Going against the grain: Exploring opportunities for novel grains in the Australian food supply

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AUSTRALIA

Going against the grain: Exploring opportunities for novel grains in the Australian food supply

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Bachelor of Commerce (Economics) (University of Wollongong)

Bachelor of Science (Nutrition) (University of Wollongong)

Honours Class 1 (University of Wollongong)

This thesis is presented as part of the requirement for the award of the Degree of

Doctor of Philosophy

University of Wollongong

2017

ABSTRACT

Background: Grains are present in a myriad of recognisable food products, such as bread, pasta and breakfast cereals. The vast majority of grain consumption (over 90%) is however dominated by wheat, rice and corn. As the global population grows and the demand for food increases, current farming systems are under pressure to enhance their productivity to meet these future demands. However, in the face of global climate change, land degradation and water scarcity, productivity gains for the major dietary grains may be increasingly hard to capture, requiring a rethink of the current grain supply strategy. Rather than being reliant on a homogenous group of staple commodities, there may be value associated with the diversification of production systems to incorporate underutilised novel grains. The research presented in this thesis aimed to explore the potential sources of value associated with the incorporation of novel grains into the Australian food supply.

Research Approach: Sorghum and quinoa, two examples of underutilised ancient grains were selected as case studies to investigate potential sources of value associated with their incorporation into the food supply. The research presented in this thesis conceptualised the incorporation process as an example of an incremental innovation. By adopting an interdisciplinary research approach, sources of value across the domains of strategic planning, nutrition science and economics were explored. Three distinct studies that utilised a combination of qualitative and quantitative methods underpinned the analysis.

Study 1 – Stakeholder Considerations: Part A of Study 1 conceptualised the range of activities that are required to deliver a grain from farm to fork, as a business ecosystem. A series of semi-structured interviews were performed to identify potential sources of stakeholder value associated with incorporating novel grains into the food supply. This value was captured as strategic, operational and end-user. The diffusion of innovation theory was then applied to evaluate variables influencing the potential for novel grains to be adopted by stakeholders across the ecosystem. Factors such as relative advantage, complexity, compatibility, trialability, observability and the new dimension of impression revealed that behavioural changes and information flow were likely to influence the scope for novel grains to diffuse across the ecosystem. Part B of Study 1 identified the type and

position of risk across the ecosystem. Execution risk, co-innovation risk and adoption chain risk were identified across the business ecosystem. This classification of risk recognised that activities occurring upstream and downstream of specific stakeholders must be considered when incorporating novel grains into the food supply. Ultimately, the results from Part A and Part B revealed that stakeholder collaboration and alignment of objectives were critical to the capture of value in the business ecosystem.

Study 2 – Nutritional Attributes of Sorghum and Quinoa: As consumers become increasingly aware of the link between nutrition and health, identifying nutritional attributes of novel grains may enhance their attractiveness as a component of product formulations. Part A of Study 2 systematically reviewed the nutritional attributes of sorghum by exploring the effects on human health outcomes. The results indicated that sorghum could attenuate blood glucose responses and decrease oxidative stress. Part B of Study 2 systematically reviewed the nutritional attributes of quinoa by exploring the effects on animal health. The results suggested that animals consuming quinoa experienced less weight gain than animals consuming a control diet. The combination of results from Part A and Part B suggested that sorghum and quinoa may have superior nutritional attributes to other staple grains. Despite the rigour and potential applicability of this method to other novel grains, the importance of nutrition as a source of value in product development must be balanced against factors such as price and taste. Research exposing the nutritional attributes of a novel grain is therefore valuable, but not sufficient to guarantee product development and ultimately incorporation into the food supply.

Study 3 – Supply and Acreage of Novel Grains: Empirical Modelling: The final component of the thesis involved the development of an empirical model to quantitatively assess the impact that a range of variables had on the planting of sorghum acreage by Australian farmers. A panel data model that captured sorghum acreage over time and across Australian geographic regions demonstrated that previous planting decisions, crop prices, fertiliser prices and rainfall all had a statistically significant (all $p<0.05$) impact on the area of land planted to sorghum. The unexpected positive coefficient on the variable representing the price of fertiliser implies that farmers switch to sorghum acreage when fertiliser prices rise. This suggests that sorghum requires lower fertiliser inputs and may therefore be more environmentally sustainable. More generally, these results highlight the economic rationale (captured through crop prices) behind farmer’s acreage decisions.

The results suggest that price incentives must be present for farmers to supply sorghum and potentially other novel grains to market. This has implications for the continuity of supply of novel grains and their potential incorporation into the food supply.

Summary and Conclusions: The application of sorghum and quinoa as case studies enabled an overview of the potential pathway to market for novel grains to be identified. Collaborative orchestration of the business ecosystem and the scope to generate monetary returns were identified as key factors that could contribute to the generation of value in the market for novel grains. The interdisciplinary approach adopted by this research enabled a framework that captured insights from strategic planning, nutrition science and economics to be developed. This framework revealed potential sources of value associated with an agricultural innovation, offering clear practical and theoretical contributions. In addition, this framework may have applicability to other novel grains as a means of evaluating potential sources of value associated with their incorporation into the Australian food supply. This will have implications for the diversity of the Australian food system and the potential for stakeholders across the business ecosystem to engage in innovation to deliver novel grains to market.

DECLARATION

I, Thomas Simnadis, hereby declare that this thesis, submitted in fulfilment of the requirements for the award Doctor of Philosophy, in the Faculty of Science, Medicine & Health, University of Wollongong, is my own work unless otherwise referenced or acknowledged. This document has not been submitted in whole, or in part, for qualification at any other academic institution.

Thomas G Simnadis

Date:

ACKNOWLEDGEMENTS

To begin with, I would like to thank my supervisors for their unwavering patience and support. Without your guidance I would have struggled to pull together a document that presented a coherent and logical argument. Things may have gotten off to a slow start, but we picked up the momentum and were running like a well-oiled machine by the end of the journey. I really enjoyed working in that broader team environment and taking on board the myriad of valuable advice along the way. Linda, it always scared me going into your office. I never knew how our meetings would go, or if I was producing material that was up to standard. I always imagined that you and Eleanor would discuss the perils of taking on an unpredictable student like myself after I left the room, although I have no evidence to support this notion. Eleanor, you have been such a fantastic supervisor to have looking over my shoulder. All that friendly banter in the corridors and those unexpected visits to your office kept me going. You were always ~~happy~~ forced to listen to my mundane struggles and bring a sense of reality to life. Finally, Oleg, the discussions we shared were always enlightening and keep me on my toes. If anything, it showed me that interdisciplinary research is impossible without the right team, or as Matt Jackson in his book *The Age of Affect*, put it, you need "…the right people on the bus first and then get those people into the right seats…"

It goes without saying that the last few years as a PhD student have been made immensely more enjoyable by having such a great group of like-minded guys around to break the monotony of EndNote and Microsoft Word. Lachy, you managed to repeatedly traumatise me in the lab of death. The day you stuck a tube down my throat for the purposes of science really galvanised the friendship. As an adjunct, Delbridge, you also managed to subject me to repeated trauma, but you were successful at breaking me, more specifically, my back. Mike, you introduced me to the pear and raz, which I can confirm is significantly ($p<0.05$) superior to your run-of-the-mill banana bread. Critiquing the anaemic nature of the Sherwood Report, engaging in friendly banter through the guise of ATN-LEAP and venting our incredulity at the blatant disregard of company ethics by stocks on the ASX kept each day real. I also have to give a special mention to Hayes for his ability to provide nuggets of wisdom when they are most in need. "Sor-gum, more like Sorg-yum" is my case in point. Jono, you only saw the latter end of the journey and were no doubt tarnished by my lethargic attitude. If I learnt anything from our conversations, it's that I still have no idea what your research is about. I will however take solace in knowing that despite being an IHMRI researcher, you haven't yet crossed over onto the dark side and abandoned all contact with the folk of Building 41. Lastly, Anita, the one person who could relate to the trials and tribulations of a grain goon. We shared a laugh on more than one occasion and often had conversations that put life back in perspective. Thanks for all the wise words and your ability to make a serious situation into one that we could laugh about!

The financial support I received from the University of Wollongong as well as the Grains Research Development Corporation and Rural Industries Research Development Corporation provided me with the flexibility to immerse myself in my research. In addition, this research has been conducted with the support of the Australian Government Research Training Program Scholarship. I would like to thank everyone that worked in the background to organise these scholarships and ensure that I could afford to feed myself each week. I also have to give a special mention to John de Majnik, previously at RIRDC, who would always encourage and support me in my efforts. The confidence that it brought me was invaluable in developing the direction of my PhD and keeping on track to meet deadlines.

Now to all the important people: Karly, thank you for never giving up on me and giving me endless love and affection. All those trips to Perth made me wish I could be there with you, but it was all worth it in the end. I justified more than one of the trips over west as being for the purposes of "research", but I daresay these excuses would have been wearing thin on those around me. How convenient that quinoa was being grown in WA – although it was pointed out to me by a friend who noticed pictures of the ocean while I was on one of these fact-finding missions that he had never heard of aquatic quinoa. That last day of long distance was sweeter than that bottle of expensive champagne that we popped that night!

To Dean, the voice of reason, and the one person capable of keeping my head screwed on. Thank you for all the time you put into reading my drafts and revisions and providing me with invaluable feedback. Those beers on sunny Sunday afternoons discussing which shares we would be investigating next, kept me going for another week. Despite all the depression that Sherwood imparted on the financial world, I think we didn't do too badly.

Thank you to Stefanie, my dear sister who would probably consider wringing my neck if I didn't mention her name here. I'm not entirely sure what you did to deserve a mention…only joking. You were always up for giving me some advice, there to bounce ideas off, and answer incompetent dietetic related questions. You'll claim that you designed all my surveys but I could never admit to that – you can be my collaborator.

To my parents, thank you for putting up with me while I honed my talents as a professional student. You may have spent more time overseas than in the same country as me, but you were always willing to give up your time to help. The only thing I would have changed is the volume of alcohol you brought back home with you each time came back from an overseas odyssey. Although, had you brought ouzo back more frequently, it probably would have tipped me dangerously close to becoming a functioning alcoholic.

As odd as it may seem, I have to give a mention to my 90 year old Austrian grandfather, Tati. If it wasn't for the fact that you had made arrangements for your 90th birthday celebration, by inviting the whole family to an extended birthday lunch, I doubt the title of my thesis would have taken on the form that it has. As much as it pains me to say it, I have to give credit to Michali and the incoherent rabble of Riley and Kyle at this particular luncheon. Who would have thought that listening to you three strugglers would have inspired such a creative thesis title. All jokes aside, thanks and my advice still stands. Don't do a PhD.

I would like to extend a thank you to all the other people who helped me throughout my journey. To all the facilitators of courses that I attended, academics that I met along the journey and people from the industry who had valuable insights, I cannot thank you enough for helping me to get where I am today. Having access to such a broad network of people both in Australia an overseas helped me in ways that I could never have imagined. If anything, I learnt that it was all about **who** you know, rather than **what** you know.

Finally, I would like to thank everyone who ever listened to the countless variations of the elevator pitch that I spent the best part of three years trying to refine. No doubt the patience of those close to me began to wane after the 300th incantation of the hodgepodge

of words that I used to describe life as a grain researcher. In the words of Stefanie, I was just “a glorified farmer with too much time on my hands”. Maybe she was right, but it didn’t matter because I loved ~~every~~ most of the journey.

