote sensing technologies to identify harvestable patches • Develop alternative collection methods
Access restrictions (legislative)	Low – Approvals and permits required for commercial collection, from the government and landholders.	Restricted access and ability to collect.	• Collection has been allowed previously • Address access and collection concerns well in advance of planned collections • Address benefit sharing obligations and opportunities [Recommendation 5]
Difficulty in threshing, milling and processing	High – Has been identified as an issue (Wurm et al. 2012; Wurm and Bellairs 2018).	High processing cost restricts enterprise development. High percentage of harvest is lost during milling and processing. These difficulties discourage uptake by harvesters.	• Greater development of technology will lead to advances and efficiencies in processing • Look to other wild grains to investigate/develop alternative milling and processing methods • Trial and improve commercial milling infrastructure
Wild seed predation	Low – Wild seed is naturally predated by native birds and native rodents.	Reduced grain availability at particular sites.	• Preliminary field observations indicate that there is enough wild rice for collection to occur in parallel to natural predation • Identify multiple sites for collection
Depletion of wild stock	Low – Wild sources of native rice are over-exploited to support commercial use.	Conservation concerns about impacts to floodplain food chain, and wild rice.	• Develop baseline assessments to identify the proportion of the resource that is harvested

		Commercial concerns about impact on supply, due to reduced yields in the future.	and develop a monitoring plan • Work with herbariums and seed banks to ensure native rice genetic material is preserved • Only a small percentage of the area where wild rice grows will be accessible and utilised for collection; native rices are abundant and widespread in certain regions of northern Australia (Wurm et al. 2012)
High collection and processing costs	Medium – The wild traits of native rice plants make processing labour intensive; the environment where native rice occurs naturally is difficult to access and variable from year to year.	Unsustainable cost-benefit margins.	• Preliminary market assessment suggest that the product will attract high prices (Wurm and Bellairs 2018) • Investigate cost-benefit of larger-scale processing methods and improved infrastructure • Consider growing native rice under cultivation
Weeds and diseases	High – Invasive grasses have displaced native species including native rice (Boyden et al. 2018); fungal diseases have destroyed entire collections (Wurm and Bellairs 2018).	Large scale loss of source populations for harvest due to weeds; reduced health and/or grain yield caused by disease.	• Translate floodplain weed and native rice research for planners and managers • Support implementation of weed management plans, in areas of native rice, by Indigenous and conservation ranger groups to control weeds [Recommendation 7] • Support wild rice restoration activities by Indigenous and conservation ranger groups [Recommendation 9]
Uncertain marketability	Low – There is a small risk that wild harvested Australian native rice will not find a place in an increasingly diverse rice market.	Lack of market for final products.	• Engage with existing and emerging wild, ethically and sustainably produced, culturally identified and functional food supply chains and markets • Preliminary surveys of consumers/retailers suggest there is an eager market for Australian wild rice products (Wurm and Bellairs 2018) • Ensure marketing focuses on the unique provenance, cultural and health attributes of native Australian rices for the high-end market or as novelty 'bush tucker' products for tourism/native

			foods markets [Recommendation 3]
Lack of knowledge about options and models for Australian native rice value chains	High – Local supply and niche value chains may be threatened by competing 'cultivars', production systems, or business models.	Lack of interest in Australian and Indigenous-led enterprises due to high risks; early-adopting Australian and Indigenous-led enterprises lose market share.	• Research into the benefits of different production systems, supply and value chains and markets – assessing who benefits and under what circumstances [Recommendation 3]

7.2.2 Key challenges that will need to be addressed for local commercial cultivation of native rices

Research is needed to investigate the agronomy of Australian native rices. This will reduce production costs and make costs more certain for potential growers and investors. Knowledge transfer with potential Indigenous growers will increase the number of suppliers and reduce variability of market supply [Recommendations 9, 2, 3]. Options and market value for organic versus non-organic production of native rice should be investigated and optimised. Understanding of consumer values and priorities will assist in ensuring maximum value and return on the native rice produced.

Research into the agronomy and threshing, milling and processing is needed to reduce the high and uncertain costs of producing wild rice grain [Recommendation 4]. Information on options for control of diseases, weeds and vertebrates that affect plant growth or yield is needed as part of an agronomic package for producers. Difficulty in threshing, milling and processing is a major cost of production of the grain for consumption. Investigation towards the development of efficiencies in these techniques for native rice need to be done in order to reduce the costs of producing cultivated native rice. Increasing knowledge of costs and optimal production protocols is also needed to promote producer and investor confidence and to increase the number of growers and suppliers [Recommendation 3].

Research should also investigate options and models for Australian native rice value chains and investigate the implications for small and medium enterprises and for Indigenous producers of native rice. Supporting local Indigenous producers of native rice is important as value is maximised for a native, culturally identifiable, ethically and sustainably produced and locally grown native rice product. Support for small producers will need to consider the supply chain structure options for threshing, milling and processing of the grains. This could include cooperative or other market structures.

Table 7.3 Assessment of the major barriers to commercial production from cultivated native rice.

Barrier	Risk level (high, medium, low) and explanation of risk	Impact	Control options
Lack of knowledge of agronomy of Australian native rices	High – Little research into the agronomy of native rice has been undertaken, so the effects of agronomic management on growth and yield are not known.	Protocols for optimal management of the crop are unknown. Costs and risks for enterprises and investors are uncertain. No established supply of Australian native rice. No established native rice market.	• Undertake agronomic trials to optimise inputs to maximise profit [Recommendation 4] • Undertake agronomic trials according to standard protocols for variety assessment [Recommendation 4] • Collate existing research-scale production data • Collate data on growth in wild conditions • Develop agronomic protocols to maximise value of the rice produced in different productions systems (e.g. organic, ethically and sustainably produced) [Recommendations 4, 6]
Difficulty in threshing, milling and processing	High – Has been an issue with wild harvest grain (Wurm et al. 2012; Wurm and Bellairs 2018),	High processing costs restrict enterprise development. High percentage of harvest lost during milling and processing. These difficulties discourage uptake by growers.	• Investigate customisation of standard rice processing machinery to advance efficiencies in processing • Look to other wild grains to investigate/develop alternative milling and processing methods • Trial and improve commercial milling infrastructure
Lack of growers	High – Without agronomic knowledge, customised processing technology, identified value chains and markets, there is unlikely to be uptake	No established supply of Australian native rice. No established native rice market.	• Agronomic, processing and market to support industry development • Readily accessible agronomic knowledge needed for potential growers • Training, awareness raising and knowledge transfer among Indigenous and non-Indigenous growers [Recommendation 3]

			• Multiple growers to facilitate a stable supply required to support market demand
High production costs	Medium – Preliminary market assessment suggest that the product will attract high prices, but these may not be high enough to cover the high labour costs and resources needed to process native Australian rices (Wurm and Bellairs 2018)	Optimising inputs is required to manage cost-benefit margins and ensure production is profitable.	• Investigate cost-benefit of production via cultivation, larger-scale production and processing methods and improved infrastructure
Predation by native floodplain fauna	High – Cropping locations may be targeted by vertebrate animals such as magpie geese and native rodents (Wurm 1998; Redhead 1979; H. Campbell, personal communication)	Crop damage. Reduced or irregular grain availability.	• Investigate cost-benefit of production via open versus enclosed cultivation settings • Improve understanding of pest ecology • Investigate options for improved infrastructure to reduce predation
Diseases	High – Fungal diseases have decimated entire collections and may build up when native rice is grown repeatedly in the same location (Wurm and Bellairs 2018)	Reduced health of the crop or reduced grain yield caused by disease.	• Investigate agronomy and agricultural systems to minimise diseases, while maintaining supply, sustainable cost margins and market position (such as organic certification, ethical production) [Recommendation 4]
Weeds	Low – Knowledge of likely weeds is poor; invasive grasses have the potential to compete with and displace native rice (Boyden et al. 2018), they can be managed in controlled environments	Reduced vigour and grain yield caused by competition from introduced weeds. Various control measures would likely be effective for small production areas.	• Investigate protocols to manage weeds, while maintaining supply and sustainable cost margins and market position (such as organic certification, ethical production) [Recommendation 10]

Uncertain marketability	Low – There is a small risk that cultivated Australian native rice will not find a place in an increasingly diverse rice market	Lack of market for final products	• Further confirm market interest with wider research - preliminary surveys of consumers and retailers suggest there is an eager market for Australian native rice products (Wurm and Bellairs 2018) • Ensure marketing focuses on the unique provenance, cultural and health attributes of native Australian rices for the high-end market or as novelty 'bush tucker' products for tourism/native foods markets [Recommendation 3] • Investigate options for Australian native rice value chains [Recommendation 3]
Lack of knowledge about options and models for Australian native rice value chains	High – Local supply and niche value chains may be threatened by competing 'cultivars', production systems, or business models.	Lack of interest in Australian and Indigenous-led enterprises due to high risks. Early adopting Australian and Indigenous-led enterprises lose market share.	• Research into the benefits of different production systems, supply and value chains and markets – for whom and under what circumstances [Recommendation 3]

7.3 Growing domesticated rices

While domesticated rices have been very successful in southern Australia, the tremendously different northern Australian environment poses a variety of significant agronomic challenges to current domesticated rice varieties and production methods. The temperate japonica varieties that have been so successfully grown in southern Australia tend to have stiff, short stalks, are erect with round grains and are highly responsive to nutrient inputs (Prasad et al. 2017). Conversely, indica varieties are more typically grown throughout tropical and subtropical regions of the world. Indica's are traditionally characterised by tall stature, weak stem, droopy leaves, high tillering capacity, long grains, and poor response to high nutrient input conditions (Prasad et al. 2017). Rices grown in the temperate conditions of southern Australia require flooded conditions; however, aerobic methods may prove to be most opportunistic in northern Australia. These significant differences would require revised agronomic management strategies and dedicated efforts to adapt current varieties to northern environments, climate and biological threats (e.g. pests and diseases) [Recommendation 1]. Obtaining similar yields through aerobic growing practices is also expected to present a substantial challenge. As growing established domesticated rice varieties is the most straight-forward option for northern Australia, and indeed, has already begun in north Queensland, addressing these challenges will be critical to the success and timely growth of the industry.

8 Scoping Studies

Scoping investigations were carried out to investigate strategies around the use of native Australian rices for commercial purposes in northern Australia. These studies were designed to provide a degree of insight into the feasibility and limitations of growing, collecting/harvesting and milling the rice, as well as consumer views of native Australian rice. The studies were conducted to the greatest extent possible in the limited timeframe of the *Situational Analysis* project.

8.1 Testing of the legislative processes

Complex and lengthy approval processes and uncertainty stemming from bespoke and sometimes conflicting policies across jurisdictions remain major impediments to development in northern Australia (Stokes et al. 2017). Regulations set by the Australian Government relate to the taking of biological resources of native species for research and development on genetic resources (or biochemical compounds, comprising or contained in the biological resource) (Department of the Environment and Heritage 2005). The Commonwealth regulations do not apply to lands and waters owned or managed by the States or Territory governments.

Over the past twenty years, two overlapping legal regimes have been [partly] adopted in [parts of] Australia. 1) Biodiscovery laws have been enacted in respect to Commonwealth, Queensland and Northern Territory regulations that give effect to the obligations of the multilateral Convention on Biological Diversity (CBD); and 2) the FAO *International Treaty on Plant Genetic Resources* established a multilateral legal framework for the sharing of 64 species of crops and forage plants that form part of the public domain for breeding for food security (listed in Annex I of the Treaty), including rice.

The Biodiscovery laws require that prior consent from the land/title holders be obtained and that Benefit Sharing Agreements are in place prior to the collection of biological native resources that may be used for commercial purposes. However, these laws fail to recognise the same exceptions as the FAO treaty (Annex 1), leading to the impossibility of being able to abide by both sets of legislation for these crop species.

Policy reform to minimise conflict and confusion could make a significant difference to biodiscovery progress; achieving a harmonised approach to policy and governance within and across jurisdictions through policy would lead to noticeable progress in more effective and efficient development (Dale 2018) [Recommendation 5]. Similarly, greater and more active stakeholder engagement in identifying issues in policy would facilitate easier navigation of legislative hurdles [Recommendation 2]. Work conducted as part of this project tested the permitting process in Queensland and the Northern Territory, identifying and advocating for the rectification of problem spots within legislation.

8.1.1 Queensland

The process of gaining approval to use wild rice commercially is complex. The use of biodiversity on government land (including leasehold property) in Queensland requires a Benefit Sharing Agreement with the Queensland Government. The University of Queensland completed such an agreement in 2019. This determines the sharing of benefits of any commercial use between the University and the Government. A Biodiscovery Plan is required to work with any specific project under this agreement. A Biodiscovery Plan for rice was approved in 2019. The plan was referred to Crown law and on advice revised before a final version was agreed. Collection permits were then obtained under the Biodiscovery Plan. Collection permits are required for each collection site or property. Only one site (Olive Vale Station) has an approved collection permit. This approval was delayed due to the need to write to the government to seek approval to link the Biodiscovery Plan to the Benefit Sharing Agreement. All approvals were obtained and a rice sample was collected for use in assessing sensory properties for commercial uses.

Of note, the use of wild rice resources is simplified by the FAO *Treaty on Plant Genetic Resources for Food and Agriculture*, of which Australia is a signatory. Annex 1 of the Treaty lists rice (*Oryza*). This is important as the Nagoya Protocol (covering access and benefit sharing with Indigenous stakeholders) provides that if the FAO treaty requirements are met then the material is compliant with the Nagoya Protocol. The Queensland Biodiscovery Act does not recognise the FAO treaty, however, creating a barrier to the ability to meet both state and international legislation following best practice. The proposed new legislation recently introduced to the Queensland Parliament addresses this issue. We have been active in ensuring that this is considered in any updating of the local laws. The project team are working with DivSeek International to hold workshops to improve international understanding of these issues. The first workshop is proposed for Brisbane in 2020 (historical collections), then San Diego in 2021 (data issues) with another in Brisbane in late 2021 (access and benefit sharing overview). We are additionally working with Professor Brad Sherman (Professor of Law, The University of Queensland) to promote these issues to government and the international community (Sherman and Henry 2020).

8.1.2 Northern Territory

In the Northern Territory, permits for the collection of any native flora or fauna are issued under the *Territory Parks and Wildlife Conservation Act 1976* (TPWC Act), which is administered by NT Parks and Wildlife Commission. Under this act, permits are issued 'to interfere with wildlife' for either research purposes or commercial use. Permission to access land for either of these purposes must be secured from the land holder or lessee, known as the 'resource access provider'. This permission is requested or confirmed by Commission staff during the processing of applications. Also, government natural resources scientists are consulted as part of the application processing on matters such as the sustainability of the collection volumes requested by the applicant.

Applications to interfere with wildlife are also assessed under the *Biological Resources Act 2006* (NT). This act is administered by the Northern Territory Department of Trade Business and Innovation (NT DTBI). Applications are forwarded by Commission staff to NT DTBI for assessment. The purpose of this act is to protect the Northern Territory's interests in potential benefit flowing from the use of biological resources derived from native Northern Territory species, through bioprospecting and biodiscovery (which are defined in the act). This act specifically requires a benefit sharing agreement to be developed between the permit holder and the resource access provider. The act states that the benefit sharing agreement must include 'a statement regarding any use of Indigenous people's knowledge, including details of the source of the knowledge, such as, for example, whether the knowledge was obtained from the resource access provider or from other Indigenous persons' and 'the agreed disposition of ownership in the samples, including details of any proposed transmission of samples to third parties'.