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Published Papers

Simnadis, TG, Tapsell, LC & Beck, EJ 2015, 'Physiological effects associated with quinoa consumption and implications for research involving humans: a review', *Plant Foods for Human Nutrition*, vol.70, no.3, pp238-249

Simnadis, TG, Tapsell, LC & Beck, EJ 2016, 'Effect of sorghum consumption on health outcomes: a systematic review', *Nutrition Reviews*, vol.74, no.11, pp690-707

Published Abstracts from Oral Presentations

Simnadis, TG, Tapsell, LC & Beck, EJ 2016, 'Sorghum and quinoa: health benefits and implications for future research, *American Association of Cereals Chemists International Annual Meeting*, Savannah, GA, USA, October 23rd – 26th

Simnadis, TG, Tapsell, LC & Beck, EJ 2017, 'Risks in the innovation ecosystem for novel grains', *67th Australasian Grain Science Conference*, Christchurch, New Zealand, September 20th – 22nd

Other Presentations

Simnadis, TG, Tapsell, LC & Beck, EJ 2013, 'Sorghum: an overview of the factors affecting the possible introduction into the human food supply in Australia', *American Association of Cereals Chemists International Annual Meeting*, Albuquerque, NM, USA, September 29th – October 2nd

Simnadis, TG, Tapsell, LC & Beck, EJ 2017, 'Diversifying the Australian food system: Conceptualising the incorporation of novel grains into the food supply as an agricultural innovation', *TropAg 2017*, Brisbane, Australia, October 20th – 22nd

AWARDS

Scholarships

- Australian Post Graduate Award, 2014 – 2017
- GRDC Grains Industry Research Top-Up Scholarship, 2014 – 2016
- RIRDC Postgraduate Research Top-Up Scholarship, 2014 – 2016

Travel Grants

- Association of American Cereal Chemists International, USA
  To: AACCI Conference, Savannah, 2016

Other Awards

- University Medal, December 2013
- Health Impacts Research Cluster 3 Minute Thesis (3MT) Prize, 2015
- University of Wollongong 3MT Final, People's Choice Award, 2016

LIST OF ABBREVIATIONS (A-Z)

ABARES	Australian Bureau of Agricultural and Resource Economics and Sciences
ABS	Australian Bureau of Statistics
AEGIC	Australian Export Grains Innovation Centre
ARC	Australian Research Council
ART	Anti-retroviral therapy
ASGC	Australian Standard Geographical Classification
ASGS	Australian Standard Geographical Standard
ASX	Australian Securities Exchange
AUC	Area Under the Curve
AUD	Australian Dollar
BC	Before Christ
BOM	Bureau of Meteorology
CAT	Catalase
CCK	Cholecystokinin
CD4	Cluster of Differentiation 4
CD68	Cluster of Differentiation 68
CME	Chicago Mercantile Exchange
CPI	Consumer Price Index
CSIRO	Commonwealth Scientific and Industrial Research Organisation
dL	Decilitre
EAT	Epididymal Adipose Tissue
ESCC	Oesophageal squamous cell carcinoma
GCA	Gastric cardia adenocarcinoma
GILZ	Glucocorticoid-induced Leucine Zipper
GRDC	Grains Research and Development Corporation
DAFF	Department of Agriculture, Fisheries and Forestry
FAO	Food and Agriculture Organisation of the United Nations
FAOSTAT	Food and Agriculture Organisation Corporate Statistical Database
FFQ	Food Frequency Questionnaire
g	Gram

GAE	Gallic Acid Equivalent
GI	Glycaemic Index
GL	Glycaemic Load
GNCA	Gastric noncardia adenocarcinoma
GPX	Glutathione Peroxidase
HDL	High-density lipoprotein
HF	High Fat
HFQ	High Fat Quinoa
HHS	US Department of Health and Human Services
HIV	Human Immunodeficiency Virus
HMG-CoA	3-hydroxy-3-methyl-glutaryl-coenzyme A
IARC	International Agency for Research on Cancer
ICE	Intercontinental Exchange
IMF	International Monetary Fund
ITTC	Industrial Transformation Training Centre
kg	Kilogram
LDL	Low-density lipoprotein
LF	Low Fat
LGA	Local Government Area
LPL	Lipoprotein Lipase
MCP-1	Monocyte Chemoattractant Protein-1
MDA	Malondialdehyde
mg	Milligrams
ml	Millilitres
mm	Millimetres
MQA	Methodological Quality Assessment
MRL	Maximum Residue Limit
NHMRC	National Health and Medical Research Council
ORS	Oral Rehydration Solution
OST	Osteopontin
QI	Quality Index
PAI-1	Plasminogen Activator Inhibitor-1
PER	Protein Efficiency Ratio

PICOS	Participants, Interventions, Comparisons, Outcomes and Study Design
PPAR-γ	Peroxisome Proliferator-Activated Receptor-γ
PEPCK	Phosphoenolpyruvate Carboxykinase
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
R&D	Research and Development
RCT	Randomised Control Trial
RQ	Respiratory Quotient
RIRDC	Rural Industries Research and Development Corporation
SA4	Statistical Area Level 4
SD	Statistical Division
SME	Small and Medium-Sized Enterprise
SOD	Superoxide Dismutase
SREBP-1c	Sterol Regulatory Element-Binding Proteins
TLR4	Toll-Like Receptor 4
UCP2	Uncoupling Protein 2
UCP3	Uncoupling Protein 3
UL	Upper Limit
US	United States
USA	United States of America
USD	United States Dollar
USDA	United States Department of Agriculture
VCA	Value Chain Analysis
WHO	World Health Organisation

Chapter 1: Considerations for Novel Grains in the Australian Context

1.1 Exploration of the Australian Grains Industry

1.1.1 An Insight into Novel Grains

The production and supply of grain for the Australian food industry is underpinned by a network of interdependent stakeholders that add value by transforming raw grains into a final product ready for human consumption. Adopting an innovation-driven approach across this intrinsically competitive industry may foster competitive advantages and was identified by the Australian Government National Food Plan White Paper as a key tactic to capture market share and cope with the dynamic challenges facing the food industry into the future(1). The research presented in this thesis recognises that stakeholders positioned from farm to fork play an instrumental role in the creation and capture of value associated with an innovation. By conceptualising the incorporation of currently underutilised or novel grains into the Australian food supply as an example of incremental innovation, this thesis explores factors that may influence the pathway to market and potential value creation process.

Generating unique sources of value from underutilised grains aligns with the broader strategic priorities of industry bodies that are seeking to foster diversity and innovative capabilities as a tool to better respond to the changing dynamics of the agri-food industry. To assist in the formulation of potential solutions, the research presented in this thesis extends the conceptual work of Longin and Würschum(2) who argue that communication, coordination and interdisciplinary research are necessary to pursue the application of underutilised grains into the food supply. Specifically, an inter-disciplinary approach that considers insights from strategic planning, nutrition science and economics is applied to highlight potential sources of value associated with the incorporation of novel grains into the Australian food supply and reveal interactions that will assist in establishing the pathway into this food system.

1.1.2 Grain Production in Australia

Australian agricultural production generated 43.5 million tonnes of crops over the course of the 2014-15 season(3). To provide an international comparison, the Australian production volume is comparable to countries such as Indonesia, Pakistan and Mexico(4). Wheat and barley are the major Australian grains and have historically dominated cropping systems. For example, in the 2014-15 season, wheat and barley accounted for 75% of Australian grain production volume[3].

As a consequence of the dominance of wheat and barley (both winter crops) a larger volume of grain (in Australia) is produced in the winter growing period compared to the summer growing period[3]. The winter period commences with planting between March and July and harvest from September to December, while summer crops are planted between September and February and harvested between February and May[5]. Planting and harvesting occur across a range of time periods due to the range of agro-ecological zones that persist across growing regions. This contributes to subtle differences in climate, soil characteristics and agronomic management strategies, which in turn influences planting and harvest times[6].

1.1.3 Value of Australian Crop and Grain Production

Agricultural activities occur across Australia, with an estimated 10% of agricultural land currently allocated to the production of crops[7]. These crop growing activities generate $26.8 billion in revenue for producers, or approximately half of all value generated by the Australian agricultural industry[8]. Value is also generated through international trade, with grains (or cereals) the second largest contributor (after meat products) to the $29.2 billion Australian animal and food export industry[9]. The value generated through export income indicates the importance of Australian agricultural production, specifically grain production in the context of the global market. By focussing on grains that are underutilised in the Australian food supply, the research presented in this thesis reveals a range of factors that require consideration when exploring the creation of potential sources of value.

1.1.4 Strategies to Grow the Value of Grain Production

The desire to enhance the competitiveness of the grains industry and deliver growth opportunities are motivating industry bodies, such as the Grains Research and Development Corporation (GRDC) and Rural Industries Research and Development Corporation (RIRDC) to conduct research, development and extension activities. Their work focuses on identifying opportunities to expand rural industries (RIRDC) and specifically, the grains industry (GRDC). For example, identifying and meeting market requirements is a core pillar of the strategy set out by the GRDC to secure the profitability and sustainability of the Australian grains industry[10]. Moreover, the combined efforts of these organisations can provide the scope to improve the performance of existing grain production activities and assist in the development of strategies that can unlock the potential of the Australian grains industry[a].

Strategies that seek to enhance the value of the grains industry must wary of current industry dynamics. Agricultural producers have shown a tendency to expand their operations[11], potentially in response to the allure of economies of size, where the cost per unit of production decreases as farm size increases[12]. Intuitively, the ease with which grains can be substituted (due to their perceived homogeneity)[13] suggests that the primary driver of revenue growth will be through increases in production volume and a decrease in average cost per unit of output[12].

These strategies to enhance the value of the grains industry assume that the agricultural industry is an example of a perfectly competitive market, where output is seen as being homogenous, there is perfect information available for market participants, and no single buyer or seller can influence the price of the product. Sexton[14], however, argues that agricultural markets rarely conform to the requirements of a competitive market. Contemporary departures from this concept of a competitive market include micro-distilleries and artisan bakeries, which differentiate between grains on the basis of endogenous quality attributes that can influence the final product. The emergence of high value markets has diversified the potential end-uses for grain and opened attractive sales channels for industry stakeholders that are willing to expose themselves to these unique opportunities.

To expand the Australian grains industry beyond traditional markets, the skills and expertise (knowledge capital) of stakeholders must also be considered. Their insights can assist in the development of realistic strategic growth objectives that can be executed by industry partners. A key element of this thesis is to capture the perceptions of stakeholders involved in the market for novel grains. This will be combined with research highlighting

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[a] As this thesis aligned with the strategic objectives of the GRDC and RIRDC, additional support for the research efforts were provided through a grains industry research scholarship (GRDC) and a postgraduate research scholarship (RIRDC) awarded to the candidate, TS.

potentially desirable nutritional properties and an empirical overview of factors influencing the supply of novel grains. The combination of findings from this research can highlight potential sources of value in the market for novel grains and direct attention to strategies that could be formulated to capture this value. Before outlining further details of the planned research, the current grain consumption paradigm and potential challenges that may influence the attractiveness of adopting novel grains into the food supply are considered.

1.1.5 Current Grain Consumption and Future Challenges

Grains form an integral component of the human diet[15], with their history of use stretching back to the time of the Neanderthals[16]. They remain an important component of the food system, with their consumption accounting for an estimated 35% of daily dietary energy intake across the globe[17]. In Australia, grains have been recognised as one of five core food groups that should be included as part of a healthy and nutritious diet[18] with an estimated 97% of the Australian population consuming grain-based products on a daily basis[19]. This figure, however, masks the quantity that is being consumed, with only 30% of individuals meeting the dietary intake of grains recommended by health authorities[20].

The growing global population is contributing to an increase in demand for grains, with an estimated 45% increase in the quantity of grain (compared to levels produced in 2005-07) required to meet projected demand[21]. Achieving these productivity improvements will be challenging in the face of land competition, climate change and water scarcity[22]. In addition, translating these forecasts to an expanding urban population is difficult[23], which is resulting in the emergence of an increasingly fractured relationship between the population and the food supply[24].

The challenges associated with having sufficient food to feed the global population were first expressed by Thomas Malthus in the late 18th century. He concluded that by 1830 population growth would be constrained by the food supply. While this did not occur, the task of feeding the growing population is an on-going challenge. Historically this has been achieved through a combination of expanding the area of land under cultivation and generating sustained productivity (yield) improvements over time (**Figure 1.1**). These yield improvements have been driven by a combination of technological (e.g. seed genetics and fertiliser use), economic (e.g. agricultural investment) and institutional factors (e.g. agricultural policies)[25].

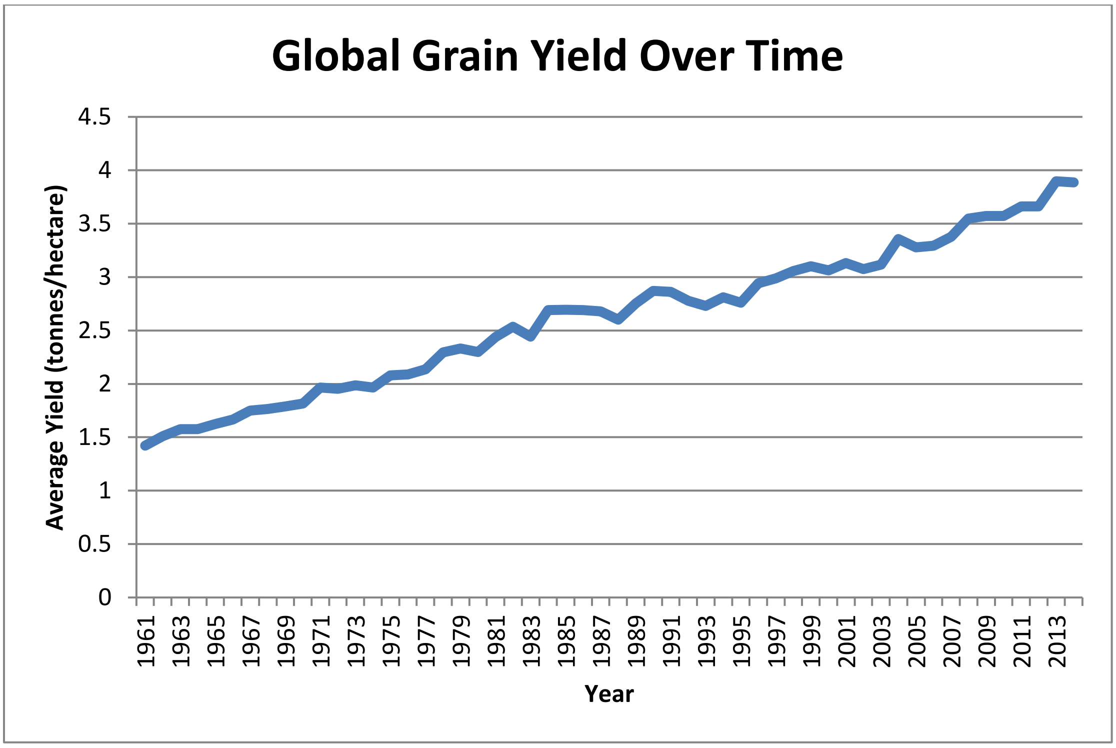

Figure 1.1 Average global grain yields 1961-2014[26]

Yield improvements have tended to cluster on a small group of grains, leading to the current situation, where over 90% of global grain consumption is in the form of wheat, corn and rice[27] (**Figure 1.2**). The ability of these grains to continue feeding the global population remains unclear, with research suggesting that yields for these grains will not keep pace with demand in the years leading up to 2050[28]. For example, modelling of Australian wheat yields, between 1990 and 2015, identified that climate change had contributed to a 27% reduction in yield potential over this time period[29]. It has been proposed that precision agriculture, which involves the application of the appropriate agronomic management practices to specific tracts of land at the right time[30] is the future of agriculture and may enable some yield gains to be realised. In contrast, Hochman *et al.*[29] argue that technological advances will be nullified by negative climatic influences leading to a stagnation and eventual reversal in yield gains. In addition, other factors such as population hubs moving further from food production centres[31] and a tendency to rely on homogenous global food systems[32] are likely to add further complexities to the supply of food for the global population.