If a permit to collect is approved the permit holder is required to report back on the quantities of material collected, as a condition of the permit. If the material is to be moved out of the Northern Territory for any reason (commercial or research) a supplementary Permit to Import or Export Wildlife must be applied for an approved before transfer can occur.

During the course of this project we submitted permit applications to collect *Oryza meridionalis* and *Oryza rufipogon* for both research purposes and commercial use. The paperwork associated with these permit applications was straight forward. Our experience during this project (and previously) has been that the processing of permits for research purposes, such as ecological studies, milling trials and food quality assessments, is straight forward and timely (potentially finalised in as little as two weeks, depending on the volume of permits in the pipeline). However, for this project we found the permit application to collect from the wild for commercial purposes took longer. The permit to collect, process and sell wild harvested seed and to cultivate from wild collected seed for sale was submitted in November 2019, but by mid-April 2020 we are yet to receive feedback and have not been approached about the development of a benefit sharing agreement.

8.1.3 Western Australia

No legislation currently exists in Western Australia around the collection of biological material for biodiscovery purposes. This is, however, expected to change in the near future. It is recommended that this be closely monitored, and that pre-emptory influence is put on the Western Australian government for workable legislation that will encourage forward biodiscovery progress and the ability to utilise Australia's biodiversity for sustainable improvements to agriculture.

8.1.4 Actions

While a great deal of complexity still exists around the legislation and regulatory frameworks, it would be of great advantage to the industry if methods could be produced that ensured compliance with relevant Commonwealth/State law, as well as international treaties and protocols [Recommendations 5]. The establishment and solidification of links with Indigenous communities would be a clear benefit to these actions [Recommendation 9]. Furthermore, establishing a framework for these processes and the demonstration of legal provenance would help to future-proof the industry. It would also represent a significant advantage in global markets through the provision of confidence and security to retailers and consumers and potentially allowing northern Australian rice to enter into markets where other product may not be able to due to non-compliance with international biodiscovery protocols. This would represent a valuable transformational shift towards global best practice for the Australian rice industry.

8.2 Growth and harvest of native rice in northern Australia

Growing native rice (QLD):

Rice (Taxon B) was planted at Olive Vale Station. Seedlings were visible in the shallow water at an estimated germination rate of 70%. The plants established during the really wet conditions of February 2019. However, during March and April 2019, the whole area dried out, and it was not possible to maintain the rice in a semi-waterlogged condition. As a result, that particular seeded area failed. For commercial harvest, that taxon of rice clearly needs a low level of water to germinate the seed, followed by an opportunity for the plants to sit just above the water level, allowing them to dry enough to get oxygen to establish, but then they need to return to semi-waterlogged conditions for the rest of their lifespan to grow.

Wild rice needs to consistently be waterlogged. Shifting from wild harvest to commercial harvest conditions means that paddy-type waterlogged systems will need to be maintained. The native rice plants (Taxon B) do not tolerate complete drying at all, particularly during the establishment phase, so cannot be allowed to dry out to any degree.

Harvest of wild rice (QLD):

Wild rice found naturally growing at Olive Vale Station was harvested by hand. The rice appeared to be relatively free of diseases, which may prove to be an extremely strong advantage for breeding programs seeking natural disease resistance genes for rice in northern Australia. The rice also appeared to tiller very well, suggesting it could be safely managed through traditional herbicides, and it would likely be able to successfully compete with weeds. It is also expected that it would respond well to nutrition and fertilisers. The challenge of being able to collect enough seed for commercial production, as well as for planting in subsequent years, could be difficult, though.

Through this process, several issues with harvesting wild rices were identified (Figure 8.1). Native Australian rices have a number of weedy characteristics, which have undoubtedly facilitated their long-term survival. However, these work against commercial production [Recommendation 4]. The most significant hurdle that would need to be overcome is that once mature, the seeds easily fall out of the panicle (rice head). Seeds are easily dislodged by anything from wind, rain or animals that brush against the plant. In the wild, this feature enables seed transfer and dispersal. In terms of commercial harvest, though, it would mean that traditional mechanical harvesters would be ineffective, unless a process for getting the seeds to stick better could be devised. Vegetable-based bonding/sticking agents are currently available that stick the seed to the panicle, which could permit mechanical harvesting. The other alternative is modifying commercially grown native rices through genetic selection if the genes that provide a natural occurrence of holding the seed tighter in the head could be found in the wild [Recommendation 1].

Figure 8.1 Project members Russell Ford and Tony Matchett examining the attributes of wild native Australian rice for identification purposes. Photo: Blake Chapman

Another weedy feature of native Australian rices is that the side of the awn has a small, jagged, serrated horn. From a planting perspective, that characteristic could present issues when using a commercial seed planter. Consequently, the seeds may need to be de-awned for planting. This limitation is likely to be manageable, with further research and specialised agronomic procedures. For example, the solution may rely on using a spreader (which would replicate someone just throwing the seed out into the field) instead of using a traditional row planter that would seed it out in distinctive rows. The 'horn' could also create problems with collecting the right amount of seed.

It has become apparent in wild rice that even within a very small area, you can simultaneously find plants with ripe seed, directly adjacent to plants with half mature seed, and even those that are just starting to flower. This could be a result of minor differences in water level from slightly different land contours, or variation in the timing of water inundation. However, while this proved to be an added difficulty during wild harvest, under a commercial situation, this would likely be negated by the fact that the entire plot area would be flooded at the same time and to the same depth, providing more even maturation.

Vertebrate pests are not expected to be a major issue for commercially grown native rices. However, if they did prove to be formidable, management strategies could be introduced for more intensive commercial production [Recommendations 4, 6]. Rice paddies could be set up similar to shallow aquaculture ponds with netting over them to keep the birds out.

In the context of the difficulties native rices present around harvesting, water requirements and relatively high production costs, the commercial viability of native rices would come down to how much premium you could extract out of the products. It seems that while challenges do exist, none are insurmountable through further research and the refinement of management strategies, and that commercial wild rice production could prove to be a very reasonable small, northern Australian boutique industry (potentially in the order of 10-50 tonnes per annum) that sustains a niche market. The operational size would put it outside of the realm of sending seed for production to growers more broadly, but it could present an attractive enterprise for Indigenous communities that want to gain additional value from their land.

8.3 Processing and milling test for native Australian rices

Queensland Taxon B harvested rice: The wild-collected sample milled quite nicely, in line with other commercially milled products and comparable to domesticated rices, and resulted in a purple-brown grain colour. Within the ½-1 kilogram of milled rice, an unexpectedly small (<15%) percentage returned cracked. This was used for cooking and sensory analysis of the polished ('white') rice.

Wild rice (Northern Territory):

Studies into harvesting wild rice in the Northern Territory identified several challenges for processing the grains of the Australian native rices, *Oryza meridionalis* and *Oryza rufipogon.* They have a grain with a long stiff awn approximately 70–120 mm long that protrudes from the lemma and the palea and the lemma tightly enclose the caryopsis. Processing the grains requires removing the awn, palea and lemma, to expose the 'brown rice' grain. It is desirable to achieve this with the seed coat intact as the seed coat has nutritional properties and it also gives a red-brown colour to the grain. The red-brown colour makes it distinctive and attractive as an identifiable Australian native food.

Difficulties in processing of the grain are due to the long awns, the tightness of the palea and lemma, and variable grain size. The long, stiff, brittle awns easily clog processing equipment and the palea and lemma require force to remove. The variable grain size means that some small grains still enclosed in the palea and lemma may be of similar size to the largest grains that have had the palea and lemma removed.

Successful processing of the grains has occurred by first breaking off the awn near the lemma, followed by a second stage of processing removing the palea and lemma using a Satake Testing Husker (Figure 8.2). Several designs of mesh cylinders were trialled to remove the awns. A stainless-steel mesh cylinder with a mesh aperture of 1.4 mm was effective at allowing the awns to protrude through the mesh without having any of the enclosed grains become caught in the mesh (Figure 8.2). A slightly larger mesh aperture of 1.5 mm resulted in some caryopses enclosed in the palea and lemma catching and being retained in the mesh. A stiff plastic blade on the inside of the rotating mesh cylinder effectively snapped off the awns, causing them to fall outside the cylinder, while the grains were retained inside.

After removal of the awns, the grains enclosed in the husk were treated in a Satake Testing Husker. The spacing between the cone mill was able to be adjusted to remove most of the husk fragments from the grains while leaving the seed coat on the grain. This combination of processes resulted in sufficiently clean 'brown rice' grains for cooking trials. However, current processing issues include a high proportion of cracked grains and the presence of some small grains that pass through the Testing Husker with the palea and lemma present (Figure 8.2).

Figure 8.2 Research-scale Satake Testing Husker (left), native rice thresher (middle) and milled wild-harvested native Australian rice (right). Photos: Penny Wurm

Improved equipment to more efficiently remove the awns has been developed, but further work is needed to reduce the proportion of cracked grains and remove all husk material from the processed grains.

8.4 Sensory analysis

A sensory analysis study was done on brown wild Australian native rice in comparison to current commercial options (see Tikapunya et al. 2018; Figure 8.3). Additional rice was collected, which will be used for further sensory evaluation, but this time on white rice. The white rice market is much larger; however, the question remains as to if wild rice fits into the traditional white rice market. Consumers are always looking for 'healthier' white rice, so perhaps wild rice could provide a new option in this space. Sensory analysis will lend insight towards these questions. Sensory analysis was unfortunately delayed by the COVID-19 pandemic; results will be included as an addition to this report once available.

Figure 8.3 Heather Smyth preparing rice samples for sensory analysis. Photo supplied: Heather Smyth

9 Recommendations: Strategies and Implementation Pathways for Sector Development

The development of a northern Australian rice industry is a large and complex proposition that needs to account for and coordinate numerous important, but varied factors. These can be broken down into the general themes of guidance, varietal development, communication and engagement, advocacy, and infrastructure. On the basis of our *Situational Analysis*, we have prioritised 10 recommendations for initiating and growing the industry along the most efficient, practical and forward-thinking path (Table 9.1) One of our strongest recommendations is that a cross-sectoral stakeholder support and guidance steering committee be developed to discuss and align the direction of major efforts and to serve as a centralised point of call for information about the progression of the industry [Recommendation 2].

The need to develop the right varieties of rice for commercial production in northern Australia is critical to the predicted success of the industry as a whole. To be productive and profitable, the rice grown in the north needs to be high-value, as well as high-yielding (Figure 9.1). Furthermore, rice varieties will significantly benefit from the introduction of genes (through non-GM methods) that carry resistance to important pests and diseases, provide specific adaptation to overcome local production constraints, make them stronger against undesirable environmental factors and different agronomic practices for the north, and preferably integrate novel traits (e.g. the distinct colour of native Australian rices) or added health benefits. Developing rice varieties that meet all, or even some, of these criteria will be a substantial undertaking and extremely challenging. Still, the goal is certainly considered achievable and sources of most of these traits (and in some cases, even the genes of interest) are already known. Therefore, we recommend that funding first-and-foremost be directed towards developing a tropical rice breeding and varietal development program for northern Australia [Recommendation 1]. This will include genetic diversity studies, backcrossing different species/cultivars of native and domesticated rices, conducting breeding trials and developing agronomic methods (including crop protection strategies) specifically suited to the new varieties. Varietal stimulation modelling will also prove very useful in this space [Recommendation 6]. It must be noted and understood that, while important, this milestone for the industry will take time, and research, development and breeding activities will take some time to come to fruition.

As the industry is expected to have significant impact on the northern Australian community, communication, education and outreach will be a major component of developing the industry and maximising its potential within the region. We recommend that a ‘Sector Development Officer’ role be created to promote the industry within the community, but also advocate for the industry more broadly throughout the supply chain and to target consumers [Recommendation 3]. This role will have an important job of linking the three northern Australian jurisdictions.

Regulatory frameworks have proven to be a major hurdle to agricultural industries in the north previously. Therefore, advocacy for the industry should also be directed towards developing sound legal frameworks across the north that enables workable biodiscovery processes and improve benefit sharing [Recommendations 5, 2, 3].

Along with appropriate benefit sharing agreements being put in place, it is really important that the industry engages considerably with local Indigenous communities [Recommendation 9]. It is expected that there would be numerous and varied economic and job opportunities that stem from the development of a northern Australian rice industry. Many of these jobs would be ideally suited to Indigenous people. Including Indigenous culture, creativity and insight into the rice production process would additionally present novel, highly regarded provenance and marketing attributes to the products developed. Strategies targeted to individual jurisdictions will be developed by the Standing Industry Steering Committee in collaboration with Indigenous groups and state/territory governments [Recommendation 2].

The industry should also strongly advocate for heightened management and conservation of living and genetic native rice resources and the minimisation of negative environmental impacts on the very important and valuable land and waterways of northern Australia [Recommendation 7, 10].

Figure 9.1 Commercial rice fields. Photo: Blake Chapman

The most pressing infrastructure needs to enable a profitable industry relates to storage and drying capacity [Recommendation 8]. The north presents unique climactic attributes to the south, which mean that new options for this part of the supply chain will need to be explored. Adding further complexity to this, the great expanses and remoteness of northern Australian regions can mean that transport costs, alone, can render agri-businesses unsuccessful. This will need to be carefully considered. Substantial research and predictive modelling should be applied to project immediate and future potential product yields, as this will be important for ensuring infrastructure is appropriately scaled [Recommendations 6, 4]. Links with other northern grain producing industries should be explored [Recommendations 3, 2]. Shared resources between grain industries throughout the supply chain can provide cost-savings to all industries involved and allow for better market position of Australian products.

Table 9.1 Recommendations for progressing the northern Australian rice industry from this Situational Analysis.

Key priority actions for sector development	Action owner and key partners	Pathways to implementation and timeline	Intended industry impacts
1. Develop a Tropical Rice Breeding and Varietal Development Program for North Australia (Domesticated Rice): Establish a research program to develop and trial the most appropriate rice varieties and agronomic practices for the conditions and pathogens present in northern Australia to ensure maximum yield and minimum damage from pests/diseases.	**QAAFI UQ (Rice Improvement Officer)** ·SunRice ·QDAF ·NT DPIR ·WA DPIRD ·AgriFutures ·NSW DPI	This will be the focal project for establishing a successful and sustainable rice industry in northern Australia. The overall aims for this activity are the breeding and development of rice varieties that provide: a. grain quality attributes for specific desirable markets; b. abiotic stress tolerance for an aerobic growth system; c. improved root morphology for improved water use efficiency; d. biotic stress tolerance for multiple diseases and pests; e. disease resistance (with particular focus on rice blast disease); and f. the advancement of the molecular technologies for the above traits. The study should assess the genetic stocks of both wild and domesticated rice varieties to develop new varieties (or optimised agronomic processes for existing varieties) that combine the optimal attributes for growth in the north. Using current domesticated varieties is the most straightforward course of action for developing a rice industry in northern Australia; however, a variety of factors are limiting the productivity of these varieties under current practices. For example, rice blast disease, as well as a variety of other pests and diseases, and sub-optimal plant structure for aerobic farming are major concerns for growers. This study will work with domesticated rice varieties to encourage disease-resistant cultivars, as well as survey important gene markers from wild rices for inclusion in newly developed varieties. Trials will be conducted in both inundated systems as well as aerobic systems. Once specific gene markers of interest are determined from wild rices, backcrossing programs should be used to develop maximised varieties. Breeding and growth trials can then be initiated to test for the desired genes, yield and grain quality.	Benefits from the implementation of this R&D activity are expected to include: • Two successful high-yielding rice varieties developed specifically for northern Australia that are expected to directly deliver ~$85 million per annum into the north Queensland economy alone within 5-10 years[1]; • *Sustainable* annual production targets of 100,000 tonnes of paddy rice [12,000 ha] per annum[1]; • The creation of ~70 jobs in rural communities for rice production that span across the value chain; • The option to produce rice aerobically in the north, which will be essential for inserting rice into current crop rotation systems, as well as working within practical water resource limits; • Significant environmental and productivity benefits, as tailored varieties for conditions in the north will lead to a reduced requirement for chemical pesticides (up to 53% of Australian rice is attributable to herbicide use; 13% to fungicide use

		The appointed 'Rice Improvement Officer' will coordinate and oversee the day-to-day activities of the breeding trials and the development of associated agronomic methods, in collaboration with SunRice. SunRice will largely support this activity through the contribution of knowledge and resources from the southern industry. Trials will be performed in collaboration with the relevant state agencies and/or farm managers at trial sites. The WA DPIRD will be responsible for leading joint research into rice blast disease resistance (in collaboration with other organisations); SunRice will continue to focus efforts on introduced disease resistance and the genetics of this resistance through research partnerships and further testing. This challenging and significant undertaking will require substantial planning, project organisation, project management, and resourcing. In the first instance, it is recommended that state/territory government agencies, academic institutions and industry partners all contribute cash and/or in-kind funding to resource this work. Once the industry becomes more established, research funding applications will be submitted for further work. *It is recommended that this activity be resourced for a 5-year period by multiple partners:* • *QAAFI to fund an ongoing research position (e.g. Academic Level B-C 'Rice Improvement Officer'; $200,000/yr);* • *Ongoing in-kind support from SunRice for variety evaluation (two staff; $200,000/yr);* • *In-kind contributions for trial site use and water from QDAF and private landholders ($200,000/yr);* • *In-kind contributions from the NT government and the WA government ($100,000/yr, each)* • *Matched funding ($400,000/yr) from the CRCNA for operating costs; and*	and 54% to fungicide use[1]) and pest/disease-resistant rice will reduce yield losses (e.g. rice blast disease accounts for up to 100% crop loss and previously caused the fledgling rice industry in Western Australia to fold); • Varieties with roots designed for agronomic processes for northern Australia will allow for more efficient growth and product yield; • The development of premium-grade rices for health and high-end markets, which align with the SunRice strategy; and • The development of a distinct northern Australian variety with traits from native rice will result in a unique product with expected improved market value.

		• *In-kind support from the Australian Rice Partnership for pre-breeding ($100,000).*	
2. Establish a Standing Industry Steering Committee: Create an ongoing Steering Committee to serve as a stable, longitudinal resource for the developing industry. The committee will provide leadership, guidance, support and oversight of sector progress. (Refer to Recommendation 3).	**SunRice** ·QAAFI UQ ·CDU ·QDAF ·WA DPIRD ·CRCNA ·Savannah Ag Consulting NT Farmers NACRA	This recommendation will formally establish a strategic leadership committee that supports the developing northern industry and allows for stakeholder ownership of the sector. Committee members will be drawn from each jurisdiction and include sectoral stakeholders from across the supply chain to ensure that the leadership and guidance provided is up-to-date, accurate and representative of the whole industry. Members of the CRCNA Project 'A Situational Analysis for Developing a Rice Industry in Northern Australia' will be invited to serve as the inaugural Steering Committee; however, the committee should have the flexibility to recruit new representatives as it evolves. The first point of business for the committee should be to establish strong governance arrangements that effectively represent all of the relevant stakeholders within the sector needed to advance the industry. The committee should commit to meeting twice a year to develop, implement and review a clear Industry Development Plan and to encourage, discuss and monitor the progress of the ongoing development of the rice industry in northern Australia. Ensuring that the committee continues to have the correct membership and is comprehensively representative of the industry will be an ongoing responsibility of the committee. This committee can be used to review and critique future proposals for research and development funding for the sector, to ensure that funds and efforts are broadly beneficial, maximised and aligned for the greatest benefits. The Steering Committee will also aid in the broad promotion of the industry and its developments. *Initially, to avoid delays in the achievement of this important activity, committee members will be asked to use existing resources to fund any required travel costs for foundational committee meetings. Small funding allocations in the order of $5-10k per meeting may be sought from partners or stakeholder*	Implementing this recommendation will: • Provide the leadership and guidance that will help the industry grow; • Leverage requisite government support and buy-in for the forward development of the northern Australia rice industry; • Reduce industry input costs by aligning strategies for mutually beneficial outcomes; and • Provide a beneficial core resource for consultation by funding bodies, growers and other relevant stakeholders.

		groups (e.g. SunRice, QAAFI, the three state governments and the CRCNA) to cover meeting space, secretariat services (which will include communication around the development of meeting arrangements, minute taking and report preparation) and incidental meeting costs. The development of a more sustainable funding source for meeting activities will be discussed.	
3. Develop a 'Sector Development Officer' Role. This role will monitor the growth of the sector and oversee the research and development programs for the industry across northern Australia. It will convene the Standing Industry Steering Committee. It will also increase the capacity for growers, generate momentum and pride for the industry within local communities and improve overall sector knowledge across the supply chain.	**SunRice** ·NT DPIR ·WA DPIRD ·QDAF ·CRCNA ·QAAFI UQ NT Farmers Growcom NACRA	This should be a part-time predominantly strategic **communications and engagement** role. The role would work very closely with the Steering Committee to help fulfil their objectives and deliver the industry targets listed above (refer to Recommendation 2). The Sector Development Officer should work to promote the industry to stakeholders across the value chain. A successful northern Australian rice industry will require the support of local growers and communities. The potential benefits rice can provide to farmers and the northern Australian economy are clear, but growers still need to be persuaded. This position will engage with growers, processors and end-users, including local restaurants to understand consumer needs and requirements and target future efforts towards these desires. The role would work comprehensively across the three jurisdictions. The objectives (and potentially time commitment) of this role will evolve and shift as the industry develops over time. *This role is proposed as a 0.5 FTE position. It is recommended that the position be funded as an in-kind contribution from SunRice ($100,000/yr for 5 years). Additional operational funding for the role is expected to come jointly from multiple organisations across the sector, for example industry bodies, government agencies from the three jurisdictions and potentially academic institutions (e.g. QAAFI).*	This role will provide benefits through: • Fostering the emerging rice grower base to lift current productivity in the northern industry by ~15x; • Value addition to the industry through partnership building; and • Increased community and stakeholder awareness and buy-in for the industry through media, field days and promotional events.
4. Develop an 'Industry Research and Development Coordinator' Role.	**QDAF/ SunRice** ·NT DPIR	A role should be created through SunRice/QDAF for a Northern Australia Rice Industry Development Officer. This will provide a significant **research** development component for the industry. The role will work across the three northern Australian jurisdictions.	Implementing this recommendation will: • Link the three northern jurisdictions, which would provide

The Industry Research and Development Coordinator will broadly coordinate the R&D efforts of the sector. They will help identify R&D needs and promote these needs to raise funds for the work.	·WA DPIRD ·CRCNA ·Savannah Ag Consulting NT Farmers Growcom NACRA	This position should be responsible for prioritising, facilitating and coordinating work on the development of crops and agronomic processes for native wild rice, domesticated rice grown in the north, and developing new genetic varieties specifically targeted to the conditions of northern Australia. The position will also look into agronomic strategies for developing the most effective and economically viable crop rotation options for northern Australian farmers. For example, this could include the exploration of options (and timing) for rotational farming systems in northern Australia, such as • Sugarcane • Pulses/Safflower/Sunflower • Hemp/Linseed/Canola/Mustards/Nigella/Camelina/ Sunflowers This position will also critically assess the best agronomic processes in consideration of local regulations (e.g. farming practices in the GBR runoff region). The role will report to the Steering Committee. *The lead role is proposed as a 0.5 FTE role funded 50/50 by SunRice and QDAF (at a cost of $100,000/yr for 5 years), with supplemental resourcing from the other two northern Australia jurisdictions. The position will be based at Mareeba.*	capacity to assess different environments and improve the diversity of options available; • Increase regional R&D capacity; • Attract a greater degree of R&D investment towards developing the industry and ensure that the funding is maximised in terms of value-for-money and in-line with the most pressing industry needs; • Generate rice development capacity and capability in northern Australia; and • Generate awareness of the research headway made by the industry through scientific forums.
5. Create a Work Program to Establish a Sound Legal Framework and Improve Access and Benefit Sharing of Northern Australian Rice:	**QAAFI UQ** ·CDU ·QLD Government ·NT Government ·WA Government	A major challenge in progressing new developments in agribusiness is legally and ethically gaining access to and utilising natural assets (such as plant material) with consideration to land owners. There is also considerable conflict between state/territory and international laws such as the *International Treaty on Plant Genetic Resources* and the *Nagoya Protocol*. In collaboration with state/territory government bodies, the process needs to be tested and eased to prevent unworkable legislation from being a barrier to biodiscovery and agribusiness growth. This process will help to develop access	Implementing this recommendation will: • Ensure fair and equitable sharing of benefits that flow back to the most appropriate party/parties as rice varieties are developed for northern Australia;

Continue to test and advocate for more workable biodiscovery legal frameworks.	Land councils eg. NLC, KLC Centrefarm NT Farmers Growcom NACRA	and benefit sharing arrangements across all three northern Australian jurisdictions, which will aid the development of a successful rice industry that follows international best practice (and allows product access to international markets). Discussions should continue with the Queensland and Northern Territory governments on how the acts might need to be changed in order to harmonise legislation with the FAO Treaty and how benefit sharing arrangements can operate through FAO multilateral arrangements. Discussions should also be held with the Western Australian government to influence relative legislation as it develops. This action has already begun and is ongoing. It is recommended that this work continue on as a service to the industry, through the contribution of researchers' time. In some cases, progress in this space may result from externally funded activities. The Sector Development Officer should aid in liaising with government representatives and stakeholders and coordinate efforts towards achieving this activity. *This work will be a contribution of QAAFI and others partners who will continue to lead the activity. The initiative should be matched by access and support from the state and territory governments.*	• Preserve the important cultural, ecological and economic value of native Australian rices; • Ensure that access to native wild rice is possible for R&D and commercialisation purposes; • Assist with capacity building and facilitate opportunities for Indigenous enterprise development using native rice; and • Inform biodiscovery and agribusiness best practice, more broadly.
6. Develop Varietal Simulation Modelling and Evaluation: Extend capacity and studies using APSIM next-gen modelling for growth/yield and management strategies for rice cultivars developed for northern Australia.	**USQ (modelling)** **SunRice (evaluation)** ·Savannah Ag Consulting	Modelling the growth and yield of a range of cultivars by management scenarios (sowing date and fertiliser regimens) is currently being done under a Rural R&D for Profit project. Modelling results are being backed-up with nitrogen fertiliser and cultivar evaluation field experiments on the Tablelands and in the Burdekin. The aim of modelling is to identify potential site-specific management packages to maximise yield and minimise negative effects on the environment (e.g. the Great Barrier Reef). Results can feed into a simple mapping tool that highlights go/no-go areas for rice crops and management practices. The Rural R&D for Profit project will conclude in April 2020, but further work using next-gen APSIM modelling that builds on the significant foundations developed would be beneficial.	The implementation of this recommendation will mean that efforts are focused on the most desirable and likely rice variety candidates for growth in the northern Australian environments. This work will provide important insight that will feed into the Rice Breeding and Varietal Development Program (see Recommendation 1).

		Future modelling should be improved to capture tillering (as there is significant diversity in the tillering behaviours of some of the cultivars grown in north Queensland) and the uniqueness of the northern Queensland rice cropping system. The new rice model would enable more accurate modelling of the rice system and specific cultivars, the option to bring in diseases and pests, and better modelling of irrigation and nutrients other than nitrogen. This would allow for greater potential to provide new growers site-specific recommendations to maximise yields and minimise environmental impacts and expansion to crop protection recommendations. Modelling should also be extended to Western Australia and the Northern Territory, and include new cultivars and varieties, as they evolve, and be applied not only to present conditions, but also used to predict and mitigate potential issues for future production due to changing climate/environmental conditions. This activity will expedite the generation of agronomic best practice for growing rice in different regions within the north. It will also help to identify where the yield gap between modelled outcomes and actual production could be. Detail from the variety assessment trials will feed into modelling work. *The modelling work will require a 0.5 FTE position ($75,000/yr for 5 years), plus operational and field trial expenditure of $200,000/yr for 5 years. Funding for the role is proposed to come from the CRCNA.* *SunRice will contribute a 1.0 FTE position to lead variety evaluation ($100,000/yr for 5 years).*	This study will provide advantages in: • Substantial time and resource saving for the industry through prediction of the most productive and profitable cultivars/agronomic practices; • Curtailing detrimental industry impacts due to biotic and abiotic stressors; • Identifying the most profitable and sustainable site-specific rice varieties and production processes; • Ensuring the industry can be productive, while also compliant with current and evolving environmental protection regulations and for future climate/environmental conditions; • Providing support for recruiting new growers into rice production; and • The production of higher quality, more differentiated rice products.
7. Development of a Management/ Conservation Plan for Australian Native Rices: Identify the management and conservation	**JCU/Australian Tropical Herbarium** ·CDU ·QAAFI UQ	Australian native rices are a significant asset (genetically and from a biodiversity perspective), but their conservation is under threat from land use change and weed invasion. Conservation efforts are important for the ecological sustainability of northern Australian ecosystems, but also the genetic material that will likely be required for developing a successful and sustainable commercial rice industry in the north.	Implementing this recommendation will: • Ensure that Australian wild rice genetic resources are maintained for use in breeding locally adapted rice in northern Australia;