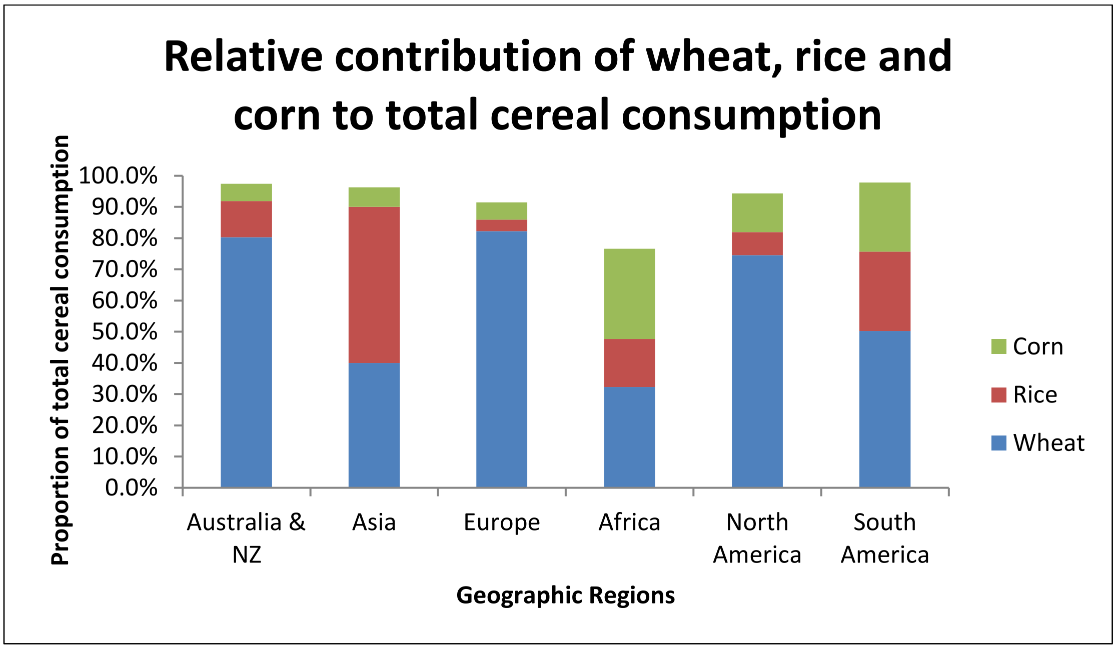

Figure 1.2 Major cereal consumption across geographic regions[27]

Solutions to these challenges may lie in the adoption of other novel grains that are currently underutilised in the food supply[33]. One of the key arguments in favour of exploring the potential application of these grains relates to their ability to provide a deeper level of diversification to current crop growing systems[33]. This has implications for resiliency in production systems and associated food security into the future[34]. These attributes present potential sources of value that may be attractive for stakeholders considering the incorporation of a novel grain into the food supply. The potential pathway to market for novel grains, their nutritional attributes and the influence of economic factors on supply warrant further investigation and in combination form the basis of this thesis.

1.1.6 Background Shaping the Utilisation of Novel Grains

As outlined previously, wheat, rice and corn are the three major staple grains consumed in the diet[35]. Historically, their application to production systems and adoption by manufacturers and processors increased their utilisation and resulted in concomitant advances in their research and development (R&D) and breeding programs[36]. This had the effect of increasing commercial returns, further perpetuating the concentration of commercialisation and development efforts. In contrast, smaller scale crops tend to be viewed as being less important and have been neglected from the perspective of performance improvement[36].

The resulting market traction experienced by these (now) staple grains, coupled with the perceived risk associated with adopting a novel grain into the production system (relative to incumbent staples), has contributed to the hesitancy shown among stakeholders towards the adoption of novel grains[37]. Moreover, for the farmer, the adoption process will also be influenced by the experiences of other farmers and the potential returns that can be generated[38]. The combination of these variables begins to provide an explanation behind the existence of staple and novel grains in the food supply.

A subset of these novel grains, colloquially referred to as 'ancient grains', due to the absence of significant genetic alteration over time[39, 40], include examples such as spelt, teff, millets and sorghum as well as pseudo cereals such as quinoa, amaranth and buckwheat[15] (**Table 1.1**). Research investigating the potential application of these grains into production systems has tended to be overshadowed by research focussing on strategies to enhance and optimise incumbent production systems[41, 42]. Thus, the question of how to incorporate novel grains into modern growing systems, supply and distribution networks and ultimately the diet of the consumer remains underexplored.

1.1.7 Applications of Novel Grains

An attractive property of grains (novel grains included) are their versatility and application to a range of food and non-food uses. Traditional food applications include the preparation of breads, cereals, pasta, porridge (for human populations) as well as forage and feed for farm animals such as cows, pigs, sheep, horses and chickens. In addition, alcoholic beverages such as beer rely on a fermentation reaction, which requires a source of sugar as a starting input. Grains are a repository of starch, which are composed of sugar subunits, and therefore viable inputs into the production of alcohol.

Table 1.1 Summary of ancient grains and their historical origins

Grain	*Scientific Name*	*Origin*	*Cultivated*	*Reference*
Spelt	Triticum spelta	Fertile Crescent[a]	7,000 BC	Peng *et al.*[43]
Emmer	Triticum dicoccum	Fertile Crescent	8,500 BC	Cooper[39]
Einkorn	Triticum monococcum	Turkey	9,000 BC	Cooper[39]
Camelina	Camelina sativa (L.)	Europe	1,500 – 400 BC	Zubr[44]
Khorasan Wheat	Triticum turanicum	Fertile Crescent or Anatolia[b]	Unknown	Grausgruber *et al.*[45]
Millet	Panicum miliaceum	East Asia	8,000 BC	Dodson and Dong[46]
Teff	Eragrostis tef	Ethiopia	4,000-1,000 BC	Cheng *et al.*[47]
Sorghum	Sorghum bicolor (L.) Moench	Ethiopia	4,000-3,000 BC	Dillon *et al.*[48]
Quinoa	Chenopodium quinoa	Andean Region[c]	2,000-1,000 BC	Cooper[39]
Amaranth	Amaranthus	South America	5,000 BC	Arreguez *et al.*[49]
Buckwheat	Fagopyrum esculentum	China	4,000 BC	Dodson and Dong[46]
Chia	Salvia hispanica	Mexico	1,500-900 BC	Muñoz *et al.*[50]

[a] Fertile Crescent is an area that spreads across the Persian Gulf
[b] The exact origin is still disputed
[c] Ecuador, Bolivia, Colombia and Peru

A review by Charalampopoulos *et al.*[51] identified grains as being potential candidates for the development of functional foods. Components of the grain could offer functional potential, while these components (e.g. starch) could also act as an encapsulation method for other functional compounds. Value-add opportunities also lie in the manufacture of plant-based oils from the seeds of grains. Quinoa oil, for example, is rich in Vitamin E, which has multiple end-use applications[52].

Other applications of novel grains may lie in the manufacture of biodegradable polymers (biopolymers). Compounds, such as kafirin (sorghum protein), may have the potential to be transformed into viable biopolymers[53], if the raw materials were competitively priced and the final polymer possessed the same functional characteristics as incumbent materials[54]. For example, if by-products from the processing of grains resulted in materials with a cellulose composition that would make biopolymer manufacture feasible[55]. At present this is not seen on a commercial scale, but presents an innovation opportunity for novel grains.

1.1.8 Potential Factors Influencing the Uptake of Novel Grains

A brief outline of supply and demand-based market forces and their influence on the emerging interest in novel grains provides the foundation for the deeper analytical work to be performed in this thesis. From the supply front, proponents arguing for the diversification of the grain-growing base point to the relative over-supply of major staple grains. For example, US wheat inventories are at their highest levels since 1987[56], which is decreasing the price that farmers are able to receive at the point of sale[57]. Increasingly unpredictable weather patterns are also encouraging farmers to explore crops that are more tolerant to heat and water stress[58]. The adoption of novel grains that do not have a current surplus of supply and are less susceptible to crop losses due to adverse weather presents a potentially desirable risk mitigation strategy. The added advantage of growing environmentally robust crops is the potential to expand their production into locations that were not previously suitable for incumbent crops, augmenting revenue streams for the farmer.

Trends in consumer demand are also contributing to the emergence of novel grains as a potentially viable market proposition. As an example, the innate health connotations associated with foods containing whole grains has contributed to the twenty-fold increase seen in whole grain product launches in 2011 compared to 2000[59]. Other contemporary examples include innovation in fast food, where nutrition and convenience are being embraced as a point of value. For example, Eatsa®, a fast food outlet based in the US have adopted the mantra of ‘Better, Faster Food’ and are experiencing significant consumer traction through their approach to serve quinoa in ‘fast’ formats[60]. Coupling these trends with emerging consumer desires for naturally functional foods that possess unique health imparting properties[61] may provide further impetus for stakeholders to explore the opportunities for incorporating novel grains into product formulations.

Of critical importance is recognising the complexities that underpin the food industry and the role of innovation in overcoming these challenges[62]. This has encouraged food manufacturers to engage in product innovation that aligns with market trends, such as health, nutrition and product quality[63]. In addition, the search for sources of competitive advantage, potentially through new product development[64] to stand out in the market is a powerful incentive for food industry stakeholders[65]. The research presented in this thesis adopts the position that the incorporation of novel grains into the food supply is underpinned by a combination of interdependent factors that have the potential to be a catalyst for realising competitive advantages. While the influence of demand is explicitly acknowledged, a supply-orientated approach is taken to capture the potential pathway to market. Furthermore, by exploring the potential sources of value associated with the incorporation of novel grains into the food supply, it may be possible to identify unique competitive advantages. This may have implications for the degree to which stakeholders adopt novel grains and ultimately deliver them to the consumer.

1.1.9 Implications for Research Investigating Novel Grains

The research presented in this thesis will attempt to provide an insight into the potential sources of value associated with the incorporation of novel grains into the Australian food supply. It will be argued that the adoption of novel grains into the food system is an example of an incremental innovation, where innovation is defined as the development of new products or methods to process these products into value added outputs[66, 67]. By drawing on insights from business and science, this thesis will present an interdisciplinary framework that can be applied to evaluate the opportunities for incorporating novel grains into the Australian food supply. This will be addressed by applying a case-study approach that seeks to evaluate the potential for incorporating two underutilised, novel grains, represented by sorghum (*Sorghum bicolor* [L.] Moench) and quinoa (*Chenopodium quinoa*) into the Australian food system.

1.1.9.1 Application of the Case Study Approach

By selecting sorghum and quinoa as examples of novel grains, it is possible to expose the potential pathway to market and identify unique sources of value associated with their incorporation into the Australian human food supply. The findings from the exploratory analyses are discussed with respect to sorghum and quinoa, but are also considered more broadly in the context of novel grains. The exploratory nature of the research seeks to capture attributes relevant to the case studies, while simultaneously developing a robust framework that has the scope to be implemented to other novel grains and their potential application into the food system.

A combination of qualitative and quantitative research methods will form the basis of this investigation and contribute to addressing the underlying research question. The formal research is divided into three main sections. In Study 1, the concept of the business ecosystem is introduced and applied to the market for novel grains. A sample of key stakeholders involved in the transformation of novel grains into final products are identified and interviewed. Their insights towards possible sources of value and factors influencing the diffusion pathway into the food supply are gathered. The interviews also expose the type of risks that may persist and their relative position, in relation to the roles of key stakeholders within the business ecosystem. Study 2 systematically reviews the health attributes of sorghum and quinoa. The results are discussed with respect to the ability to translate scientific evidence into consumer-friendly messages that could be used for promotional purposes. The final component of the research (Study 3) explores the empirical influence of a range of variables on the area of land planted to sorghum over time. The results are considered in the context of the supply of a novel grain with overarching sources of value associated with their incorporation into the food supply exposed. A brief background description of these grains and the system that enables them to move from farm to fork is considered next.

1.1.10 Background and Current Utilisation of Sorghum in Australia

Sorghum is the 5th most cultivated crop in terms of global production volume(68) with the largest producers identified in **Figure 1.3**. In the Australian context, sorghum is grown across northern New South Wales and Queensland (**Figure 1.4**) and is the major Australian summer crop(3). Over two thirds of global sorghum consumption occurs in Africa(27) where its origins lie(69). In contrast, outside population subgroups that have traditionally consumed sorghum in their diet (e.g. African migrants who have immigrated to Australia) sorghum is used almost exclusively as an animal feed in Australia and large parts of the developed world(70). This historical paradigm is the subject of renewed interest with **Table 1.2** outlining commercially available products containing sorghum and the manufacturers responsible for developing these products.

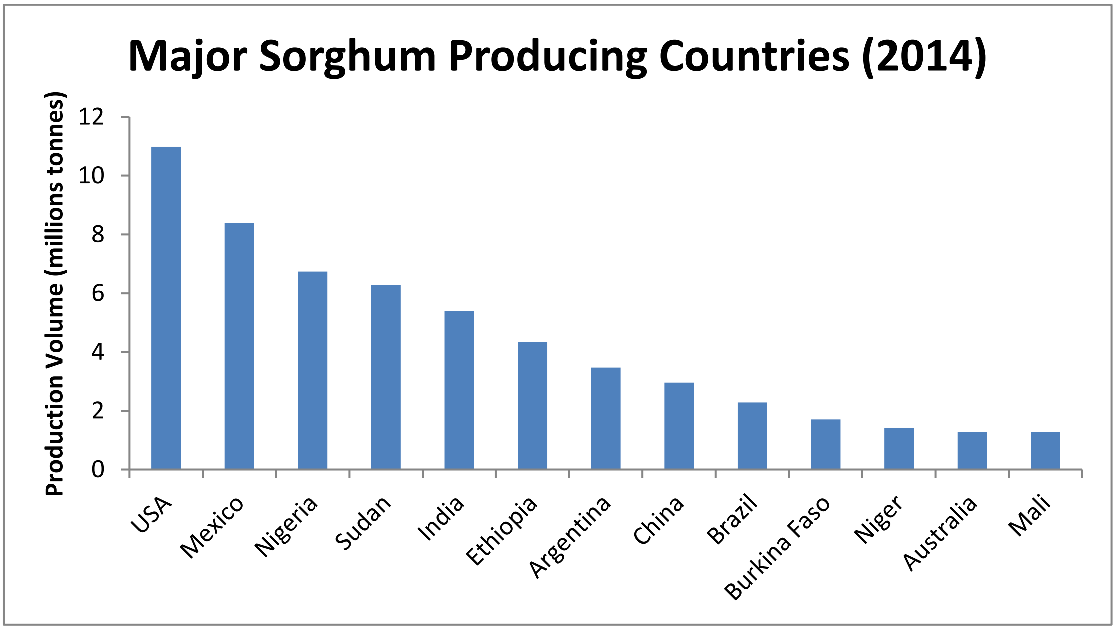

Figure 1.3 Major producers of sorghum in 2014[68]

Table 1.2 List of brands that include sorghum in their product range

Brand	Example Products
Sanitarium	Gluten Free Weet-Bix
Freedom Foods	Muesli Snack Bars, Breakfast Cereal
Bob’s Red Mill	Flour

Despite the current paradigm underpinning its utilisation as a low value crop, (due to its primary use as an animal feed), potential opportunities lie in altering this perception by focussing on its desirable attributes[71]. For example, sorghum is rich in potentially health imparting bioactive compounds which have been shown to have potent antioxidant activity[72] and provides a source of slowly digestible starch, which may have positive implications for attaining desirable energy balance outcomes[73]. In addition, sorghum is more robust to heat and water stress than substitute crops, such as corn[74] placing it in a desirable position as climate patterns become more volatile[75] and extreme weather events, such as heat waves, increase in frequency[76].

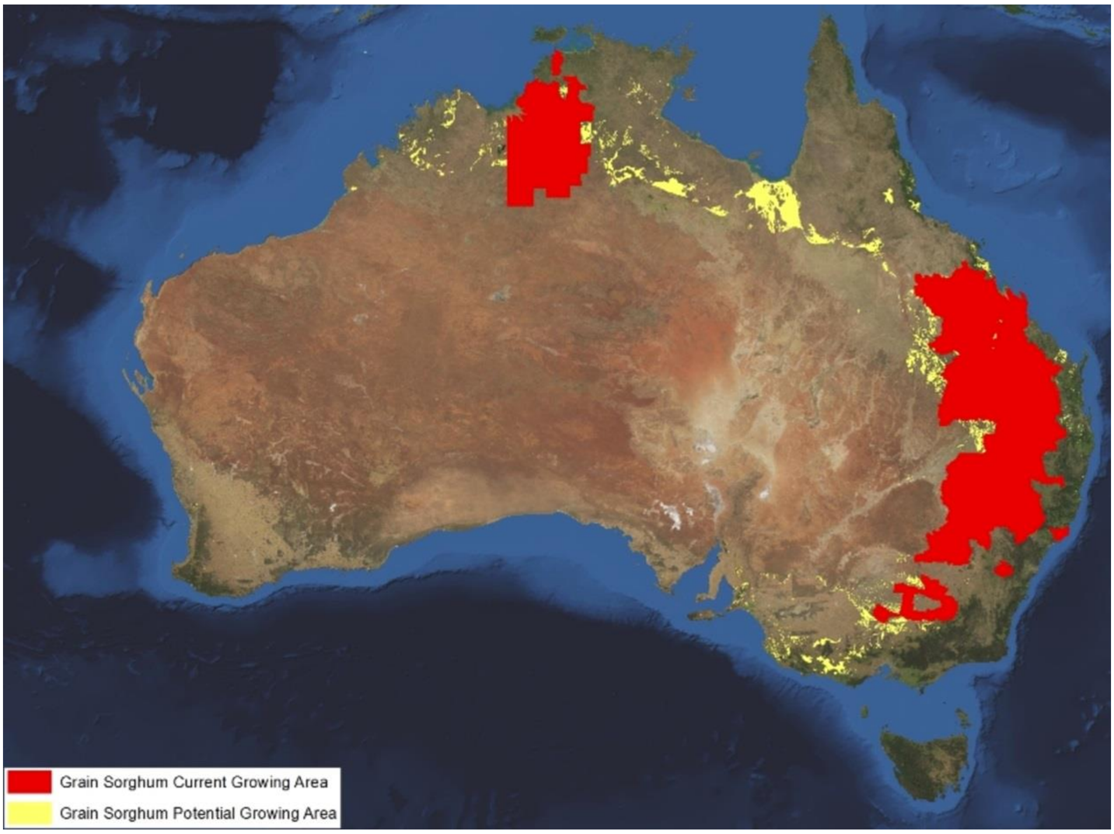

Figure 1.4 Current and potential future sorghum growing regions[77]

1.1.11 Background and Current Utilisation of Quinoa in Australia

Quinoa originates from South America and was seen as the 'mother of grains' by the Incas, as a mark of respect for the unique properties it possessed[39]. While officially classified as a pseudo-cereal[15], before being consumed, quinoa requires very similar agronomic management, processing and preparation as a grain. In order to maintain consistency and flow throughout the thesis, quinoa will be referred to as a grain rather than a pseudo-cereal.

Quinoa is the 13th most produced crop with Bolivia and Peru dominating global production[68] and traditionally consumed as a staple in South American communities[52]. The western palate has however responded positively to quinoa, and its resulting rise in popularity can be attributed to it being embraced by a wider audience. A partial explanation for this stems from the perceived nutritional benefits associated with the grain and the ease with which it can be substituted for other dietary staples, such as rice. It's versatility is reflected through the range of conventional grain-based products (e.g. bread and cereals) as well as less conventional products (e.g. yoghurt and milk) it has been incorporated into. Popular brands that produce products that contain quinoa in their ingredient list are outlined in **Table 1.3**.

Table 1.3 List of brands that include quinoa as an ingredient in their product range

Brand	Example Products
Celebrate Health	Instant Meal
San Remo	Instant Meal
Mountain Bread	Wraps
Tilda	Instant Rice
Uncle Bens	Instant Rice
Sunrice	Instant Rice
Seven Sundays	Breakfast Cereal
Celebrate Health	Breakfast Cereal
Freedom Foods	Breakfast Cereal
Uncle Toby’s	Breakfast Cereal
Mckenzie’s	Flour
Red Tractor	Raw Quinoa
Three Farmers	Raw Quinoa
Be Natural	Muesli Bars
Nice and Natural	Muesli Bars
Orgran	Crispbread
Helgas	Bread
La Zuppa	Soup
Campbell’s	Soup
Continental	Soup
Heinz	Baby Food

Quinoa is a complete source of protein(78) and possesses unique bioactive compounds, such as saponins(79), that have been implicated in delivering various nutritional outcomes. Moreover, quinoa is being recognised as a potential crop that can be robust to the emerging challenges of climate change(80), particularly in global regions that have agronomic issues such as soil and water salinity(81).

While the majority of quinoa sold in the Australian context has been sourced from international markets (**Figure 1.5**), price spikes induced by a surge in demand(82) motivated a small group of growers (located in Western Australian and Tasmania) to explore the potential applicability of quinoa to their growing systems. Opportunities to increase this level of adoption may transpire as a deeper understanding of the agronomy and genetic attributes of the grain emerge. This is being supported by extensive RIRDC led field trials, which aim to elucidate the agronomic suitability of the grain across a range of geographic regions[83]. Moreover, research has identified that quinoa would be suitable to be grown across vast regions of Australia (**Figure 1.6**). This suggests it has significant potential to be incorporated more widely into Australian growing systems.

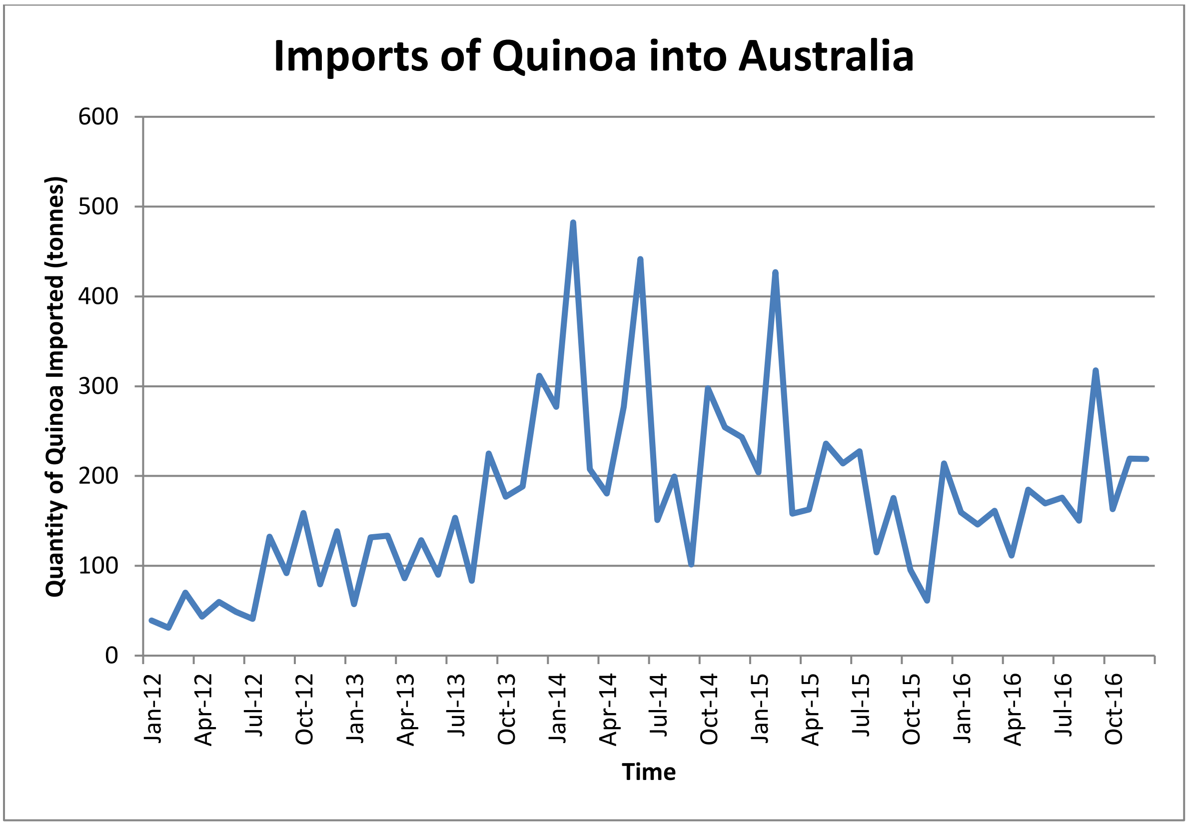

Figure 1.5 Imports of quinoa into Australia between January 2012 and December 2016[84]

The first stage of this research involves a consideration of the stakeholders that are required to deliver novel grains from farm to fork. This is conceptualised as a business ecosystem where interdependent stakeholders work in tandem to co-create value.