needs/actions for protecting the living and genetic resources of native (wild) Australian rices.		This project should trial control strategies considering factors such as weeds and cultural/ environmental/biodiversity implications for commercial harvesting. Based on those considerations, feasible management plans for native rices should be developed in conjunction with government and non-government land managers. The priority management issue should be aquatic weeds. Weed invasion is one of the biggest threats to wild stocks of native rice, so effort needs to be initially focused here. Innovative new strategies are also needed to raise the profile of the value of wild rice resources. Efforts should also be made to integrate research outcomes into management applications in a translational capacity. This activity could potentially lead into a very significant cross-northern Australia biodiversity investment in partnership with Traditional Owners and philanthropic donors within a few years. Collaborations will be investigated with regional natural resource management bodies, Indigenous land management organisations (e.g. NAILSMA) and national parks. *This activity is recommended as a PhD study, with the student scholarship funded by JCU or CDU. Operating costs ($15,000/yr for 4 years) should be provided by the CRCNA.*	• Help to maintain native rice populations in their natural habitats for cultural purposes; • Ensure that the ecological roles of wild rice species are maintained and they continue to contribute to the sustainability of northern Australian ecosystems, especially wildlife; and • Contribute to more extensive collections in seed banks for ongoing research and development.
8. Review Options for Storage and Drying Infrastructure: Develop a report into the best options for storage and drying infrastructure for the north, and cross-industry storage capacity and compatibility.	**SunRice**	The ability to adequately store and dry rice in tropical climates is considered to be one of the greatest challenges to the development of the industry. It is recommended that a report be developed into storage and drying infrastructure options for use in northern Australia. The report should consider emerging information about storing and drying other crop products in northern Australia (e.g. GRDC study on grain storage), as well as investigating strategies used for rice in comparable high-humidity climates around the world (e.g. southern USA). This should also be an exploratory activity to see where the rice industry can link in with other tropical grain industries to maximise research efforts and funding in this space. Industry funding and research partner collaborations (e.g.	Implementing this recommendation will: • Provide the best options for tackling this current hurdle within the rice production process in northern Australia; • Ultimately lead to reduced loss of product from damage due to improper storage and drying, and therefore greater income for producers; and

		through the establishment of a PhD project) can potentially be used to leveraged further funding. *This activity will be linked to a broader grains storage initiative. This should be costed within the CRCNA grains program. It is suggested that the report is produced as a PhD project on understanding tropical grain storage.*	• Create a platform to seek funding for this costly, but crucial infrastructure.
9. Further Engagement with Indigenous groups: Commercial production of wild and native rices could present excellent opportunities for Indigenous enterprises. Regional Indigenous groups should be identified and engaged in order to initiate collaborations.	**SunRice (Sector Development Officer)** ·CRC FFS ·CDU ·QAAFI UQ ·Regional/state governments Land Councils eg. NLC & KLC Centrefarm NAILSMA	One of the initial steps in the process of Indigenous engagement will be to develop mutually beneficial access and benefit sharing agreements (refer to Recommendation 5). Following this, opportunities for engagement and collaboration with regional Indigenous groups across the north should be explored. This comprises a significant component of the CRC Future Food Systems (CRC FFS) project. Collaborations and input should be sought from new potential partners, such as state/territory agencies, land councils, Indigenous corporations and enterprises, government agencies, and third-sector partners across jurisdictions. This initiative should come from the Steering Committee. *SunRice has already appointed a staff member who will work in this space. QAAFI leads an ARC Training Centre for Uniquely Australian Food and will connect into this activity.*	Implementing this recommendation will: • Assist with capacity building and facilitate opportunities for Indigenous enterprise development using native rice; and • Create jobs in rural and remote Australia.
10. Develop Crop Protection Strategies: Identification and control of weeds, assessment of pests and establishment of the best pesticides and treatment regimes.	**JCU** **QAAFI UQ** ·Agripraisals	A greater understanding of the presence and biology of current and future weeds relevant to rice production in northern Australian will need to be gained. Once identified, appropriate measures for control will need to be established. Similarly, control measures and management strategies will also need to be established for pests and diseases. *It is recommended that this work be carried out as two PhD projects, run through JCU, QAAFI or other universities, as relevant. $15,000/yr for 4 years for operating costs should be contributed from the CRCNA.*	This study will provide: • Improved productivity in rice crops in northern Australia; • Reduced environmental impact from growing rice through more targeted and environmentally friendly ways of controlling weeds; and • The development of integrated weed management for rice systems.

[1] SunRice 2019. Developing the North Queensland Rice Industry.

[2] Deloitte Access Economics (2018). Economic activity attributable to crop protection products. CropLife Australia.

10 References

ABARES [Australian Bureau of Agriculture and Resource Economics and Science] (2019). Australian Crop Report. No. 192. December 2019. https://www.agriculture.gov.au/sites/default/files/documents/austcroprrt20191203_v1.0.0.pdf

ACIAR [Australian Centre for International Agricultural Research] (2016). Improved rice germplasm for Cambodia and Australia. Final Report: CSE/2009/005.

AEGIC [Australian Export Grains Innovation Centre] (2018). Australia's grain supply chains: Costs, risks and opportunities. https://www.aegic.org.au/wp-content/uploads/2019/01/FULL-REPORT-Australias-grain-supply-chains-DIGITAL__.pdf

AgriFutures Australia (2017). Rice. [Accessed May 2019]. https://www.agrifutures.com.au/farm-diversity/rice/

AgriFutures Australia (2018). Improving the productivity, profitability and sustainability of the Australian rice industry — 2018. Rice R&D Update Publication No. 18/026. [Accessed May 2019]. https://static1.squarespace.com/static/5a03c05bd0e62846bc9c79fc/t/5bab1c517817f7d7fb0f6726/1537940692521/Rice+RD+Update-2018.pdf

Airey DR, Dasari NR, Drover DP, Williams N (1981). Rice Research and Demonstration Program for the NT— A Protocol, Technical Bulletin No. 50. NT Department of Primary Production. 17 pp.

Akihisa T, Yasukawa K, Tamaura T, Ukiya M, Kimura Y, Shimizu N, Takido M (2000). Triterpene alcohol and sterol ferulates from rice bran and their anti-inflammatory effects. Journal of Agricultural and Food Chemistry 48, 2313–2319.

Aladedunye F, Przybylski R, Rudzinska M, Klensporf-Pawlik D (2013). γ-Oryzanols of North American wild rice (*Zizania palustris*). Journal of the American Oil Chemists' Society 90, 1101–1109. DOI 10.1007/s11746-013-2252-x

Aldrick S, Buddenhagen I, Reddy A (1973). The occurrence of bacterial leaf blight in wild and cultivated rice in northern Australia. Australian Journal of Agricultural Research 24(2), 219–227.

Aljumaili SJ, Rafii MY, Latif MA, Sakimin SZ, Arolu IW, Miah G (2018). Genetic diversity of aromatic rice germplasm revealed by SSR markers. BioMed Research International. 2018, Article ID 7658032. https://doi.org/10.1155/2018/7658032

Ammiraju JS, Lu F, Sanyal A, Yu Y, Song X, Jiang N, Pontaroli AC, Rambo T, Currie J, Collura K, Talag J, Fan C, Goicoechea JL, Zuccolo A, Chen J, Bennetzen JL, Chen M, Jackson S, Wing RA (2008). Dynamic evolution of *Oryza* genomes is revealed by comparative genomic analysis of a genus-wide vertical data set. The Plant Cell 20(12), 3191–3209. doi: 10.1105/tpc.108.063727

Asafu-Adjaye J (1996). Traditional production activities and resource sustainability: The case of Indigenous societies in Cape York Peninsula, Australia. International Journal of Social Economics 23, 125–135.

Ash A, Gleeson T, Hall M, Higgins A, Hopwood G, MacLeod N, Paini D, Poulton P, Prestwidge D, Webster T, Wilson P (2017). Irrigated agricultural development in northern Australia: Value chain challenges and opportunities. Agricultural Systems 155, 116–125. https://doi.org/10.1016/j.agsy.2017.04.010

Ash A, Watson I (2018). Developing the north: Learning from the past to guide future plans and policies. The Rangeland Journal 40, 301–314. https://doi.org/10.1071/RJ18034

Bajwa AA, Chauhan BS (2017). Rice production in Australia. In: B.S. Chauhan et al. (eds). Rice Production Worldwide. Springer International Publishing. Pp. 169–184. DOI 10.1007/978-3-319-47516-5_6

Ballini E, Nguyen T, Morel J-B (2013). Diversity and genetics of nitrogen-induced susceptibility to the blast fungus in rice and wheat. Rice 6, 32. doi:10.1186/1939-8433-6-32

Barber M (2018). Settling for dams?: Planning for sustainable Indigenous livelihoods within large-scale irrigated agricultural development in north Queensland, Australia. The Rangeland Journal 40, 365–379.

Berger A, Rein D, Schäfer A, Monnard I, Gremaud G, Lambelet P, Bertoli C (2005). Similar cholesterol-lowering properties of rice bran oil, with varied γ-oryzanol in mildly hypercholesterolemic men. European Journal of Nutrition 44,163–173.

Bhattacharjee P, Singhal SR, Kulkarni PR (2002). Basmati Rice: A review. International Journal of Food Science and Technology 37, 1–12.

Boyden J, Wurm P, Joyce KE, Boggs G (2018). A spatial vulnerability assessment of monsoonal wetland habitats to para grass invasion in Kakadu National Park, northern Australia. International Journal of Applied Earth Observation and Geoinformation 71, 43–55.

Bradbury LMT, Fitzgerald TL, Henry RJ, Jin Q, Waters DLE (2005). The gene for fragrance in rice. Plant Biotechnology Journal 3, 363-370.

Brar D, Khush G (1997). Alien introgression in rice. In: Oryza: From Molecule to Plant. Springer. Pp. 35–47.

Brozynska M, Furtado A, Henry RJ (2016). Genomics of crop wild relatives: Expanding the gene pool for crop improvement. Plant Biotechnology Journal 14(4), 1070–1085. doi: 10.1111/pbi.12454

Brozynska M, Omar ES, Furtado A, Crayn D, Simon B, Ishikawa R, Henry RJ (2014). Chloroplast genome of novel rice germplasm identified in northern Australia. Tropical Plant Biology 7, 111–120. https://doi.org/10.1007/s12042-014-9142-8

Brozynska M, Copetti D, Furtado A, Wing RA, Crayn D, Fox G, Ishikawa R, Henry R J (2017). Sequencing of Australian wild rice genomes reveals ancestral relationships with domesticated rice. Plant Biotechnology Journal 15, 765–774. https://doi.org/10.1111/ pbi.12674

Burt J (2002). Review of the potential for growing rice at the Ord River Irrigation Area in Kununurra Western Australia. Trade and Development Technical Report. Department of Agriculture Western Australia.

Calingacion MN, Laborte A, Nelson A, Resurreccion AP, Concepcion JCT, Daygon VD, Mumm R, Reinke R, Dipti SS, Bassinello PZ, Fitzgerald MA (2014). Diversity of global rice markets and the science required for consumer-targeted rice breeding. PLoS One 9, e85106.

Cardello AV (1995). Food quality: Relativity, context and consumer expectations. Food Quality and Preference 6(3), 163–170. doi.org/10.1016/0950-3293(94)00039-X

Carlson RR, Foo SA and Asner GP (2019) Land use impacts on coral reef health: A ridge-to-reef perspective. Frontiers in Marine Science 6, 562. doi: 10.3389/fmars.2019.00562

CBI [Center for the Promotion of Imports] (2017). Exporting specialty rice varieties to Europe. CBI, Ministry of Foreign Affairs. [Accessed 15.04.2020]. https://www.cbi.eu/market-information/grains-pulses-oilseeds/specialty-rice-varieties/

Chen H, Siebenmorgen T, Griffin K (1998). Quality characteristics of long-grain rice milled in two commercial systems. Cereal Chemistry 75**,** 560–565.

Chen S, Li W, Huang X, Chen B, Zhang T, Zhou G (2019). Symptoms and yield loss caused by rice stripe mosaic virus. Virology Journal 16, 145. doi.org/10.1186/s12985-019-1240-7

Concepcion JCT, Ouk M, Zhao D, Fitzgerald MA (2015). The need for net tools and investment to improve the accuracy of selecting for grain quality in rice. Field Crops Research 182, 60–67. http://dx.doi.org/10.1016/j.fcr.2015.05.003

Cother E (2006). Survey of Australian rice blast races and cultivar susceptibility: CRCNPB-RIRDC CRC0005 Milestone 1 Report. CRC National Plant Biosecurity, Canberra.

Dale AP (2018). From conflict to collaboration: can better governance systems facilitate the sustainable development of the northern pastoral industry, communities and landscapes? The Rangeland Journal 40(4), 331–340. https://www.publish.csiro.au/RJ/RJ18010

Darby J (2000). Aeration control developments. Australian Postharvest Technical Conference. Pp. 39–46.

Dasgupta P (2007). Nature and the economy. Journal of Applied Ecology 44, 475– 487.

Department of Agriculture, Water and the Environment (n.d.). Rice. [Accessed 19.04.2020]. https://www.agriculture.gov.au/ag-farm-food/crops/rice

Department of the Environment and Heritage (2005). Genetic Resources Management in Commonwealth Areas. https://www.environment.gov.au/system/files/resources/3c2b83b4-290a-413a-b56d-c9083bdc05c7/files/regs.pdf

DPIR [Department of Primary Industry and Resources] (2018). Northern Territory 2018 Plant Quarantine Manual. Northern Territory Government, Department of Primary Industry and Resources. https://dpir.nt.gov.au/__data/assets/pdf_file/0011/396587/Plant-Quarantine-Manual.pdf

FAO [Food and Agricultural Organisation] (2012). Rice Market Monitor. XV (4): November 37.

FAO [Food and Agricultural Organisation] (2013). FAOSTAT Database. Food and Agricultural Organization, Rome.

FAO [Food and Agriculture Organization of the United Nations] (2018). FAO Rice Market Monitor, April 2018, Volume XXI – Issue No 1. Trade and Markets Division, Food and Agriculture Organization of the United Nations. 27 April 2018. 38 pp. http://www.fao.org/3/I9243EN/i9243en.pdf

FAO [Food and Agriculture Organization of the United Nations] (2020). World Food Situation. [Accessed 19.04.2020]. http://www.fao.org/worldfoodsituation/csdb/en/

FAO [Food and Agriculture Organization of the United Nations] (n.d.). FAOSTAT: Crops. [Accessed 10.04.2020]. http://www.fao.org/faostat/en/#data/QC/visualize

Fitzgerald MA, McCouch SR, Hall RD (2009). Not just a grain of rice: The quest for quality. Trends in Plant Science 14, 133–139.

Ford R (2019). Meeting the Consumer Preference of High Quality Rice Grown in a Tropical Environment. [Oral Presentation]. TropAg 2019 Conference: Brisbane, Australia, 13 November 2019.

Gaydon DS, Probert ME, Buresh RJ, Meinke H, Suriadi A, Dobermann A, Bouman B, Timsina J (2012). Rice in cropping systems – modelling transitions between flooded and non-flooded soil environments. European Journal of Agronomy 39, 9–24.

Ge S, Sang T, Lu B-R, Hong D-Y (1999). Phylogeny of rice genomes with emphasis on origins of allotetraploid species. Proceedings of the National Academy of Science of the USA 96, 14400–14405.

Giraud G (2013). The world market of fragrant rice, main issues and perspectives. International Food and Agribusiness Management Review 16(2), 1–20.

Gray MC, Altman JC, Halasz N (2005). The economic value of wild resources to the Indigenous community of the Wallis Lakes catchment. Centre for Aboriginal Economic Policy Research, The Australian National University, Canberra, ACT.

GRDC [Grains Research and Development Corporation] (2018). Research, Development and Extension Plan 2018-23. https://rdeplan.grdc.com.au/wp-content/uploads/grdc-rde-full-plan-2018-23.pdf

Greer CA, Webster RK (2001). Occurrence, distribution, epidemiology, cultivar reaction, and management of rice blast disease in California. Plant Disease 85, 1096–1102.

Gross BL, Zhao Z (2014). Archaeological and genetic insights into the origins of domesticated rice. Proceedings of the National Academy of Science of the USA 111, 6190–6197.

Grunert KG (2005). Food quality and safety: Consumer perception and demand. European Review of Agricultural Economics 32(3), 369–391.

Henry RJ, Rangan P, Furtado A (2016). Functional cereals for production in new and variable climates. Current Opinion in Plant Biology 30, 11–18.

Henry R, Rice N, Waters DE, Kasem S, Ishikawa R, Hao Y, Dillon S, Crayn D, Wing R, Vaughan D (2010). Australian *Oryza*: Utility and conservation. Rice 3, 235–241.

Hibino H (1996). Biology and epidemiology of rice viruses. Annual Review of Phytopathology 34(1), 249–274.

index mundi (n.d.). Commodity Prices: Rice. [Accessed 14.04.2020]. https://www.indexmundi.com/commodities/?commodity=rice&months=120&currency=aud

IRRI [International Rice Research Institute] (n.d.). Rice Knowledge Bank: Storage. [Accessed 11.10.2019]. http://www.knowledgebank.irri.org/step-by-step-production/postharvest/storage

Itani T, Fushimi T (1996). Influence of pre- and post-harvest conditions on 2 acetyl-1-pyrroline concentration in aromatic rice. Proceedings of the Second Asian Crop Science Conference, Fukui, Japan, 21–23 Aug 1995.

Jarvis D, Stoeckl N, Addison J, Larson S, Hill R, Pert P, Lui FW (2018). Are Indigenous land and sea management programs a pathway to Indigenous economic independence? The Rangeland Journal 40(4), 415–429. doi.org/10.1071/RJ18051

Jena KK, Jeung J-U, Lee J-H, Choi H, Brar DS (2006). High-resolution mapping of a new brown planthopper (BPH) resistance gene, Bph18(t), and marker-assisted selection for BPH resistance in rice (*Oryza sativa* L.). Theoretical and Applied Genetics 112(2), 288–297.

Jeung J, Kim B, Cho Y, Han S, Moon H, Lee Y, Jena K (2007). A novel gene, Pi40 (t), linked to the DNA markers derived from NBS-LRR motifs confers broad spectrum of blast resistance in rice. Theoretical and Applied Genetics 115, 1163–1177.

Juliano C, Cossu M, Alamanni MC, Piu L (2005). Antioxidant activity of gamma-oryzanol: mechanism of action and its effect on oxidative stability of pharmaceutical oils. International Journal of Pharmaceutics 299, 146–154.

Kato H (2001). Rice blast disease. Pesticide Outlook 12, 23–25.

Khemmuk W (2016). Plant pathogenic *Magnaporthales* in Australia, with particular reference to *Pyricularia oryzae* on wild and cultivated rice. PhD Thesis, The University of Queensland, Brisbane, Australia. 193 pp.

Khemmuk W, Shivas RG, Henry RJ, Geering ADW (2016). Fungi associated with foliar disease of wild rice and cultivated rice (*Oryza* spp.) in northern Queensland. Australasian Plant Pathology 45, 297–308. doi:10.1007/s13313-016-0418-3

Khush G (1997). Origin, dispersal, cultivation and variation of rice. In: T Sasaki, G Moore (eds). *Oryza*: From Molecule to Plant. Springer Netherlands. Pp. 25–34.

Khush GS, Angeles E, Virk PS, Brar DS (2004). Breeding rice for resistance to tungro virus at IRRI. SABRAO Journal of Breeding and Genetics 36(2), 101–106.

Kiprop V. Continents by Population. WorldAtlas, 12 Jun 2019. [Accessed 13.04.2020]. worldatlas.com/articles/continents-by-population.html.

Lanoiselet VM, Cother EJ, Ash GJ (2002). CLIMEX and DYMEX simulations of the potential occurrence of rice blast disease in south-eastern Australia. Australasian Plant Pathology 31(1), 1–7.

Lanoiselet V (2016). Characterisation of rice blast races present in Australia. RIRDC Publication No 17/002. Australian Government Rural Industries Research and Development Corporation, Canberra. 62 pp. https://www.agrifutures.com.au/wp-content/uploads/publications/17-002.pdf

Lerma-García MJ, Herrero-Martínez JM, Simó-Alfonso EF, Mendonça CRB, Ramis-Ramos G (2009). Composition, industrial processing, and applications of rice bran c-oryzanol. Food Chemistry 115, 389–404.

Li X, Guo Z, Lv Y, Cen X, Ding X, Wu H, Li X, Huang J, Xiong L (2017). Genetic control of the root system in rice under normal and drought stress conditions by genome-wide association study. PLoS Genetics 13(7), e1006889. https://doi.org/10.1371/journal. pgen.1006889

Liu J, Wu X, Yao X, Yu R, Larkin PJ, Liu C-M (2018). Mutations in the DNA demethylase *OsROS1* result in a thickened aleurone and improved nutritional value in rice grains. Proceedings of the National Academy of Sciences 115(44), 11327–11332. DOI: 10.1073/pnas

Lu F, Ammiraju JSS, Sanyal A, Zhang S, Song R, Chen J, Li G, Sui Y, Song X, Cheng Z, de Oliveira AC, Bennetzen JL, Jackson SA, Wing RA, Chen M (2009). Comparative sequence analysis of MONOCULM1-orthologous regions in 14 *Oryza* genomes. Proceedings of the National Academy of Sciences of the USA 106, 2071–2076.

Matsumoto K, Ota Y, Seta S, Nakayama Y, Ohno T, Mizobuchi R, Sato H (2017). Identification of QTLs for rice brown spot resistance in backcross inbred lines derived from a cross between Koshihikari and CH45. Breeding Science 67(5), 540–543. https://doi.org/10.1270/jsbbs.17057

Mejía DJ (2003). An overview of rice post-harvest technology: Use of small metallic silos for minimizing losses. In: Sustainable Rice Production for Food Security. Proceedings of the 20th Session of the International Rice Commission. Food and Agriculture Organization of the United Nations, Rome. [Accessed Dec 2019]. http://www.fao.org/3/Y4751E/y4751e0o.htm#bm24

Meyer RS, Choi JY, Sanches M, Plessis A, Flowers JM, Amas J, Dorph K, Barretto A, Gross B, Fuller DQ, Bimpong IK, Ndjiondjop M-N, Hazzouri KM, Gregorio GB, Purugganan MD (2016). Domestication history and geographical adaptation inferred from a SNP map of African rice. Nature Genetics 48(9),1083–1088. pmid:27500524

Mizobuchi R, Fukuoka S, Tsushima S, Yano M, Sato H (2016). QTLs for resistance to major rice diseases exacerbated by global warming: Brown spot, bacterial seedling rot, and bacterial grain rot. Rice 9, 23. doi: 10.1186/s12284-016-0095-4

Molina J, Sikora M, Garud N, Flowers JM, Rubinstein S, Reynolds A, Huang P, Jackson S, Schaal BA, Bustamante CD, Boyko AR, Purugganan (2011). Molecular evidence for a single evolutionary origin of domesticated rice. Proceedings of the National Academy of Science of the USA. 108(20), 8351–8356. https://doi.org/10.1073/pnas.1104686108

Mollah WS (1982). Humpty Doo: Rice in the Northern Territory. Australian National University. 30 pp.

Moner AM, Furtado A, Chivers I, Fox G, Crayn D, Henry RJ (2018). Diversity and evolution of rice progenitors in Australia. Ecology and Evolution 8(8), 4360–4366. DOI: 10.1002/ece3.3989

Moskowitz HR (1995). Food quality: conceptual and sensory aspects. Food Quality and Preference 6, 157–162.

Nalley L, Tsiboe F, Durand-Morat A, Shew A, Thoma G (2016). Economic and environmental impact of rice blast pathogen (*Magnaporthe oryzae*) alleviation in the United States. PLoS ONE 11(12), e0167295. doi:10.1371/journal. pone.0167295

OECD/FAO (2018). Chapter 3. Cereals. OECD-FAO Agricultural Outlook 2018-2027, OECD Publishing, Paris/Food and Agriculture Organization of the United Nations, Rome. Pp. 109–265. https://doi.org/10.1787/agr_outlook-2018-en

Ou SH (1972). Studies on stable resistance to rice blast disease. In: Rice Breeding. International Rice Research Institute, Los Banos, Laguna, Philippines. Pp 227–237.

Ou SH (1985). Rice Diseases (2nd ed). Commonwealth Mycological Institute, Kew, UK.

Orge R, Abon JEO (2014). Local development of a hermetic storage container for quality preservation of rice seeds in the Philippines. OIDA International Journal of Sustainable Development 7(9), 11–20.

Petheram C, Gallant J, Wilson P, Stone P, Read A, Eades G, Tickell S, Commander P, Moon A, McFarlane D, Marvanek S (2014). Northern Rivers and Dams: A Preliminary Assessment of Surface Water Storage Potential for Northern Australia. CSIRO Land and Water Flagship Technical Report. CSIRO, Australia.

Petheram C, Tickell S, O'Gara F, Bristow KL, Smith A, Jolly P (2008). Analysis of the Lower Burdekin, Ord and Katherine-Douglas-Daly Irrigation Areas: Implications to future design and management of tropical irrigation. CRC for Irrigation Futures Technical Report No. 05/08, February 2008. [Accessed May 2019]. http://www.clw.csiro.au/publications/science/2008/sr19-08.pdf

Pietsch D (2019). 2019 proves a year for sugar to forget and reset. Queensland Country Life. 30 Dec 2019. [Accessed 04.03.2020]. https://www.queenslandcountrylife.com.au/story/6561267/sugar-2019-proves-a-year-to-forget-and-reset/

Plant Health Australia (2017). National Plant Biosecurity Status Report 2016. Plant Health Australia, Canberra, ACT. https://www.planthealthaustralia.com.au/wp-content/uploads/2019/05/2016-National-Plant-Biosecurity-Status-Report.pdf

Prasad R, Shivay YS, Kumar D (2017). Current status, challenges, and opportunities in rice production. In: BS Chauhan et al. (eds). Rice Production Worldwide. Springer International Publishing AG. Pp 1–32. DOI 10.1007/978-3-319-47516-5_6

QEAS [Queensland Economic Advocacy Solutions] (2019). The economic contribution of the sugarcane industry to Queensland and its regional communities. Prepared for: Canegrowers. July 2019. [Accessed March 2020]. http://www.canegrowers.com.au/icms_docs/310175_economic-contribution-of-the-sugarcane-industry-to-queensland.pdf

Rathna Priya TS, Nelson ARLE, Ravichandran K, Antony U (2019). Nutritional and functional properties of coloured rice varieties of South India: A review. Journal of Ethnic Foods 6,11. https://doi.org/10.1186/s42779-019-0017-3

Redhead TD (1979). On the demography of *Rattus sordidus colletti* in monsoonal Australia. Australian Journal of Ecology 4(1), 115–136.

RGA [Ricegrowers' Association of Australia INC] (n.d.). The Rice Industry: About the Rice Industry. [Accessed Feb 2020]. https://www.rga.org.au/Public/The_Rice_Industry/About-the-Rice-Industry/Public/Content/The_Rice_Industry/Rice-Industry.aspx?hkey=a60cd680-81fb-468d-8037-74fc74cc58c3

RGA [Ricegrowers' Association of Australia Inc.] (2019a). [Accessed May 2019]. https://www.rga.org.au/.

RGA [Ricegrowers' Association of Australia Inc.] (2019b). Australia is the best country in the world to grow rice. [Accessed 15.04.2020]. https://www.rga.org.au/Public/Content/Education_and_Resources/Social-and-Economic-Facts.aspx

Ricepedia (n.d.). Rice productivity. [Accessed May 2019]. http://ricepedia.org/rice-as-a-crop/rice-productivity.

Rosentrater K, Evers A (2018a). Chapter 1: Introduction to cereals and pseudocereals and their production. In: Kent's Technology of Cereals (Fifth Edition): An Introduction for Students of Food Science and Agriculture. Woodhead Publishing Series in Food Science, Technology and Nutrition, Elsevier. Pp. 1–76. https://doi.org/10.1016/B978-0-08-100529-3.00001-3

Rosentrater K, Evers A (2018b). Chapter 2: Production, uses and trade of cereals by continental regions. In: Kent's Technology of Cereals (Fifth Edition): An Introduction for Students of Food Science and Agriculture. Woodhead Publishing Series in Food Science, Technology and Nutrition, Elsevier. Pp. 77–204. https://doi.org/10.1016/B978-0-08-100529-3.00002-5

Saleh ASM, Wang P, Wang N, Yang L, Xiao Z (2019). Brown rice versus white rice: Nutritional quality, potential health benefits, development of food products, and preservation technologies. Comprehensive Reviews in Food Science and Food Safety 18, 1070–1096. doi: 10.1111/1541-4337.12449

Samal P, Babu S (2018). The shape of rice agriculture towards 2050. 2018 International Association of Agricultural Economists, No 277550. DOI: 10.22004/ag.econ.277550

Schueneman T, Rainbolt C, Gilbert R (2001). Rice in the crop rotation. University of Florida, IFAS Extension. SSAGR23. 6 pp. https://ipm.ifas.ufl.edu/pdfs/AG12300.pdf

Shahbandeh M (2019). Global health and wellness food market value 2016-2021. Statista. [Accessed 14.04.2020]. https://www.statista.com/statistics/502267/global-health-and-wellness-food-market-value/

Sherman B, Henry RJ (In Press). The Nagoya Protocol and the problem of historical collections of plants. Nature Plants.

Shibata Y, Cabunagan RC, Cabauatan PQ, Choi I-R (2007). Characterization of *Oryza rufipogon*–derived resistance to tungro disease in rice. Plant Disease 91,1386–1391.

Sivapalan S (2016). Agronomic options for profitable rice-based farming system in northern Australia. RIRDC Publication No. 16/048. Rural Industries Research and Development Corporation, Barton ACT.

Sotowa M, Ootsuka K, Kobayashi Y, Hao Y, Tanaka K, Ichitani K, Flowers JM, Purugganan MD, Nakamura I, Sato Y, Sato T, Crayn D, Simon B, Waters DL, Henry RJ, Ishikawa R (2013). Molecular relationships between Australian annual wild rice, *Oryza meridionalis*, and two related perennial forms. Rice 6, 26. https://doi.org/10.1186/1939-8433-6-26

State of Queensland (2018). Queensland AgTrends 2018-19: Forecasts and trends in Queensland agriculture, fisheries and forestry production. CS8763 12/18. https://www.publications.qld.gov.au/dataset/83d36400-85ee-48d3-a05d-2c6aabc8f109/resource/ba9b0b4b-e60a-40d4-9cca-f6da11fc3eb6/fs_download/agtrends-dec-2018.pdf

Stein JC, Yu Y, Copetti D, … Wing RA (2018). Genomes of 13 domesticated and wild rice relatives highlight genetic conservation, turnover and innovation across the genus *Oryza*. Nature Genetics 50(2), 285–296. DOI: 10.1038/s41588-018-0040-0

Stoeckl N, Jackson S, Pantus F, Finn M, Kennard MJ, Pusey BJ (2013). An integrated assessment of financial, hydrological, ecological and social impacts of ‘development’ on Indigenous and non-Indigenous people in northern Australia. Biological Conservation 159, 214–221. doi.org/10.1016/j.biocon.2012.12.007

Stokes C, Addison J, Macintosh A, Jarvis D, Higgins A, Doshi A, Waschka M, Jones J, Wood A, Horner N, Barber M, Lau J (2017). Costs, benefits, institutional and social considerations for irrigation development. A technical report to the Australian Government from the CSIRO Northern Australia Water Resource Assessment, part of the National Water Infrastructure Development Fund: Water Resource Assessments. CSIRO, Canberra, Australia.