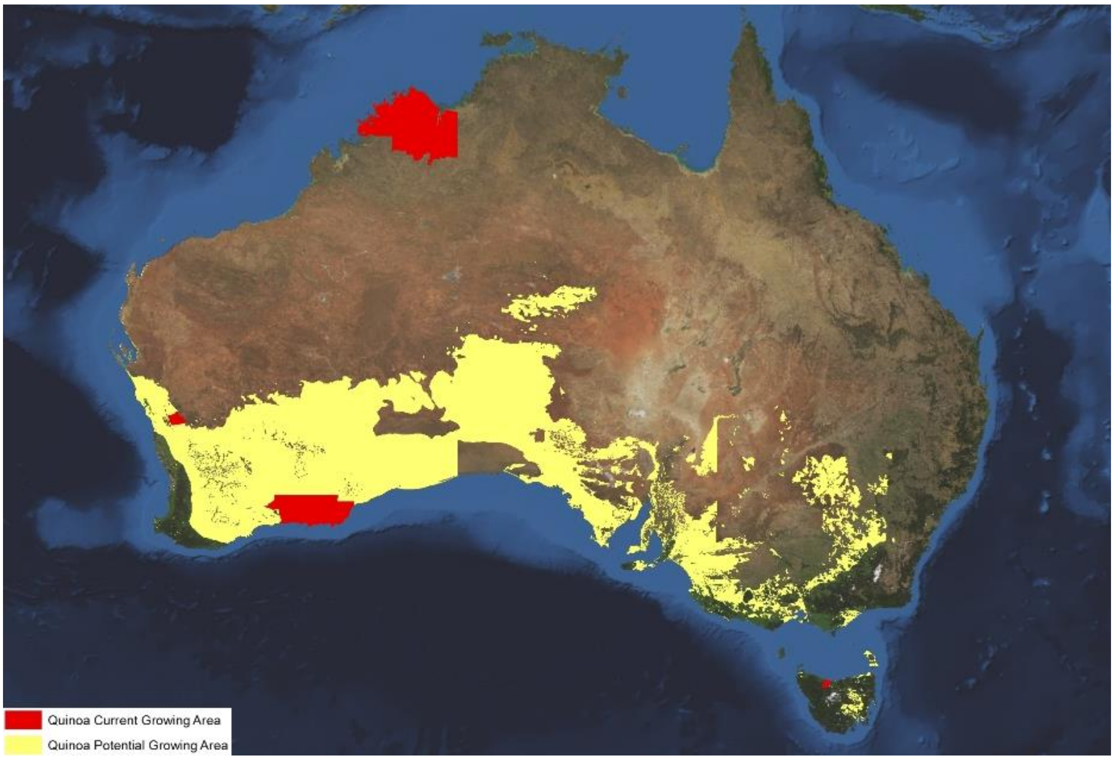

Figure 1.6 Current and potential future quinoa growing regions[85]

1.2 Exploring Stakeholder Considerations

1.2.1 The Business Ecosystem, Sources of Value and Diffusion Pathways

At the core of this thesis lies the question of how novel grains can be incorporated into the Australian food supply. This implies the need to understand the process that is required to deliver a grain from the farmer to the end-use customer. Capturing this process, as the movement of a product from one stakeholder to another is a traditional supply chain view[86]. The activities that occur across the supply chain contribute to the generation of value, which is an important consideration given that competition has shifted from individual businesses to competition between entire supply chains[87]. Rather than focussing exclusively on their internal processes, businesses are increasingly exploring opportunities to streamline and co-ordinate their upstream (e.g. suppliers) and downstream (e.g. distributors) linkages to enhance their competitive performance[88].

The presence of connections between functional areas of the agricultural industry (such as plants and livestock) were noted in the works of G.L. (Bill) McClymont. The elegant frameworks he developed to describe an agricultural ecosystem continue to inspire contemporary scholars[89] and reflect the importance of recognising linkages between stakeholders. In the context of delivering novel grains to market, there is a need to capture the value created by the range of interdependent stakeholders, commencing prior to planting (e.g. through selective breeding) and concluding at the point of sale (e.g. consumers)[90]. The business ecosystem approach highlights the interdependencies across stakeholder groups, their opportunity to work together[91] and the value that can be created through co-ordination and collaboration[92]. This thesis draws on the work of Adner[93] to conceptualise an ecosystem as "*the alignment structure of the multilateral set of partners that need to interact in order for a focal value proposition to materialize*"(p40). Embracing an ecosystem perspective is important because the adoption of an innovation revolves around product and relationship and/or reputational-related benefits[94]. By identifying the perceptions of key stakeholders within this ecosystem, potential themes that underpin the sources of value and the diffusion pathway for novel grains into the food supply can be explored. Given that novel grains are an example of an innovation in the agricultural system, it is also crucial to consider the potential risks associated with their incorporation into the food system.

1.2.2 Risks across the Business Ecosystem

Risks are ubiquitous in the agri-food industry with unique challenges such as perishability[95], power relationships[96] and uncertainty in production due to unpredictable weather events[97] plaguing the industry. By analysing the insights of stakeholders across the business ecosystem and applying a blueprint mapping method, it is possible to expose the types of risk and their relative position with respect to the business ecosystem[98]. The identification of potential risks can assist in the formulation of prescriptive strategies that can support the approach taken by ecosystem stakeholders towards the incorporation of novel grains into the food supply[99]. The next element of the research involves the exploration of the nutritional attributes of novel grains and the potential value that could be leveraged from having an awareness of these properties in the product development phase.

1.3 Exploring Nutritional Attributes and Commercial Implications

Perceived health is emerging as an important element of consumer purchasing behaviour. Examples include messages related to 'naturally functional' and 'free from' gaining traction in the market[61]. Identifying the nutritional attributes of novel grains may help to build a value proposition for consumers and encourage ecosystem stakeholders to invest resources into identifying the types of health messages that are most influential for a consumer. This has implications for the use of nutrition and health-related messages on product packaging and if appropriate, may be used as a point of differentiation and promotion from other grains used in product formulations.

While the consumption of grains is advocated by national health authorities throughout the world[100, 101], the majority of consumers are unlikely to purchase a product purely on the basis of health. Nonetheless, by evaluating the health attributes of novel grains it is possible to suggest potential health related messages that are intrinsically valuable to the consumer. Evaluating these attributes in a scientifically rigorous manner also adds a layer of validity to marketing claims, which may augment the perceived consumer value. As with any plant-based agricultural product though, the supply to market will be contingent on the presence of farmers growing the grain in sufficient quantities. This is considered in the next section.

1.4 Exploring Factors Relating to Acreage and Supply

The potential incorporation of novel grains into the food supply is contingent on securing a stable supply from the farm. By exploring the area of land planted to novel grains and modelling this as a function of variables that influence planting behaviour, it is possible to assess the magnitude of the effect of these variables on acreage decisions. Previous empirical acreage models have tended to focus on crops such as corn, soybeans and wheat[102-106]. The majority of these studies have been performed in North America, with a paucity of research evaluating acreage for sorghum, quinoa and other novel grains in the Australian context. This presents a gap in the extant literature that must be evaluated to adequately address the question of supply. As a caveat, the modelling approach requires a sufficiently rich dataset to conduct the analysis. For this reason, sorghum, which has had its acreage recorded for over 30 years, will be used as the primary case study. The empirical approach could however be extended to other novel grains and may provide scope to develop insightful agricultural policies that seek to encourage a greater level of adoption of novel grains into production systems.

The three major components of research outlined in this chapter span strategic planning, nutrition science and economics. By implementing an interdisciplinary approach, it is possible to explore the incorporation of novel grains into the food supply and expose potential sources of value from this activity. The elements of the interdisciplinary approach will now be discussed in relation to the research framework and the potential implications for evaluating novel grains other than sorghum and quinoa.

1.5 Thesis Framework

Institutions that are seeking to understand complex phenomena that cannot be adequately addressed through traditional methods are increasingly adopting an interdisciplinary research strategy[107]. This approach is advocated by the Australian Research Council[108] as a means of fostering excellence and advancing research in Australia. By conducting research at the interface of business and science, this thesis presents a unique exploration of innovation in the market for novel grains and assists in the identification of potential sources of value associated with their incorporation into the food supply. In particular, the focus will be on applying the conceptual work of Longin and Würschum[2] by leveraging the notion that interdisciplinary research can act as a tool to establish market avenues for value creation in the grains industry. The application of insights from business and science enables an overarching research framework to be considered. This framework may be applied to future scenarios where the value associated with other novel grains is being evaluated.

By examining sorghum and quinoa as case studies, the research presented in this thesis highlights three broad components of the value creation process. Exploring the business ecosystem for novel grains investigates the interplay of stakeholder perceptions towards the market for novel grains and the type and position of risk with respect to the ecosystem (Study 1). Investigating the nutritional attributes of novel grains identifies how these properties can influence the commercial decision to explore these grains as inputs into product formulations (Study 2). Finally, the supply of grain to market is considered through an empirical exploration of factors that influence the area of land planted to novel grains (Study 3). In combination, the interdisciplinary approach adopted by this thesis enables potential sources of value associated with the incorporation of novel grains into the food supply to be revealed. This has implications for stakeholders across the business ecosystem and may highlight potential strategies that could be crafted to diversify the food supply and leverage unique sources of value.

1.5.1 Research Question

Historically, the adoption of novel grains into existing food systems has been subdued, leading to the current situation where the business ecosystem supporting the pathway to market is underdeveloped. The relatively new idea of incorporating novel grains into the Australian food supply is therefore conceptualised as an example of incremental agri-innovation. To address the current paucity of research exploring the approach to include novel grains into the food supply, this thesis considers factors from strategic planning, nutrition science and economics to explore the potential value embedded in the market for novel grains. The critical question that this thesis investigates is:

What are the potential sources of value associated with the incorporation of novel grains into the Australian human food supply?

1.5.2 Thesis Aims

The research to be carried out in this thesis aligns with the broader recognition that agricultural innovations are key to the future success of the agri-food sector(109). By applying an inter-disciplinary approach that combines insights from business and science, this research explores a range of factors that are likely to influence the incorporation of novel grains into the food supply. Therefore, the aim of this thesis is to:
Explore potential sources of value that can be leveraged from the inclusion of novel grains into the Australian food supply.

1.5.3 Thesis Hypothesis

It is anticipated that unique sources of value associated with the incorporation of novel grains into the food supply would be identified.

Moreover, this incorporation process will require the consideration of attributes specific to strategic planning, nutrition science and economics.

1.5.4 Thesis Overview

Chapter 1 has introduced the motivation behind this thesis, presented a brief background to novel grains, outlined the research aims and provided an overview of the proposed interdisciplinary research approach to address the underlying research question. Chapter 2 presents the methodological foundations of the proposed case study approach. A deeper exploration of the interdisciplinary approach and additional background information relevant to the three major areas of research is also presented. This includes an overview of the qualitative and quantitative methods that will be implemented. Chapter 3 formally extends the business ecosystem concept to the market for novel grains (by adopting sorghum and quinoa as case studies) and explores stakeholder perceptions towards these grains. An overview of stakeholder sources of value, the diffusion pathway for an agricultural innovation and potential risks associated with the incorporation of sorghum and quinoa into the food supply are also explored. Chapter 4 presents systematic reviews of the nutritional attributes of sorghum and quinoa and the potential implications for promotional activities and product development. Chapter 5 provides an empirical analysis of variables that influence sorghum acreage and the implications for consistency in the supply of grain. Finally, Chapter 6 summarises the research findings, suggests areas for future research and presents a series of strategic recommendations to inform the process of incorporating novel grains into the Australian food supply.

Chapter 2: Research Methodology

2.1 Overarching Methodological Framework

Chapter 1 outlined the motivation behind the research and provided an overview of the current role of novel grains in the Australian food supply. It was noted that the food supply is currently reliant on a subset of staple grains that will require productivity improvements to meet future demand forecasts. Recognising that it is currently uncertain whether these improvements will materialise has stimulated discussion that explores the potential to diversify the food supply to include underutilised novel grains. This thesis uses an interdisciplinary research approach to further examine this issue and ultimately argues that value lies in incorporating novel grains into the food supply.