SunRice (2019). Developing the north Queensland rice industry [Brochure]. Leeton, NSW.

SunRice (n.d.). Fact Sheet: History of Australian Rice. [Accessed 20.04.2020]. https://www2.sunrice.com.au/media/6663/history_of_australian_rice.pdf

SunRice (n.d._2). Our Story. [Accessed 10.01.2020]. https://www.sunrice.com.au/about-us/our-story

Thorburn PJ, Wilkinson SN, Silburn DM (2013). Water quality in agricultural lands draining to the Great Barrier Reef: A review of causes, management and priorities. Agriculture, Ecosystems and Environment 180, 4–20.

Tikapunya T, Fox G, Furtado A, Henry R (2016). Grain physical characteristic of the Australian wild rices. Plant Genetic Resources 15, 1–12.

Tikapunya T, Henry RJ, Smyth H (2018). Evaluating the sensory properties of unpolished Australian wild rice. Food Research International 103, 406–414. doi:10.1016/j.foodres.2017.10.037

Tikapunya T, Zou W, Yu W, Powell P, Fox G, Furtado A, Henry RJ. Gilbert R (2017). Molecular structures and properties of starch of Australian wild rice. Carbohydrate Polymers 172, 213–222.

Tonello P (1980). Rice - a new crop at Mareeba. Queensland Agricultural Journal 106, 241–247.

Veltman MA, Flowers JM, van Andel TR, Schranz ME (2019). Origins and geographic diversification of African rice (*Oryza glaberrima*). PLoS ONE 14(3), e0203508. https://doi.org/10.1371/journal.pone.0203508

Villers P, Bruin TD, Navarro S (2006). Development and applications of the hermetic storage technology. Alternative Methods to Chemical Control. 9th International Working Conference on Stored Product Protection. PS7-8 – 6119, 719–729. http://bru.gmprc.ksu.edu/proj/iwcspp/pdf2/9/6119.pdf

Wailes EJ, Chavez EC (2012). World rice outlook-International rice baseline with deterministic and stochastic projections 2012–2021. Department of Agricultural Economics and Agribusiness, University of Arkansas, Fayetteville.

Wambugu P, Brozynska M, Furtado A, Waters DL, Henry RJ (2015). Relationships of wild and domesticated rices (*Oryza* AA genome species) based upon whole chloroplast genome sequences. Scientific Reports 5, 13957. https://doi.org/10.1038/srep13957

Wang A, Pang L, Wang N, Ai P, Yin D, Li S, Deng Q, Zhu J, Liang Y, Zhu J, Li P, Zheng A (2018). The pathogenic mechanisms of *Tilletia horrida* as revealed by comparative and functional genomics. Scientific Reports 8, 15413. https://doi.org/10.1038/s41598-018-33752-w

Waters DLE, Nock CJ, Ishikawa R, Rice N, Henry RJ (2012). Chloroplast genome sequence confirms distinctness of Australian and Asian wild rice. Ecology and Evolution 2, 211–217.

Williams PR, Collins EM, Grice AC, Nicholas DM, Perry JJ (2011). The role of fire in germinating wild rice (*Oryza meridionalis*), an annual grass of northern Australian wetlands threatened by exotic grass invasion. Ecological Management and Restoration 12, 74–76. https://doi.org/10.1111/j.1442-8903.2011.00564.x

Wilson TA, Nicolosi RJ, Woolfrey D, Kritchevsky D (2007). Rice bran oil and oryzanol reduce plasma lipid and lipoprotein cholesterol concentrations and aortic cholesterol ester accumulation to a greater extent than ferulic acid in hypercholesterolemic hamsters. Journal of Nutritional Biochemistry 18, 105–112.

Wurm PAS (1998). A surplus of seeds: High rates of post-dispersal seed predation in a flooded grassland in monsoonal Australia. Australian Journal of Ecology 23, 385–392.

Wurm P, Bellairs S (2018). North Australian native rice: Market evaluation of a potential new wild food enterprise. AgriFutures Emerging Industries Publication No. 18/032.

Wurm PAS, Campbell L, Batten GD, Bellairs SM (2012). Australian native rice: A new sustainable wild food enterprise. Research Project No PRJ000347/Publication No 10/175, Rural Industries Research and Development Corporation, Canberra. https://rirdc.infoservices.com.au/items/10-175

Yasukawa K, Akihisa T, Kimura Y, Tamaura T, Takido M (1998). Inhibitory effect of cycloartenol ferulate, a component of rice bran, on tumor promotion in two-stage carcinogenesis in mouse skin. Biological and Pharmaceutical Bulletin 21, 1072–1076.

Zenna N, Senthilkumar K, Sie M (2017). Rice Production in Africa. In: Rice Production Worldwide. Springer International Publishing, Cham. Pp. 117–135. https://doi.org/10.1007/978-3-319-47516-5_5.

Zhao D, Makara O, Layheng S, Chhay N, Bora P, Ressurreccion A, Chin JH, Fitzgerald M, Snell P, Ford R (2016). Improved rice germplasm for Cambodia and Australia. Australian Centre for International Agricultural Research, Final Report FR2016-11.

Zheng X, Lan Y (2007). Effects of drying temperature and moisture content on rice taste quality. The Proceedings of the 5th Asia-Pacific Drying Conference. Pp. 1112–1117. https://doi.org/10.1142/9789812771957_0162

Zorrilla G, Martínez C, Berrío L, Corredor E, Carmona L, Pulver E (2013). Improving rice production systems in Latin America and the Caribbean. In: C Hershey (ed). Eco-efficiency: From Vision to Reality. International Center for Tropical Agriculture (CIAT), Cali, Colombia. Pp. 161–170.

Appendices

Appendix 1: Review of the history of commercial rice production in Australia

1.0 Rice Production in Southern Australia

Rice was one of the first crops introduced in Australia after British settlement, but the first attempts at production were largely unsuccessful. Success eventually stemmed from the early efforts of a Japanese merchant, who sowed 14 ha of rice in Nyah (Victoria) on the Murray River in 1906 (SunRice n.d.). The first seasons of crop were decimated by droughts and floods, but persistence and dedication saw the growth and production of commercial-scale crop in 1914. Subsequently, farmers in the Murrumbidgee Irrigation Area (New South Wales) began production using seed from California, USA. The cultivation of rice in southern Australia was then again boosted during World War II, with the addition of rice production areas in the Murray Valley. Rice cultivation in irrigated areas of New South Wales and Victoria have advanced greatly since (Bajwa & Chauhan 2017) and commercial production has continued in southern Australia. The Australian rice industry is currently firmly based on the riverine plains of southern New South Wales and northern Victoria.

Rice can be grown in a variety of agroclimatic/soil conditions. However, in Australia, the vast majority of rice is currently produced under irrigation (flooded conditions). Significant damage can result to crops that are fully exposed to air temperatures outside of preferred varietal ranges, even when only exposed for short periods. As a result, flooding is crucial for rice growth in the Riverina region, which regularly experiences such temperatures. The water serves as a ‘blanket’ for paddy rice, stabilising temperature and reducing the impacts of both cold stress and heat stress to plants. Flooded systems also have the advantage of being far more weed-resistant than dryland systems.

The Riverina Valley is irrigated by two major rivers, the Murrumbidgee and Murray. Rice in the Riverina region can only be grown on heavy clay soils, which minimises the amount of water needed to flood paddies. Soils with root zone drainage of more than 200 mm/ha are restricted for rice production (Thompson 2002).

Detailed rice production methods for southern Australia are well-reported (AgriFutures Australia 2017; Bajwa and Chauhan 2017; SunRice n.d.). Rice is generally sown in October or early November and harvested around April. Pre-germinated seeds may be dispersed aerially in flooded fields (wet-seeded) or dry seeds directly drilled in dry soil (dry-seeded), followed by irrigation (Thompson 2002). For dry seeding, irrigation is applied immediately after seeding, and the crop is flushed up to a few times. These fields are again fully flooded in December. Wet and dry-seeded fields are then kept flooded at a water depth of 15–25 cm (depending on crop growth stage) for most of the remaining growing season. The water cover is integral, as it protects rice plants from high day temperatures during early growth stages and low night temperatures later in the season.

Australia produces mostly (80%) temperate medium grain japonica rice varieties, due to the suitability of this variety to the regional climate and edaphic conditions. The most popular medium grain rices produced in Australia are Reiziq and Sherpa (R. Ford, personal communication). Other varieties currently produced include long grain indica types, such as Langi, and some fragrant rices. Short grain Koshihikari is also produced, specifically for the Japanese market (Department of Agriculture, n.d.).

A great deal of resources have gone into the development of rice varieties that suit local Australian growing conditions and meet market demand. In fact, Australian breeders have produced over 40 new varieties of short, medium and long grain rices (AgriFutures Australia 2017). The most widely produced include Reiziq, Sherpa, Opus, Langi and Doongara. Each season, the choice of which variety to plant is based on market demand, location, planting window, maturity type, and to some extent market requirements. Growers are supported by the New South Wales Department of Primary Industries, which produces an annual Rice Variety Guide that provides information about the grain characteristics and agronomic requirements of each variety available (e.g. Troldahl et al. 2018).

There are around 1500 registered rice growing farms in southern Australia; however, not all of them grow rice each year. Most rice farmers in the Murray Darling Basins typically also produce four or more additional commodities (Ashton and van Dijk, 2017). Over recent years, the total area planted has ranged from 27,000 ha to 113,000 ha. The decision to plant rice or not is largely due to climate and water availability forecasts. The average annual production area ranges from around 65,000 to 90,000 hectares. Average yields in the region are around 10 tonnes per hectare (AgriFutures 2017).

Overall, the Australian industry is capable of producing over 1 million tonnes of rice and generating around $800 million in revenue per annum (Ricegrowers' Association of Australia Inc. n.d.). However, a great deal of inter-annual variation exists. The majority (~85% from 2007-2017) of rice produced in Australia is exported to more than 60 counties; although in years with low yield, the amount of rice exported can drop to as little as 50%. Major export markets are within the Middle East, Japan and the Oceania region (Department of Agriculture and Water Resources 2018). Rice is Australia's third largest cereal grain export commodity, and the ninth largest agriculture export (Ricegrowers' Association of Australia Inc. n.d.). The 2016-17 export value of rice was $245 million (Department of Agriculture and Water Resources 2018).

Despite the numerous challenges surrounding rice production in Australia, the industry has been highly successful. This success is largely attributable to the adoption of new technology, immense coordination between growers, policy makers, and marketing authorities, and excellent management practices (Bajwa & Chauhan 2017). As a result of the stringent production regulations and well-refined agronomic processes, as well as the natural benefits of the Riverina environment, Australian rice growers use an average of 50% less water per kilogram of rice compared to other growing regions around the world. Yet, Australian yields of around 11 tonnes per ha are among the highest in the world.

Despite all of the advances in rice production, and world-leading water management initiatives, the sustainability of the Australian rice industry is still in question due to water shortages. Climate change and environmental/resource variability have begun to limit the capacity and productivity of rice production. Periods of drought and reduced availability of irrigation water, in particular, have had crippling results to annual rice production. The ability to grow rice is heavily dependent on water availability, as the crop requires around 12 ML/ha (Australian Bureau of Statistics 2019).

As a result of the variability in available water, Australia's annual rice production is also highly variable. A record of 1.7 million tonnes was produced in 2001–02, while less than 20,000 tonnes was produced in 2007–08 during drought conditions (AgriFutures Australia 2017), and rice farmers' incomes averaged around $56,000 per farm (Ashton and van Dijk, 2017). Recent averages show annual production values of around 600,000–800,000 tonnes. Projections for the 2018-19 season are suggesting that only around 54,000 tonnes will be produced (ABARES 2020). This would be an 84% decrease compared to the previous year (Department of Agriculture and Water Resources 2018).

2.0 Rice in Northern Australia

Northern Australia has not gone unnoticed in terms of rice production (see Fig. 1 for a map of notable locations for rice in northern Australia). In fact, some of the earliest rice domestically grown in Australia occurred in the north by Chinese migrants who came over in the 1870s during the gold rush (Bauer 1964, as referenced by Mollah 1982). However, despite a variety of attempts, domesticated rice has not been successfully produced for commercial purposes in the north. The lack of success has been attributed to multiple factors (as discussed in detail below). However, so far, all efforts have all been based on domesticated (mostly Asian) rice varieties bred specifically for temperate growing conditions.

Given the current variability in weather and climate, and the significant restrictions on water availability in southern Australia, the climate of northern Australia is presenting an extremely alluring option for rice. While the potential for cool summer night time temperatures and hot daytime temperatures requires rice in the south to be grown under flooded conditions, these extremes are not as much of a concern in the north. Therefore, there is great potential for growing rice aerobically in this part of the country. The reduced reliance on water would allow for a greater degree of production consistency and supply reliability.

In contrast to the domesticated rices currently produced in southern Australia (and in most other regions around the world), northern Australia presents a unique and potentially valuable commodity: completely wild native *Oryza* populations. Domestication of *Oryza sativa* began in Asia around 10,000 years ago, followed more recently by the domestication of *O. glaberrima* in Africa around 3,000 years ago (Brozynska et al. 2017). Now, domesticated species within the *Oryza* genus are distributed throughout the tropics. The native rice populations in northern Australia, however, are the most divergent to domesticated rice, while still being interfertile (Brozynska et al. 2017). It appears that Australian native *O. meridionalis* diverged from domesticated rice species around 3 million years ago and *O. rufipogon* around 1.6 million years ago (Brozynska et al. 2017).

Notably, Australian native *Oryza* species naturally carry genes for coping with commonly encountered rice biotic and abiotic stressors (e.g. durable blast resistance, drought tolerance, tungro resistance, aluminium tolerance, and various other stress-responses) (Henry 2017). They also naturally contain important yield, taste, quality and nutritional characteristics (e.g. low GI, favourable starch properties, polyphenols) (Wurm et al. 2012; AgriFutures Australia 2018; Tikapunya et al. 2018). One of the most notable traits of northern Australian wild rices is its natural pest resistance within this environment (including for bacterial blight, white backed plant hopper and brown planthopper) (Jena et al. 2006; Henry 2017). The disease resistance traits obtainable from wild native rices will likely be a key contributor in the establishment of a sustainable rice industry in northern Australia, as local disease strains would destroy current domesticated varieties commonly grown in the Riverina region.

Fig.1. Notable locations for historical rice production in northern Australia.

2.1 The history of commercial rice production in northern Australia

Following the success of domesticated rice in the south, many of the attempts to commercially produce rice in the north utilised the same rice varieties. However, in terms of growing rice, considerable differences exist between northern and southern Australia. The predominant differences are related to temperature/humidity profiles and root morphology. Most of the efforts to grow rice in the north have been quite similar: domesticated rice varieties were brought in from overseas and attempts were made to grow them in flooded environments. The most significant agronomic problems experienced were scavenging by birds (and other wildlife), lodging, and, in some regions, disease. Grain quality issues also prevented marketing: harvested crops didn't eat well or mill well due to the genetics of these varieties.

However, the most impactful problems have stemmed from variable and destructive weather events, incorrect rice varieties for the region, ineffective agronomic processes and improper planning.

Of particular note, though, one unknown domesticated variety from Vietnam (dubbed 'Viet 1') was consistently the most successful in trials across a variety of growing conditions in the north. It has the agronomic traits needed for growth in this region and can yield up to 13 t/ha.

2.1.1 Western Australia

Rice production has been trialled in Western Australia on-and-off for more than half of a century. Initial trials first took place in Kununurra, within the Ord River Irrigation Area (ORIA) in 1963-64. Following these trials, a small rice industry existed from 1973 to 1983, which resulted in peak paddy production of 3,500 tonnes in 1982. The reasons the industry ultimately failed included the lack of ability to control birds, namely ducks and magpie geese; climactic issues, including cold stress in seedling and tillering stages and heat stress during grain maturation, which led to reduced growth and delayed maturity, and reduced grain quality, respectively; low economic returns; unsuitable hydrologic and soil conditions; low mill-out rate, leading to insufficient supply; and inappropriate rice varieties for the region. Overall, the rice variety chosen, IR661, was deemed to be unsuitable, yield/production could not compete with the Riverina region, and the industry was underdeveloped. It was determined that rice in the ORIA should only be grown in the dry season (winter to spring), due to wet season rice being damaged by stem borer, low yield and higher production costs. Yet, dry season rice faced challenges of low temperature during establishment, leading to reduced early growth and high temperatures during grain-fill, leading to high chalk levels and reduced milling quality. Recommendations following assessment of the failed industry suggested that non-Asian cultivars should be considered for growth in this region.

Renewed interest in rice production in Kununurra grew in 1999, and meetings were held to discuss if rice could have a future in the ORIA. All of the issues from the previous attempt were addressed and a study of the economics of rice production was also completed. The conclusion was that the expected economic gains were not enough to support a profitable industry (Burt 2002), halting further efforts.

Based on recent advances in agronomic practices, the location of suitable soil regions, the warm climate and the availability of irrigation water, the ORIA, along with parts of the Northern Territory, are again being considered as viable options for rice production in the north. Commercial production was again initiated in 2009, and proved extremely productive and profitable in the first year, with 7.5 t/ha of rice harvested. However, the following year, growers expanded the planted area to 640 ha and grew only the Quest variety. The crop was affected by rice blast disease, which resulted in very serious damage. A total of AU$1.2M was lost due to the disease, and production was discontinued since the disease remains active for a couple of years.

At the same time, a thorough series of rice growth trials was initiated by the WA Department of Primary Industries and Regional Development. These trials ran from 2009 to 2015. Despite some trial plots being around only 2 km from the commercial crops, the DPI's crop remained completely unaffected by the disease. The results of the study, which consisted of 27 varieties grown under different conditions and planting times are fully detailed in the report by Sivapalan (2016). In summary, it was identified that aerobic systems are recommended for this region in order to maximise rotation options and minimise irrigation water and bird damage. To accommodate this, rice varieties need to be cold-tolerant for temperatures that drop below 15°C in June and July. However, flooded systems can also be used, providing the advantage of buffering ambient temperature by 4-8°C.

Of the rice varieties trialled during this study, Yunlu 29 was determined to be the best variety for aerobic systems and NTR 426 and NTR 587 for flooded systems. The maximum product was 13 t/ha. The amount of water required for growth ranged from 9.7 ML/ha to 13 ML/ha.

Weeds were also found to be an issue. Rice blast disease (*Magnaporthe grisea*) was the main disease encountered, having the potential to cause up to 100% crop failure. A blast-tolerant variety was deemed to be imperative for commercial production efforts in this region.

Current environment for rice production in WA

Current growers in the ORIA desire new crops, but are only wanting high-value premium rice varieties so as to not compete with NSW production. The total area that can be developed in the ORIA region spans 58,200 ha. Only 26,200 of this has been developed so far. Two of the three soil types in the region are highly suitable to rice production, as they contain 49-57% heavy clay and lose just 1 mm of water per day (considered acceptable for ground water sources). Water is available from Lake Argyle, as well as through natural rainfall. It is possible to grow two crops per year, in the wet and dry seasons. Silos and storage are still present in Kununurra from earlier production attempts, but the rice mill is no longer operational.

2.1.2 Northern Territory

Domesticated rice

Reports dating back to the early 1900s stated that rice had been successfully grown in the Northern Territory for at least half a century. This was a result of the increased Chinese population who came over for the gold rush in the 1870s and the construction of the Darwin-Pine Creek Railway from 1887-1889 (Mollah 1982). The Chinese immigrants grew rain-fed lowland rice using hand labour on seasonally flooded land in the Top End of the Northern Territory (Chapman & Basinski 1985). However, when the White Australia policy restricted Chinese cultivation methods, rice growing ceased. The high cost of labour in Australia also requires mechanised processes, which are poorly applicable to the heavy estuarine clays of this area (Chapman and Basinski 1985).

Interest in Northern Territory rice production was sparked again in the late 1930's; however, the idea was quelled due to a 'gentleman's agreement' to not oppose the growing industry in the Murrumbidgee Irrigation Area (Mollah 1982).

A 1947 trial at the Kimberly Research Station (Kununurra) on the Ord River took place with Caloro rice. The plantings survived an attack by grasshoppers, but the crop was then completely destroyed by cockatoos just before harvest. Crops over subsequent seasons continued to be attacked by birds and insects and yields were consistently low. Two Rice Research Stations were established and trials began in 1952, at Humpty Doo (80 ha) and Sixty Mile (600 ha). The Humpty Doo crop was ruined by heavy rainfall and floods in 1952-53. The following season, water was an issue during planting in December 1953. Crop growth was then further constrained by a three-week dry spell in February 1954. The crop was decimated by moth stem borer, magpie geese, grasshoppers and rats, before being completed wiped out by a cyclone in April. Yet, the suitability of the area for growing rice was supported 'beyond a doubt' by the local Agricultural Officer. In his opinion, the unique features of the area led to the claim that 'The original conception for the development of these splendid plains must not be lost sight of in a welter of ingenious hypothesis… It is a matter of extreme doubt to the writer if a similar expanse of country with similar conditions exists elsewhere' (Agricultural Section 1954, as reproduced in Mollah 1982).

Territory Rice Limited was incorporated in 1955, introducing a syndicate for rice growing at Humpty Doo. The Rice Development Agreement Ordinance 1956 ratified an agreement between the Commonwealth Government and Territory Rice Ltd that provided exclusive rights to develop the sub-coastal plains east of Darwin (Mollah 1982). This was a major and costly initiative, but was well-supported and advanced very quickly. Flooding in February 1955 meant that varietal trials were lost, but agronomic experience was still gained. Record floods in February 1956 again caused serious crop losses; however, extrapolation of what was left for harvesting in May-June showed that yields of rice varieties introduced from Malaya, Burma and Kenya were capable of yielding 4500 kg/ha. The grain was harvested at high moisture content and dried artificially. The following year was the wettest of the project, and despite planting on higher ground, the rain halted operations. As a result, to salvage the season, seed was released from aircraft. However, as the seed was released, magpie geese scavenged it from mid-air before it could even hit the ground. What did land was apparently then dug up by the birds. Only half of the seed germinated; that was then further damaged by floods, insects, cockatoos and brolgas. The end result was 200 t from 243 ha. The following year was favourable, but a lack of funds meant that only 80 ha was planted for trials, and no crop was harvested.

Other attempts continued, but were unsuccessful as well, due to a lack of industry development and poor market access. Furthermore, poor planning and design resulted in broad-scale losses to land, infrastructure and equipment. Lodging occurred due to harvesting delays from heavy rainfall, and losses were further realised due to sun drying and milling. The final product proved only mediocre in quality and the grain was poorly adopted by the Australian market.

Further investment into the industry allowed production to continue, but poor seed led to low germination rate, insufficient fencing allowed cattle to damage the crop and land and water issues remained problematic (Mollah 1982). The second (wet season) planting in 1959-1960 was more successful, with 3,300 t yielding from 2,180 ha. Harvested rice was sent straight to Hong Kong for milling and sale. Ongoing efforts over the next three seasons were better, but issues with water persisted, as did weeds, variability in seed quality and lack of suitable rice varieties and the industry subsided.

Around the same time, rice production trials were also being done by the Agricultural Branch. These took place at the Upper Adelaide River Experiment Station at Tortilla Flats on the Marrakai Plains Research Station and the CSIRO Coastal Plains Research Station at Middle Point. The trials identified the nitrogen and phosphorus soils that were needed for rice growing in the region, methods to counter soil salinity and strategies for weed, pest and disease control. Studies also developed procedures for extending harvesting period through the use of photo-intensive varieties, which, if pregerminated, could be sown into standing water (Mollah 1982).

Ultimately, despite the numerous failed attempts, a successful rice industry in the Northern Territory is still considered possible. The early efforts were rushed, overly-ambitious, ill-conceived and based on processes, environments and infrastructure that were simply not appropriate for Humpty Doo. To be successful, the technical, economic and social components of rice agriculture in Australia must be considered and integrated (Mollah 1982). With greater options for more appropriate rice varieties tailored to the region, lessons learnt from similar environments, better capacity for monitoring and predicting weather, experienced rice agronomists, and greater focus and efforts towards addressing the known pitfalls that were identified in these earlier efforts, modern insight could very well underpin the development of a successful commercial rice industry in the region.

Native rice

Commercial production of rice in the Northern Territory has also been trialled over small-scales. *Oryza rufipogon* and *O. meridionalis* are both abundant and widespread across the floodplains of monsoonal northern Australia. These rices have been collected and consumed by Indigenous Australians for thousands of years (Fujiwara 1985). Wild harvest, in collaboration with a well-established local Indigenous enterprise, is currently being investigated.

Small-scale collection of both of these species from the northern floodplains is possible using an airboat (Wurm & Bellairs 2018). However, access to certain sites and the ability to collect rice could be temporally limited due to variable rainfall. The collection and processing of native rices is labour-intensive and costly. The long awns of *Oryza meridionalis* prevented it from being directly fed into a mill. During trials, the seed had to be cleaned from the awn by hand prior to milling (Wurm & Bellairs 2018). Also, milling failed to remove a significant proportion of the husks, yet, repeated milling increased the proportion of cracked seeds. Other de-husking methods, such as airflow and tumbling over rough fabric surfaces proved similarly ineffective. Husking by hand was ultimately effective, and revealed a variably rich brown grain. Improved or customised milling techniques would be required for this industry to be feasible.

The cooked rice was described as having a desirable nutty aroma and flavour with an interesting and appealing purple-brown colour when cooked. Commercial cooks said that it mixed well in gourmet dishes and was appropriate for whole grain bread, pilaf, rice pudding, in pancakes and as a side dish with meat and fish (Wurm & Bellairs 2018). Other noted benefits were its nutritional characteristics and the fact that it is a local product. The nutritional properties of these wild rices are similar to, if not exceeding, commercially produced rices (Wurm et al. 2012). Although the peak starch viscosity (which is often used as a proxy for cooking quality) of the wild rices is significantly lower than in commercial rices; this is a result of the higher amylose and amylopectin in the grain starch (Wurm et al. 2012). The viscosity was not expected to be a barrier to market potential, though.

Prices of up to $100-120/kg for premium, unbroken, wild harvested rice fetched interest, but $50/kg was suggested as a more realistic price for reliable sales in Northern Territory restaurants. Small sample packets sold through tourism enterprises could potentially sell for $200/kg (e.g. 50 g packs in attractive, culturally-identified packaging for $10.00). However, the costs of production during the trial were calculated to be $110/kg. This could likely be reduced to $70/kg with improved, customised milling processes and increased economy through larger scale production. However, that figure is still limiting in terms of broad marketability. It was found that approximately 2.2 kg of unprocessed grain was needed to produce 1 kg of ready-to-eat rice. The remaining 54% of harvest weight was comprised of awns, husks and seeds that failed to de-husk by milling (Wurm & Bellairs 2018).

Native rice underpins and fuels the vertebrate food chain in the Northern Territory. The most significant vertebrates in relation to the native rices are the magpie geese and the native dusty plains rat. These are important bottom-order species for the floodplain vertebrate food chain. As such, the native rices are extremely ecologically important plants. It has been shown that the at least 75% of accessible *O. meridionalis* seeds may be removed by rodent predators (Wurm 1998). However, despite the potential for such a high percentage, seed may not be heavily depleted if there is an overabundance of seed produced, which is normally accommodated by high density-dependant seedling mortality. It is also unlikely that this sort of scavenging would actually limit harvest for the small niche markets that such an industry would be targeting. Magpie geese may be a problem to those wanting to cultivate native rice, particularly during the dry season when alternative grain sources are not available to the geese (Campbell et al. 2019; unpublished data, Charles Darwin University).

However, one of the greatest challenges for this region may be introduced weeds (Boyden et al. 2018; Ferdinands et al. 2005).

2.1.3 Queensland

Rice production in Queensland has occurred spasmodically. Rice has been grown in a range of areas across the state, including the Burdekin, Mareeba, Dirranbandi, Emerald, Tully. Momentum for rice production in Queensland is quite high, and a variety of trials and rice development project are currently taking place. Although wild rices are present in north Queensland, all commercial production and trials to-date have been based on domesticated varieties.

It appears that rice was first grown in Queensland in 1898 over 350 hectares (Kealey & Clampett 2000). Production, however, declined until 1917. The industry was revived to help address food shortages during the two world wars and also because of increased research support for the industry (Kealey & Clampett 2000). In the late 1960s, a research station was established in the Burdekin River Irrigation Area. A dedicated program was established in 1969 to determine the best varieties for the region, as well as look into nutritional aspects

(Kealey & Clampett 2000). Long grain varieties brought over from southern USA improved efficiency, and were the most preferred variety, which was grown as paddy rice.

A block of lots was released in 1968 in the Old Clare district of the Burdekin-Haughton Water Supply Scheme (then called the Burdekin River Irrigation Area) for growing rice. The area under rice peaked at 3,872 ha in 1971 (QWRC 1980, as referenced by Petheram et al. 2008). In the 1980s, the Burdekin River Irrigation Area (BRIA) Scheme was established as a national development project. The Scheme was designed to provide water supplies for the irrigation of sugarcane and rice crops as a means of promoting economic growth and regional development in north Queensland. The Scheme included the construction of the Burdekin Dam; however, this was financed through a Commonwealth Government grant. Other efforts, however, were poorly executed (Burdekin River Irrigation Area Committee 2002). The Queensland State Government took land at dryland value, and resold the developed 100 hectare lots at higher prices due to the availability of irrigation water. Each of these lots was allocated 8 ML of water entitlements per hectare. Only around 50% of the farm land projected by the Scheme was developed and sold (Burdekin River Irrigation Area Committee 2002).