Chapter 2 articulates the research question and presents a detailed overview of the three studies that underpin the research undertaken for the thesis. It discusses the methods, theoretical assumptions that underpin the design of these studies, and outlines the research hypothesis, measured outcomes and the interdisciplinary approach. Finally, the potential applicability of the methodology adopted in this thesis is considered with respect to conducting research on other novel grains.

2.1.1 Research Question

An investigation that leveraged research methods from business and science disciplines was implemented to address the following question:

What are the potential sources of value associated with the incorporation of novel grains into the Australian human food supply?

As this question is exploratory in nature, a case study approach was used to address the constituent elements(110). Case studies of sorghum and quinoa – two examples of novel grains that appear underutilised in the Australian human food supply were selected.

2.1.2 Selection of Case Studies

The motivation behind selecting sorghum and quinoa as case studies stemmed from their current position as underutilised grains in the Australian food system. Specifically, sorghum is seen as a 'feed' rather than 'food'(70), while quinoa is recognised as a high value commodity, but with very little in the way of production in Australia[111]. In addition, sorghum and quinoa are associated with the strategic priorities of planned research for organisations such as the GRDC and RIRDC.

2.1.3 Novel Grains as an Agricultural Innovation

The dominance of wheat, rice and corn as dietary staples suggests that the incorporation of other grains, such as sorghum and quinoa into the food supply would be a unique undertaking. It is implicitly assumed that incorporating novel grains into operational systems by key stakeholders will leverage existing competencies, requiring relatively simple improvements and therefore constitute an example of an incremental agricultural innovation[112]. In this context, innovation is defined as the development of new products or methods to process these products into value added outputs[66, 67]. This is a fundamentally unique approach to the exploration of novel grains, and supports the view of Longin and Würschum[2] who argue that the rediscovery of novel grains will present opportunities to generate unique sources of value in the food industry. The scope of the planned interdisciplinary research is now outlined.

2.1.4 Development of Research Components

In order to explore the complex interactions that underpin agricultural activities, research strategies have increasingly recognised the importance of establishing an interdisciplinary approach[113-116]. This is an artefact of the scope of agriculture, or more accurately, agribusiness, which incorporates the range of activities required to deliver output from the farm to fork[117]. The transformation of farm produce into value-added final products involves a complex set of interactions that requires the knowledge of stakeholders with expertise across a range of disciplines[2]. This thesis presents research that engages at the interface of strategic planning (Study 1), nutrition science (Study 2) and economics (Study 3). The combination of insights supplied by these areas of research enabled the interplay of factors influencing the incorporation of sorghum and quinoa (as examples of novel grains) into the food supply to be explored.

2.1.5 Mixed Methods Research Approach

As the research question spanned three domains of knowledge, a mixed-methods approach was adopted. Creswell and Plano Clark[118] argue that using a combination of qualitative and quantitative methods provides a deeper understanding of research domains when compared to using either of these methods in isolation. Moreover, Greene *et al.*[119] identified four key benefits in adopting a mixed methods approach, providing opportunities for (1) triangulation, (2) complementarity, (3) development and (4) expansion. In the context of this thesis, a mixed-method approach allows the application of several discrete methods to "…*assess different facets of a phenomenon, yielding an enriched, elaborated understanding of that phenomenon*"[120](p35).

The literature provides examples of previous agri-food related research that has applied a mixed method approach to explore a broad range of complex issues that shape the industry. For example, research on land use decisions[121, 122], exposés of heterogeneity in farm productivity[123], identification of limitations of current food production practices[124], and entry constraints[125], examinations of carbon emissions in food supply chains[126], descriptions of consumer preferences for organic foods[127] and the critical examination of the links between the environment and food consumption[128].

In line with the position of Greene *et al.*[119], applying a mixed methods approach in this thesis enabled triangulation of knowledge from across research domains, identification of areas of complementarity, which assisted in the development of arguments that could be discussed and expanded to encompass the market for novel grains. Thus, initial knowledge and insights from key stakeholders on the two grains under study (collected through qualitative methods), was triangulated with a descriptive overview of the nutritional attributes of these grains and an analysis of crop acreage (both largely determined by quantitative means). Following the reporting recommendations of Lingard *et al.*[129], the qualitative and quantitative methods were pursued sequentially. They were given similar weight and integrated in the development of arguments. Meaningful conclusions were drawn that addressed the research question.

2.2 Design of Study 1: Stakeholder Considerations

As stated above, stakeholder considerations were assessed by qualitative methods. The study itself was composed of two discreet parts to capture elements of the pathway to market for novel grains. In considering the broader thesis investigations, Part A provided an outline of the business ecosystem for novel grains, potential sources of stakeholder value associated with their incorporation into the food supply and elements influencing the potential diffusion pathway that would underpin their incorporation into the food supply. Part B explored the types of risks that may be associated with the incorporation of novel grains into the food supply and the relative position of these risks across the business ecosystem. The qualitative findings from Part A and Part B were generated through a series of semi-structured interviews with key stakeholders involved in the pathway to market. The data for Part A and Part B were generated from the same set of research participants. For clarity, the methods that pertain to the selection of participants and interview methods are outlined in section 2.2.3 Outline of Qualitative Approach. The planned research to be performed in Part A is outlined first.

2.2.1 Design of Part A: Business Ecosystems, Sources of Value and Diffusion Pathways

The collection of stakeholder views began with an articulation of the context in which data would be collected. The process of delivering food to the consumer is underpinned by a sequence of steps that aggregate to form the food supply chain. The steps are a result of resource transformations undertaken by individual actors (stakeholders and firms) to deliver the final product to the consumer, ready for consumption. However, viewing the food system as a traditional supply chain, where inputs flow from one stakeholder to another, limits the ability to articulate the value that is created at each stage of the production process. Hines and Rich[130] introduced the notion of a *value stream*, which explicitly considers the value added to a specific product or service by actors in the supply chain and the transactions that take place to deliver a product to market. In addition, the position of actors and the flow of activities (namely, who is upstream as a supplier and downstream as a buyer) follow a clearly defined path. In other words, the positions that these actors occupy is fixed, with the focus being placed on managing the supply process rather than on shifting the positions that these actors occupy[93].

As an extension of the value stream view, James Moore drew on biological systems to put forward the notion of *business ecosystems,* which describes the community of stakeholders required to generate value for a given product(131). Faced with increasingly complex demands from consumers, firms (also referred to as businesses, organisations, corporations, companies) are forced to grapple with the need to deliver output in numerous and potentially unrelated markets(132). The concept of the business ecosystem enables firms to focus on their internal capabilities and additionally identify other stakeholders that can fill the capability gaps that are needed to deliver the integrated solution. Operating at the ecosystem level enables tangible (e.g. cash) and intangible (e.g. knowledge) assets to flow between stakeholders to co-create value(133). Put differently, the ecosystem view is distinguishable from the value chain perspective through the way users create value for other users and the nature in which value propositions emerge through multilateral partnerships that cannot be decomposed into multiple bilateral connections(93).

2.2.1.1 Mapping the Business Ecosystem for Novel Grains

Mapping the business ecosystem and identifying relevant linkages that contribute to the creation of value provided the foundation for developing stakeholder interviews. In contrast to value chains, which are characterised by supplier/buyer relationships, business ecosystems consist of complex multidirectional relationships between stakeholders(134). The complexity arises as a result of the "*…diversity of relationships, the number of diverse relationships, and the resulting interdependencies*"(132)(p113). The business ecosystem concept recognises the interdependencies between disparate stakeholders, their desire to work towards a common goal and the co-evolution needed to reach this goal(135). Apart from agricultural cooperatives that generally bring together producers (e.g. CBH Group, Norco etc), research has noted an absence of a collaborative environment in the agricultural sector(136). There appears to be a limited appreciation of relationships between key stakeholders that shape the ecosystem(137). Nevertheless, points of value addition within the ecosystem (i.e. transactional focus)(138) as well as the connections (relationships) that are able to hold the constellation of stakeholders together have been identified.

The mapping process undertaken in this thesis involved observing key points of value addition that were identified in previous agribusiness related research[90, 139-141]. Drawing on previous insights from a related domain assisted in the exploration of the business ecosystem for sorghum and quinoa. The intention was to focus on elements of value creation (namely transforming resources to drive customer value) rather than value capture (the receipt of payment associated with the perceived benefit)[142]. To characterise the value created in the ecosystem for novel grains, the value chain analysis (VCA) method was adopted[143].

2.2.1.2 Method for Value Chain Analysis

The VCA method has been previously used to guide improvements to existing value chains[144]. It is also used as a diagnostic tool to help optimise decision making by managers wishing to improve the overall chain[145]. The application of VCA tends to be through a case study approach[144] in order to answer exploratory or explanatory research questions[110]. A similar strategy was adopted in the research undertaken in this thesis by considering the business ecosystem for sorghum and quinoa.

The VCA approach has been refined into a six-staged process[145] of engaging the chain, understanding the market, mapping the flows, identifying opportunities and challenges, implementation and evaluation. For the purposes of the present research, the first three stages of this method were implemented to capture the business ecosystem. Opportunities were captured as potential sources of value derived from the perceptions of key stakeholders. The identification of challenges, (conceptualised as risk in this thesis) were captured in Study 1 Part B. While implementation was not specifically performed in this thesis, the recommendations associated with the potential incorporation process delivered a possible roadmap to implementation. Evaluation is a critical feedback mechanism that can highlight the success of the implemented opportunities. This was beyond the scope of this thesis, but could be explored in follow-up research. The same cohort of participants were also engaged to explore factors influencing the diffusion of novel grains into the food supply.

2.2.1.3 Diffusion of Innovation Theory

For novel grains to be successfully incorporated into the food supply, it will be necessary for stakeholders across the business ecosystem to adopt them into their respective systems. This has been demonstrated in previous work with the implementation of an innovation shown to be influenced by a combination of product (functional), reputational and relational advantages that it can offer(146). Furthermore, previous research has shown that adoption in the Australian agricultural context is traditionally low(147), reflecting the need to shed light on potential adoption practices for novel grains.

The diffusion of innovation theory(94) presents a theoretical framework that sheds light on the process underpinning the adoption of an innovation. The model consists of five elements: innovation, adopters, communication channels, time and social systems, which must work in harmony for an innovation to successfully diffuse(94). To clarify the application of the theory, the innovation in question is the incorporation of sorghum and quinoa into the food supply and the adopters are stakeholders within the business ecosystem. Characteristics of the innovation (explained in further detail below) will be the focus, with communication channels, time and social systems considered implicitly. These dimensions offer fruitful avenues for future research.

Previous research has applied the diffusion of innovation framework to a range of agricultural extension settings, such as an evaluation of factors that could impede and facilitate the diffusion of lignocellulosic ethanol (derived from grain) technology(148), innovation in Italian agriculture(149), the adoption of precision agriculture(150) and organic olive farming(151) to name a few. In addition, diffusion of innovation has been applied to food and beverage-specific settings, for instance, an evaluation of factors influencing the adoption of local foods in restaurants(152), consumer behaviour towards foods prepared using nanotechnology (nano-foods)(153), consumer adoption of wine(154) and consumer adoption of entomophagy (insect eating)(155). These examples reflect the application of the theory to diverse food-specific contexts and thus its suitability to assist in evaluating the potential for sorghum and quinoa, as examples of novel grains, to be adopted over time.

Rogers(94) argues that the rate with which an innovation is adopted is a function of its relative advantage, compatibility, complexity, trialability and observability. The diffusion literature has considered various combinations of these microlevel drivers[156] as factors that influence the propensity to adopt an innovation. For instance, Talke and O'Connor[157] considered product related information, such as technical information, financial or monetary attributes and usability. Chang *et al.*[153] focused on the relative advantage, observability and the new element of novelty to gauge adoption of nano-foods. Attributes such as perceived uncertainty[158] and perceived risk[159] provide further examples of instances where researchers have added additional attributes to capture adoption pathways. In other words, previous studies have carefully selected relevant elements of the diffusion framework and/or added additional dimensions to align with the purpose of the research. The research conducted within this thesis considered the five dimensions of innovations espoused by Rogers[94].

Relative Advantage

The relative advantage of an innovation is conceptualised as the perceived advantage that it offers above and beyond that which it seeks to replace[94]. Drawing on insights from Rogers[94] and Chang *et al.*[153], relative advantage is defined in this thesis as the superiority of sorghum and quinoa relative to incumbent grains used by relevant stakeholders in the business ecosystem.

Compatibility

For an innovation to have any hope of diffusing, it must align with the prevailing perceptions, routines and values of potential adopters[94]. In this thesis, compatibility is addressed by a consideration of the relative ease with which sorghum and quinoa could be integrated into the ecosystem and the relative compatibility of producing, processing and distributing these grains with legacy systems.

Complexity

The relative difficulty in using an innovation represents its level of complexity. Unlike the other attributes of innovation diffusion, a higher level of complexity is negatively correlated to the adoption of the innovation[94]. Complexity arises through the level of novelty that an innovation induces. In the case of sorghum and quinoa, addressed in this thesis, this will be related to stakeholders' ability to understand how to use these grains.