A rice breeding program in the Burdekin began in 1981 and the rice research program expanded to investigate crop production issues. Rice was grown in the summer (wet season), and in the Burdekin and Mareeba, a second planting was done in the winter (dry season). Yields in the Burdekin Valley averaged almost 6 t/ha (Kealey & Clampett 2000). Production generally fell in the range 20,000 - 30,000 tonnes per annum. All rice was serviced by the Queensland Rice Marketing Board and milled and marketed from the Lower Burdekin Rice Producers Cooperative. The rice grown in Queensland had a firmer texture compared to New South Wales rice, and it was successfully adopted by the Australian market; none of the product was exported (Kealey & Clampett 2000). Optimism for the industry stemming from the to-be-enlarged Burdekin Dam did led to the exploration of export market options in the late 1980s. However, trial exports to Papua New Guinea were unsuccessful in establishing a market (Kealey & Clampett 2000). Instead of supporting the growth of the rice industry, the extra irrigation availability from the Dam went to sugar production, which was drawing far greater prices.

During that period, rice was grown mostly in ponded systems and, although rice was considered to be a desirable rotational crop around sugarcane, setting up the field for pond rice and then returning the land for sugarcane production requires a significant amount of additional labour (Cockfield et al. 2012). Ultimately, the preference for sugarcane, combined with severe rice grain quality issues, led to the cessation of rice production and milling in Queensland in 1992/93 (Kealey & Clampett 2000).

More recent rice growing approaches by Blue Ribbon Seed and Pulse Exporters in the Burdekin used fallow land during the 3-5-year sugarcane planting cycle and centre-pivot irrigation in alternate wetting and drying (AWD) or saturated soil culture (Cockfield et al. 2012). This reduces the efforts needed to switch between rice and sugarcane production. Growing rice during the fallow period also means that farmers do not have to choose between rice or sugarcane. Instead, rice can be grown as a profitable rotation crop, which has the additional benefits of reducing weed growth and pest management costs during the fallow period and improving soil structure and organic matter for subsequent sugar crops (Schueneman et al 2001; Cockfield et al. 2012). Improved sugar yields of ~20t/ha have been reported by growers undertaking the early trials of growing rice in the Burdekin (Cockfield et al. 2012).

The Burdekin region has shown some great success with rice production, with growers producing up to 11.1 t/ha. Two planting opportunities for rice are possible per year, in the summer and winter. As a result, the number of north Queensland farmers opting into rice has increased quickly over recent years. Due to a variety of factors, only partly relating to climate and agronomic methods, 2012 projections suggested that average winter and summer rice yields from the Burdekin would be 25 and 50% less than those of the southern region, respectively (Cockfield et al. 2012). However, the opportunities afforded by aerobic production in the north present huge advantages over the southern region, which is being so heavily restricted by increasing costs and unavailability of water. These projections also assume that farm gate prices would be the same for both regions. Ideally, northern regions could focus on different, higher-value varieties that cannot be grown in the south. This would avoid competition and capitalise on the advantages of both agro-climates.

Seeing the potential value in the region, and the need for a support system for rice production in the south, SunRice has put a significant amount of resources into building a supplementary rice industry in north Queensland. They are currently managing a series of rice trials across the Burdekin, Walkamin, Ingham, Tully and Gordonvale to assess the best varieties, breeding programs, nutrition management and disease management.

An AgriFutures project is currently investigating the 'Characterisation of morphological, physiological and biochemical traits for heat tolerance in aerobic rice'. Varieties that are being trialled in aerobic conditions in the north, such as Topaz and Doongara, were bred for temperate irrigated conditions in the southern rice industry. The temperatures in north Queensland can easily exceed maximal growing conditions, and this can lead to heat stress, particularly at flowering, which causes spikelet sterility. In Tully, Topaz crops show up to 34% spikelet sterility. This equates to a yield loss of 2.0 t/ha (with typical 4.0 t/ha yield), and makes rice production commercially unviable. Research is ongoing towards developing a heat-tolerant variety specifically designed for northern Australia's tropics.

Small-scale trials in other regions have shown that aerobic agronomic procedures in northern Queensland can be nearly as effective as flooded production (unpublished data from preliminary trials). Root architecture and the ability of the rice plant to adapt to abiotic stress under an aerobic growing system are key focus areas for a successful northern Australia rice variety. Strip trials of rice at Olive Vale Pastoral on the Laura River have been conducted with rainfed summer rice. Different planting times/seasons have been trialled and it's been shown that rice can be dry sown if it is known that a wet season is approaching. Among a variety of 8-10 crop species planted in these trials, the rice excelled (unpublished data from preliminary trials). Soil and the climate at Olive Vale have undoubtedly been shown to suit rice. To date, disease damage to rice crops grown in trials has been minimal, although a small degree of stem borer was experienced (unpublished data from preliminary trials).

One of the restricting factors to the growth of present efforts is that only limited infrastructure is available for rice in north Queensland. SunRice has a small mill at Brandon in the Burdekin with a capacity of around 15,000 t of paddy rice each year. Currently, drying and storage exists for only 8,000 tonnes (2 crops x 4,000 tonne). The major expected limitation to rice production in the tropics is post-harvest grain storage and drying.

Collection and production trials of native wild rices have not been done in Queensland. However, small quantities of one native species (described as taxa B) were collected from Olive Vale Pastoral to evaluate the sensory properties of the cooked product. Tikapunya et al. (2018) established cooking profiles, measured physical traits and assessed 26 different descriptors of this Australian wild rice, in comparison with Canadian wild rice (*Zizania aquatica* L), *Oryza sativa* L.cv. Nipponbare, and commercially produced long grain, medium grain, basmati, red basmati and red rices. The Australian wild rice was determined to have a mild aroma and flavour similar to the other red rices, but without the lingering aftertaste. It had a mid-red bran layer, but was more subtle compared to the earthy/root vegetable and grassy flavours of the rices with a dark red bran layer. It was also firmer, and a bit crunchy and chewy rather than soft and fluffy, even after an extended cooking period. All tested aspects of the Australian wild rice suggested a high potential for commercialisation as a grain, as well as for the provision of suitable genetic resources for breeding programs (Tikapunya et al. 2018).

3.0 References

ABARES (2020). Australian crop report. Department of Agriculture, Water and the Environment, Australian Government. [Accessed 14.04.2020].

https://www.agriculture.gov.au/abares/research-topics/agricultural-commodities/australian-crop-report

AgriFutures Australia (2017). Rice. [Accessed 05.05.2019]. https://www.agrifutures.com.au/farm-diversity/rice/

AgriFutures Australia (2018). Improving the productivity, profitability and sustainability of the Australian rice industry — 2018. Rice R&D Update Publication No. 18/026. [Accessed 05.05.2019]. https://static1.squarespace.com/static/5a03c05bd0e62846bc9c79fc/t/5bab1c517817f7d7fb0f6726/1537940692521/Rice+RD+Update-2018.pdf

Ashton D, van Dijk J (2017). Rice growing in the Murray-Darling Basin. ABAES, Canberra. [Accessed 05.05.2019]. http://www.agriculture.gov.au/abares/research-topics/surveys/irrigation/rice#references

Australian Bureau of Statistics (2019). 4618.0 – Water use on Australian farms, 2017-18. [Accessed 05.05.2019]. https://www.abs.gov.au/ausstats/abs@.nsf/PrimaryMainFeatures/4618.0?OpenDocument

Bajwa AA, Chauhan BS (2017). Rice production in Australia. In: B.S. Chauhan et al. (eds.), Rice Production Worldwide. Springer International Publishing AG. Pp 169-184. DOI 10.1007/978-3-319-47516-5_6

Boyden J, Wurm P, Joyce KE, Boggs G (2018). A spatial vulnerability assessment of monsoonal wetland habitats to para grass invasion in Kakadu National Park, northern Australia. International Journal of Applied Earth Observation and Geoinformation 71, 43-55.

Brozynska M, Copetti D, Furtado A, Wing RA, Crayn D, Fox G, Ishikawa R, Henry RJ (2017). Sequencing of Australian wild rice genomes reveals ancestral relationships with domesticated rice. Plant Biotechnology Journal 15, 765–774. https://doi.org/10.1111/ pbi.12674

Burdekin River Irrigation Area Committee (2002). The Queensland Competition Authority Inquiry: Burdekin Haughton Water Supply Scheme Assessment of Pricing Matters. April 2002. [Accessed 05.05.2019]. https://www.pc.gov.au/inquiries/completed/urban-water/submissions/subdr105-attachment.pdf

Burt J (2002). Review of the potential for growing rice at the Ord River Irrigation Area in Kununurra Western Australia. Trade and Development Technical Report. Department of Agriculture Western Australia.

Chapman A, Basinski J (1985). Coastal Plains research station. In 'The Northern Challenge. A history of CSIRO crop research in northern Australia' (Eds. J Basinski, I Wood, J Hacker). Published by CSIRO Division of Tropical Crops and Pastures.

Cockfield G, Mushtaq S, White N (2012). Relocation of intensive agriculture to northern Australia: The case of the rice industry. [Accessed 05.05.2019]. http://era.daf.qld.gov.au/id/eprint/3603/1/Output2RiceCaseStudy.pdf

Department of Agriculture. Rice. [Accessed 05.05.2019]. http://www.agriculture.gov.au/ag-farm-food/crops/rice

Department of Agriculture and Water Resources (2018). Rice. [Accessed 05.05.2019]. http://www.agriculture.gov.au/SiteCollectionDocuments/about/factsheets/rice.pdf

Ferdinands K, Beggs K, Whitehead P (2005). Biodiversity and invasive grass species: multiple-use or monoculture? Wildlife Research 32(5), 447-457.

Henry RJ (2017). Review of Australia's role in feeding the world, the future of Australian agriculture. Australian Journal of Agricultural and Resource Economics. DOI: 10.1111/1467-8489.12207

Jena KK, Jeung J-U, Lee J-H, Choi H, Brar DS (2006). High-resolution mapping of a new brown planthopper (BPH) resistance gene, Bph18(t), and marker-assisted selection for BPH resistance in rice (*Oryza sativa* L.). Theoretical and Applied Genetics 112(2), 288-97.

Kealey LM, Clampett WS (2000). Production of quality rice in south eastern Australia. Rural Research & Development Corporation. Publication 00/2. [Accessed 05.05.2019]. https://static1.squarespace.com/static/5a03c05bd0e62846bc9c79fc/t/5a1fa5cf085229745efc2091/1512023636011/Production+of+Quality+Rice+in+South+Eastern+Australia+Pt1.pdf

Mollah WS (1982). Humpty Doo: Rice in the Northern Territory. Australian National University. 30pp.

Petheram C, Tickell S, O'Gara F, Bristow KL, Smith A, Jolly P (2008). Analysis of the Lower Burdekin, Ord and Katherine-Douglas-Daly Irrigation Areas: Implications to future design and management of tropical irrigation. CRC for Irrigation Futures Technical Report No. 05/08, February 2008. [Accessed 20.05.2019]. http://www.clw.csiro.au/publications/science/2008/sr19-08.pdf

Ricegrowers' Association of Australia Inc. (n.d.). Overview of the Australian rice industry. Leeton, NSW. [Accessed 05.05.2019]. https://www.rga.org.au/common/Uploaded%20files/RGA/Publications%20and%20Factsheets/Overview-of-Rice-Industry-2013_Web.pdf

Schueneman T, Rainbolt C, Gilbert R (2001). Rice in the crop rotation. Report SS-AGR-23. IFAS University of Florida.

Sivapalan S (2016). Agronomic options for profitable rice-based farming system in northern Australia. RIRDC Publication No. 16/048. Rural Industries Research and Development Corporation, Barton ACT.

SunRice (n.d.). [Accessed 20.05.2019]. https://www.sunrice.com.au

Thompson JA (2002) Water management of rice in southern New South Wales, Australia. In: Bouman BAM, Hengsdijk H, Hardy B, Bindraban PS, Tuong TP, Ladha JK (eds) Proceedings of the international workshop on waterwise rice production, 8–11 Apr 2002. International Rice Research Institute, Los Baños, pp. 62–67.

Tikapunya T, Henry RJ and Smyth H (2018) Evaluating the sensory properties of unpolished Australian wild rice. Food Research International 103, 406-414. doi:10.1016/j.foodres.2017.10.037

Troldahl D, Snell P, Dunn B (2018). Rice variety guide 2018-19. July 2018, Primefact 1112, 8th edition. Department of Primary Industries, New South Wales.

Wurm PAS (1998). A surplus of seeds: High rates of post-dispersal seed predation in a flooded grassland in monsoonal Australia. Australian Journal of Ecology 23, 385-392.

Wurm P, Bellairs S (2018). North Australian native rice: Market evaluation of a potential new wild food enterprise. AgriFutures Emerging Industries Publication No. 18/032.

Wurm PAA, Campbell LC, Batten GD, Bellairs SM (2012). Australian wild rice: A new sustainable wild food enterprise. RIRDC Publication No. 10/175. Rural Industries Research and Development Corporation, Barton ACT.

Appendix 2: Current Retail Values of Rice in Australia

The current retail value of different types of rice currently available for purchase in Australia. SunRice branded products were used where possible to negate discrepancy in value between brands. However, not all products could be sourced in the same package size and from the same source, presenting a degree of skewedness in price per 100 g.

Grain length	Type	Brand	Country of origin	Price (per 100g)	Package size	Source
Long grain	Premium white	SunRice	Australia	$0.20	1 kg	Coles
Medium grain	White [Calrose]	SunRice	Australia	$0.32	1 kg	Coles
Medium grain	Brown rice	SunRice	Australia	$0.32	1 kg	Coles
Long grain	Jasmine	SunRice	Thailand	$0.32	1 kg	Coles
Long grain	Fragrant jasmine	SunRice	Thailand	$0.40	5 kg	Coles
Extra long grain	Brown basmati	Riviana	Pakistan	$0.45	1 kg	Woolworths
Long grain	Aromatic basmati	SunRice	Pakistan	$0.46	1 kg	Coles
Long grain	'Low GI' White	SunRice	Australia	$0.47	750 g	Coles
Long grain	'Low GI' brown Doongara	SunRice	Australia	$0.47	750 g	Coles
Short grain	Japanese style white sushi rice	SunRice	Australia	$0.47	750 g	Coles
	Organic jasmine	Macro Organic	Thailand	$0.64	750 g	Woolworths
	Organic brown basmati		Pakistan	$1.34	1 kg	Naked Foods
	Organic jasmine		Thailand	$1.40	1 kg	Naked Foods
	Organic basmati		Pakistan	$1.48	1 kg	Naked Foods
	Organic wild rice		USA	$5.66	1 kg	Naked Foods
	Organic Australian wild harvested rice		Australia	$5.00 - $20.00	1 kg	Wurm and Bellairs 2018

Sources: Woolworths, https://www.woolworths.com.au/; Coles, https://shop.coles.com.au/; Naked Foods Organic & Health Foods, https://nakedfoods.com.au/ [all accessed 11.04.2020].