Trialability

Having the ability to experiment with the innovation forms the basis behind trialability[(94)]. This element of the framework is akin to being exposed to a snippet of the full innovation, whereby the level of risk from trialling the innovation is significantly less than from full adoption, but is able to provide sufficient information to make an informed judgement about the innovation.

Observability

The visibility of an innovation and the tangible benefits that it offers can act as a way for the innovation to be actively seen in the market. In other words, the extent to which the results accruing from adopting the innovation, contribute to its observability[(94)]. In the context of novel grains, this observability could be derived from the nutritional attributes of the grain (the observable health benefits), environmental credentials, economic benefits or some combination of these and other variables.

Part A of this thesis considered the business ecosystem for novel grains, potential sources of stakeholder value associated with their incorporation into the food system and the potential diffusion process that underpins the pathway to market. Engaging stakeholders involved in this process and exploring their insights, enabled key themes relevant to the incorporation of novel grains to be identified. This has important implications for the potential value that can be created from novel grains. Part B extends the insight of stakeholders to include potential risks across the business ecosystem.

2.2.2 Design of Part B: Risks across the Business Ecosystem

Commercial entities operate in an environment where risk and uncertainty are ubiquitous, requiring the imposition of risk management strategies to ensure continued prosperity[(160)]. The agricultural industry is no exception, with production related risk (due to factors such as unpredictable weather) a particularly common challenge[(161)]. A subtle, but important distinction between risk and uncertainty is key to understanding the different approach to capturing these two concepts. Teece *et al.*[(162)] argue that risk is associated with outcomes that are known to have a certain probability of occurring, while uncertainty is an example of unknown unknowns, which are often synonymous with innovation.

More generally, risk can be conceptualised as the "…*variation in the distribution of possible outcomes, their likelihoods, and their subjective values*"[163](p1404). In most circumstances, situations that involve an element of risk are likely to have an impact on the welfare of an entity (individual or firm)[164] and can include (but are not limited to) the loss of money, harm to human health and resource degradation[165]. This definition, suggests that a risky decision is one where there is a wide range of variation in potential outcomes. In practice, however, risk is more commonly associated with a decision where there is a threat of very poor outcomes, or where the consequences of an outcome have significant (usually negative) implications[163].

The notion of risk can be extended to the incorporation of a novel grain into the food supply, where both risk and uncertainty are likely to prevail. It is conceivable that stakeholders would have some previous exposure to novel inputs and would therefore be able to assign probabilities (with some level of confidence) to the likelihood of certain events occurring. The decision by stakeholders to participate in this type of business venture will be guided by the ability to identify the risks in the ecosystem and evaluate whether the potential returns are sufficient to justify this risk. While the economics literature has explored risks involved in agricultural production[166, 167], it has thus far neglected the entrepreneurial risk faced by key stakeholders engaged in the business ecosystem[168]. The research conducted for this thesis will attempt to fill this gap by evaluating the type and position of risks in the business ecosystem for novel grains.

2.2.2.1 Consideration of Risks

From an agricultural perspective, risk is pervasive across the ecosystem of activities that are required to bring products and services that meet consumer demands to market. Unlike other industries, the process of bringing food products to market requires a consideration of risks driven by food quality, food safety, short shelf lives[169], fluctuations in demand and weather related factors[170]. The research to be conducted as part of this thesis adopts an approach in line with Leat and Revoredo-Giha[171] who explore risks facing individual stakeholders in an agri-food context.

There is a tendency for stakeholders involved in the implementation of an innovation to focus on the development of strategies that mitigate execution risks. These are captured as the risks associated with bringing an innovation to market within the allocated budget and in a specified time frame[172]. This view, however, neglects the importance of co-innovation risk and adoption chain risk, which have been identified as critical to the formation of a businesses strategy when attempting to incorporate an innovation into a commercial setting. The value blueprint mapping method provides a means of capturing these three forms of risk (execution, co-innovation and adoption chain), enabling managers to greatly enhance their analysis of an innovation and its potential success[98].

2.2.2.2 Applying Value Blueprint Mapping

The value blueprint method, articulated by Adner[98] is a tool that extends the work of previous authors, such as Porter[173] (5 forces model) and Brandenburger and Stuart[174] (firm value creation) that explicitly locates the position of links within an ecosystem that may contribute to the success of an innovation and ultimately the proposed value proposition. In other words, the tool outlines how connections within the ecosystem contributes to the creation (or lack of creation) of value.

Ignoring this important consideration has seen the emergence of a pattern of failure among innovations that appeared to have a compelling value proposition (e.g. Michelin Run Flat Tyre, High Definition TV in the 1990's)[175]. It has become increasingly apparent that business decisions must take into account the interplay among stakeholders across the business ecosystem that are likely to be critical to the success of the innovation. Interdependencies that emerge across the ecosystem[93] result in risks extending beyond the boundaries of individual stakeholders. Adner[98] recognised that attention should be focussed at the level of the ecosystem and put forward the value blueprint method as a way to assess risk across the categories of execution, co-innovation and adoption chain risk.

a) Execution risk – associated with achieving objectives within the specified time frame and under budget,
b) Co-innovation risk – the risk that other innovations may need to be established within the business ecosystem for the initial innovation to be adopted, and;
c) Adoption chain risk – the extent to which downstream stakeholders within the business ecosystem must adopt the initial innovation for the end-user to realise the full value proposition

Intuitively, by addressing these risks, this research considers the potential bottlenecks across the ecosystem for novel grains, which may have implications for the ability to successfully deliver final products to the consumer and ultimately, value to stakeholders within the ecosystem.

2.2.3 Outline of Qualitative Approach

The background presented thus far indicates the exploratory nature of the research that seeks to investigate the ecosystem for novel grains and the associated risks. One of the advantages of adopting a qualitative approach is that it enables investigative foundations of an under-researched phenomenon to be established. By synthesising the insights from expert practitioners, in this case, through interviews with stakeholders in the ecosystem for novel grains, the research presented in Part A and Part B offers an insight into the underpinnings of the pathway to market for novel grains.

In previous research, interviewing stakeholders involved in the delivery of value in agricultural production chains to leverage their knowledge has generated particularly informative insights that would not have been possible through surveys or questionnaires alone[176, 177]. In addition, conducting interviews enabled important insights and relationships at discrete points within the business ecosystem to be explored in greater depth[178] and provided more flexibility for the interviewer to explore emerging themes that were discussed by the participants[179].

2.2.3.1 Stakeholder Interviews

The literature is limited in its discussion of the pathway to market for underutilised grains, thus reflecting the novelty of exploring sorghum and quinoa as case studies[110]. In order to shed light on the pathway to market and potential value associated with the incorporation of novel grains into the Australian food supply, key stakeholders were identified and recruited. The identification process was guided by work that had been previously conducted in agri-food chains.

The questions that were put forward to participant stakeholders were drawn from research into the value chain shaping the pork industry[144], beef and dairy industry[180], wine and grape industry[181], prawn industry[145] and specifically, the grains industry[139, 182, 183]. All questions were adapted to be relevant to the grains industry with the key research question (what are potential sources of value associated with the incorporation of novel grains into the food supply) and its operationalisation described in more detail in 3.2.2 Interview Process.

2.2.3.2 Methods of Qualitative Analysis

Conducting semi-structured interviews with key stakeholder informants provided a means of engaging with business ecosystem participants at a personal level[179]. The advantage of semi-structured interviews is the ability to uncover insight into unique phenomena. Previous examples relevant to the agri-food sector include interviews that explored entrepreneurial activity in farming[184], changes in farming land use and land cover practices over time[185] and networks that farmers use to exchange scientific advances in agriculture[186]. Once interviews were completed, an iterative process leveraging the six steps of data analysis presented by Creswell[187] was followed:

1. Organise and prepare the data for analysis

Transcribe interviews (for participants that consented to being recorded) and make summary notes for interviews where participants did not consent to be recorded.

2. Scan the data

Read through the interview transcripts and develop an appreciation for the general meaning conveyed. Make initial notes in the margins that reflect general thoughts on the data.

3. Code the Data

Organise sections of the transcripts into distinct segments and label them with a term that is based on the language used in the transcript. Group similar terms together to form codes that describe the data.

4. Develop Themes

Use the codes established in step 3 to formulate themes that can be used to categorise and describe the data in sufficient detail.

5. Present the Data

Determine how the themes will be presented in the findings sections.

6. Interpret and Abstract

Make an interpretation behind the meaning of the data, how it confirms or diverges from theory, what were the lessons that could be learnt and what this means when moving to a higher level of abstraction.

In summary, Study 1 considers the role of stakeholders in the pathway to market for novel grains and can be used to inform the potential sources of value that may be derived. Study 2 captures considerations relevant to nutrition science.

2.3 Design of Study 2: Review of Nutritional Attributes

The interplay of actions carried out by stakeholders across the business ecosystem can influence the establishment of a pathway to market for novel grains. The nutritional attributes of a novel grain may provide an additional argument for considering their adoption, particularly if a consumer segment is identified that is willing to pay for products containing unique health-imparting properties. By systematically reviewing the nutritional attributes of sorghum and quinoa, Study 2 reveals the functional properties possessed by these grains. A rigorous critical appraisal process is adopted in order to evaluate the underlying quality of the evidence that underpins the review. The potential commercial implications of these results are then considered.

2.3.1 Approach to Systematic Literature Reviews

The systematic literature review method enables data from individual studies to be summarised, evaluated and critically appraised in a rigorous and transparent manner[188]. By drawing on evidence from multiple studies, the review can establish insight into the body of research and the validity of relationships between specific foods or food components and outcomes. This approach underpins the recommendations provided in national health policy documents such as the Dietary Guidelines for Australians[189] and enables the quality of the overarching body of evidence to be comprehensively evaluated.

Once a series of studies investigating the relationship between a nutrient and a health outcome are published, they form the body of evidence on a given topic and contribute to the scientific understanding of a particular diet-health relationship. A systematic review that pools together the findings from these individual studies provides a means of evaluating the body of evidence and forms the highest level of evidence as set out by the

National Health and Medical Research Council (NHMRC) (**Table 2.1**). In the context of novel grains, systematic literature reviews enabled the nutritional attributes of sorghum (Part A) and quinoa (Part B) to be evaluated in response to their consumption in the diet.

Table 2.1 NHMRC levels of evidence[190]

Level of Evidence	***Intervention***
I	A systematic review of level II studies
II	A randomised controlled trial
III-1	A pseudorandomised control trial (i.e. alternate allocation or some other method)
III-2	A comparative study with concurrent controls: • Non-randomised experimental trial • Cohort study • Case-control study • Interrupted time series with a control group
III-3	A comparative study without concurrent controls: • Historical control study • Two or more single arm study • Interrupted time series without a parallel control group
IV	Case series with either post-test or pre-test/post-test outcomes

2.3.2 Design of Part A: Systematic Review of Nutritional Attributes of Sorghum

The systematic literature review of human studies investigating the nutritional attributes of sorghum was performed according to the recommendations outlined in the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement[191]. The level of evidence (based on NHMRC criteria outlined in **Table 2.1**) that individual studies within the review constituted, were reported. The Health Canada Quality Rating Tool was applied to evaluate the quality of the individual studies included in the review[192]. This tool was previously used in the health claims framework and represents a desirable way to evaluate the rigour of these studies, particularly if there is a longer-term view to establish a health claim.

2.3.3 Design of Part B: Systematic Review of Nutritional Attributes of Quinoa

Owing to the paucity of human studies investigating the effect of quinoa consumption, the systematic literature review of the nutritional attributes of quinoa focussed on animal studies. An emerging body of research suggests that conducting systematic reviews of preclinical studies, such as animal studies, is a valuable tool for establishing the likelihood of mechanistic understanding being translated into human research applications[(193)]. To establish the underlying rigour of the studies included in the review, a quality framework (Methodological Quality Assessment) was adopted to evaluate the quality of the evidence that underpinned the research[(194)].

2.3.3.1 Methods of Systematic Review

Study 2 systematically reviewed the evidence-base underpinning the potential nutritional attributes of sorghum and quinoa. This approach to evaluating the nutritional attributes of these grains could also be applied to other novel grains in future research. Moreover, there may be implications for the incorporation of novel grains into the food supply, particularly if ecosystem stakeholders (and ultimately the end-use consumer) consider certain nutritional attributes desirable. While nutritional attributes may contribute to uptake by ecosystem stakeholders, of additional relevance is the supply of grain for market transactions. Study 3 explores a range of variables that may influence the area of land planted to grain, which has implications for the stability of supply.

2.4 Design of Study 3: Empirical Modelling of Acreage

The outline of the research methodology has thus far identified stakeholder actions and nutritional attributes as critical components of the research exploring the incorporation of novel grains into the food supply. The final element of the research methodology was an evaluation of the empirical impact of variables on the acreage planted to novel grains. This quantitative research enabled the impact of factors influencing production decisions, by the farmer, to be quantified, which had implications for the stability and consistency of supply of novel grains. In order to complete this analysis, it was necessary to select a case study to develop a suitable empirical model.

2.4.1 Selection of Sorghum as a Case-Study

The selection of a novel grain as a case study was based on the availability of data that would enable the analysis to be undertaken. While agricultural data (such as planted land area, yield and prices) are collected nationally, the timeframe over which this data has been collected varies markedly for individual grains. For example, data pertaining to sorghum has been collected for a significantly longer period of time than for quinoa. A partial explanation for this is the relatively recent commercial uptake of quinoa production in Australia. The Three Farmers brand of quinoa, pioneered by an early adopter of the ancient grain, only began commercial operations in 2010(195). In addition, a site visit in July 2015 to this farmers operation in Narrogin, WA, confirmed the infancy of the industry and the paucity of data that would be available to conduct a thorough empirical analysis. The unavailability of relevant data for quinoa, thus provided the impetus behind selecting sorghum as the case study to examine the impact of variables on acreage decisions. The underlying research approach is however applicable to other novel grains and could form the basis behind an analogous analysis of other novel grains in the future.

2.4.2 Model Specification – Panel Data Regression

Previous empirical models evaluating acreage have tended to base their models on the impact of a range of variables on the area of land planted to a range of crops that can be grown in a specific geographic region(103, 104, 196-198). The model presented through this research represented a subtle shift from these approaches and followed the conceptual process implemented by Boussios and Barkley(196) and Hausman(106). Specifically, the exclusive unit of analysis was sorghum acreage, which was evaluated across a wide range of geographic regions where it was grown. This allowed a panel data regression approach to be implemented, where the area of land planted to sorghum was evaluated over time and across geographic regions(106, 196). An advantage of the panel data approach was the ability to control for time-invariant variables across the sample of data by using a fixed-effects estimator(106, 196). This assists in capturing attributes such as soil quality, which are inherently difficult to measure, but are assumed to remain relatively constant over time. In other regression specifications (such as cross-section regression or time-series regression), these time-invariant variables tend to be ignored and can contribute to the calculation of spurious regression results.

2.4.3 Selection of Relevant Variables

The selection of variables was based on the design of previous acreage models[103, 106, 196, 199, 200]. The majority of these variables captured economic influences, such as own and substitute prices as well as input prices (e.g. fertiliser). Price and crop output expectations (based on futures prices derived from the stock market[196, 199] and previous yields[106, 196], respectively) were also considered relevant in the context of planning future economic returns for farmers. Basis prices (the tendency for crop prices at harvest to deviate from their expected price at planting[196]) and observed weather in the lead up to planting[196, 200] were also included in the model to account for deviations of reality from expectations and seasonal variation in weather respectively. Finally, the costs associated with switching between crops was captured by adopting a partial adjustment framework, whereby the area of land planted to sorghum in the previous year was included in the model to estimate the area of land in the following year[201].

2.4.4 Methods of Quantitative Modelling

The primary motivation behind the empirical evaluation of sorghum planting was to derive a quantitative estimate of the impact of the identified variables. This complemented the research investigating the business ecosystem and provided additional scope to evaluate the extent to which farmers tolerate risk, particularly in the context of an agricultural innovation. If applied in the correct setting, this method may also have value in examining the empirical impact of planting decisions on other novel grains for the Australian food supply.

The combination of research captured through these studies contributed to the identification of potential sources of value associated with the incorporation of novel grains into the Australian food supply. It is also envisaged that this overarching research framework could be applied to the exploration of other novel grains and the sources of value associated with their incorporation into the food supply. The research to be performed in this thesis may therefore provide the foundation for future iterations of research into novel grains.

2.5 Study Hypotheses

As outlined in section 2.1.1, this thesis addresses the question:

What are the potential sources of value associated with the incorporation of novel grains into the Australian human food supply?

The methodology that was applied to address this research question combined methods from strategic planning, nutrition science and economics. The selection of sorghum and quinoa as case studies enabled the potential sources of value associated with their incorporation into the food supply to be explored.

The underlying research hypothesis was that:

Unique sources of value associated with the incorporation of novel grains into the food supply would be identified.

An adjunct to this hypothesis was that a case study approach would expose an overarching research framework that could be applied to explore opportunities for other novel grains. The sub-hypotheses for each component of the research contained in the thesis are as follows:

- H_1: *To enhance the diffusion of novel grains across the business ecosystem, collaborative activity is required by key stakeholders (Study 1 Part B).*
- H_2: *The presence of execution risk, co-innovation risk and adoption chain risk will be revealed at multiple positions across the business ecosystem (Study 1 Part B).*
- H_3: *There is evidence that the consumption of sorghum in human populations may lead to superior nutritional outcomes compared to control grains (Study 2 Part A).*
- H_4: *There is evidence that the consumption of quinoa (in the context of experimental animal studies) may lead to superior nutritional outcomes compared to control grains (Study 2 Part B).*
- H_5: *Economic (specifically price) variables will have a significant impact on acreage decisions by farmers (Study 3).*

2.6 Outcome Measurements

The business ecosystem (including the key points of value addition) required for the incorporation of novel grains into the food supply were elucidated by leveraging insights from the existing literature and applying the VCA method. Stakeholders involved in the business ecosystem were interviewed in order to capture themes pertinent to sources of value, diffusion and uptake of novel grains across the business ecosystem. This was complemented with a value blueprint method that outlined the type and position of risks in the business ecosystem. This was framed in the context of an incremental innovation and drew on the literature from the field of strategic planning to guide the development of appropriate recommendations.

The nutritional attributes associated with the consumption of sorghum and quinoa were evaluated through systematic literature reviews. The results were critically appraised in order to evaluate the underlying quality and rigour of the research. These results were then discussed in relation to their potential commercial applicability and the extent to which current promotional and marketing efforts accurately reflect the body of scientific evidence. These results were then used to highlight potential research pathways that could augment the existing body of scientific literature.

The final measured outcome was the empirical effect of a range of variables on sorghum acreage over time. This was evaluated through a panel-data regression model that captured variation in sorghum acreage over time and across spatial units. This method enabled the impact of a range of variables to explain changes in sorghum land area in a quantitative sense. This had the advantage of complementing the qualitative identification of themes within the business ecosystem.

2.7 Significance of Interdisciplinary Research Approach

By implementing an interdisciplinary research approach that explored insights from strategic planning, nutrition science and economics, this thesis revealed the underlying sources of value associated with the incorporation of novel grains into the food supply. Research of this nature is an underexplored area of agribusiness, which tends to focus on the optimisation and improvement of processes that incorporate incumbent grains. A recent example is reflected through research efforts to develop a perennial (rather than annual) variety of wheat that can capture the ecological benefits of not needing to be replanted each year[202].

The research performed in this thesis can assist in overcoming the current paucity of research into novel grains by developing a framework that enables complex, interdisciplinary questions to be appropriately addressed. This may contribute to the development of strategies that harness the potential opportunities embedded in the business ecosystem for novel grains and perhaps other inputs into the food production system. The contribution of this research to the extant literature is fourfold:

1. The sources of value associated with the incorporation of a novel grain into the business ecosystem is observed through the lens of an agricultural innovation, which extends our understanding of the scope to develop value-added final products from novel grains.
2. The blueprint mapping method used to identify the type and position of risks in the business ecosystem for novel grains is extended into the field of agribusiness. This culminates in a robust risk identification framework that acknowledges execution, co-innovation and adoption chain risk.
3. The systematic literature reviews of sorghum and quinoa are the first to the researchers knowledge to summarise and critically evaluate the current body of nutritional attributes associated with the consumption of these grains.
4. The empirical modelling of sorghum acreage is quite possibly the first to apply a panel-data approach to evaluate the impact of a range of variables on the acreage of Australian grown sorghum.

These contributions form the basis behind the evaluation of the factors influencing the incorporation of novel grains into the Australian food supply. Ultimately, the application of this interdisciplinary approach and corresponding development of a framework that seeks to capture the key attributes of the incorporation process, form the major contribution to the literature. It is envisaged that it will be possible to replicate this methodological approach and apply it to other examples of agricultural innovations in the future.

The first stage of this research was to identify the range of stakeholders that influence the pathway to market for novel grains and elucidate their perceptions towards the incorporation of these grains into the food supply, described in Chapter 3.

Chapter 3: Stakeholder Considerations

3.1 Introduction

The opening two chapters of this thesis have established the context behind the planned research and briefly outlined the use of sorghum and quinoa as case studies to explore the incorporation of novel grains into the food supply. The research presented in this thesis applies the notion of incremental innovation to the incorporation of novel grains into the food supply. This conceptualisation assumes that the utilisation of novel grains would only require incumbent stakeholders to make minor adjustments to their systems. By considering the cumulative efforts of the stakeholders required to bring about these adjustements, the pathway to market and potential innovation challenges associated with the incorporation of novel grains can be examined. The overall aim of the work presented in this Chapter is to examine stakeholder considerations in the pathway to market for novel grains.

Chapter 3 comprises a number of sections: an introductory section outlining key concepts, and the first empirical study of the thesis (Study 1). This study involved semi-structured interviews of key stakeholders. Data from these interviews were analysed and reported separately in two ways: focusing on the business ecosystem, potential sources of stakeholder value and associated diffusion pathway (Part A), and the types of risks that may influence the incorporation of novel grains into the food supply (Part B). Study 1 Part A explores the pathway to market for novel grains by introducing the concept of the business ecosystem. Conceptualising the roles of stakeholders through an ecosystem lens enables the flow of activities, from farm to fork to be captured. Exploring the perceptions of stakeholders to this process through a qualitative research approach enables considerations relevant to sources of value and the potential diffusion pathway to be revealed. Study 1 Part B explores the types of innovation risks that may influence the incorporation of novel grains into the food supply. In addition, the position of these risks with respect to ecosystem stakeholders are highlighted.

The synthesis of insights from stakeholders positioned across the business ecosystem contributes to the underlying aim of this thesis; to explore potential sources of value that can be generated from the incorporation of novel grains into the food supply. The insights generated through the research performed in this chapter may therefore enable strategies to be crafted that can capture these sources of value. To fully engage in this analysis, the background concepts relevant to the pathway to market for novel grains must be considered. Namely (1) the business ecosystem and its application to the market for novel grains, (2) stakeholder involvement in the business ecosystem, (3) value creation in the business ecosystem, (4) the diffusion process underpinning novel grains and (5) the type and position of risk within the business ecosystem. These are now briefly discussed.

3.1.1 Application of the Business Ecosystem Approach

The concept of an ecosystem was first applied in the context of the biological sciences as a method to capture the interdependent activities that shape an environment for organisms within ecological systems. In the organisational sciences, the term has emerged relatively recently as a conduit to describe the range of interactions that occur in a commercial business setting(131). It extends the concept of the value system(138) from intra-firm interactions to include the broader economic community in order to capture the set of coordinated activities that must occur between various stakeholders to generate value(131). This approach highlights the dynamic nature of the relationships between stakeholders(203) and the range of interdependencies and capabilities that are leveraged in order to overcome common challenges(92).

In the field of strategic planning, the business ecosystem approach has been applied to capture the challenges faced by firms delivering an innovative product to the customer(204). For clarity, when innovation is involved, the literature often refers to the business ecosystem as an innovation ecosystem. Adner and Kapoor(204) argue that this conceptualisation requires a consideration of the innovation challenges faced by the focal firm as well innovation challenges faced by external partners. Their argument forms the basis behind innovation systems, articulated in the Australian Innovation System Report(205) and is extended to the research performed here. In the context of novel grains, the set of complex stakeholder interactions that underpin the activities required to deliver grains from the farm to the consumer(206) form the basis of the ecosystem(92).

In the innovation context, the combination of expertise from across the ecosystem enables collaboration and value co-creation to drive innovative activities that a single firm/unit in isolation would not be able to deliver(207). For example, the development of the Airbus A380 aeroplane was underpinned by innovation among upstream and downstream stakeholders to accommodate the delivery of the A380 to market[204]. A critical point noted by Adner[93] is the distinction between ecosystems-as-affiliation and ecosystems-as-structure. The structure approach considers a value proposition, the actions required to realise the proposition and then identifies the stakeholders that would need to be aligned to achieve this outcome. In contrast, the affiliation approach captures a macro perspective of an ecosystem (for example, the ecosystem for novel grains) where stakeholders and respective linkages are first identified, followed by potential value propositions. The latter approach will form the basis behind this research into the ecosystem for novel grains.

Examination of the agri-food industry suggests that innovation in product development continues to present itself as a strategy to remain competitive and profitable[208]. However, there remains a tendency for agri-food chains to operate in a siloed environment where innovation is pursued on an individual basis, rather than at an industry level[136]. Moreover, despite the growing application of innovation strategies, such as open innovation[209], where firms use internal and external ideas to create value[210], there remains a paucity of work evaluating innovation ecosystems in the agri-food industry[62]. This thesis therefore extends the business ecosystem typology to the agri-food industry and identifies the actions that stakeholders within the ecosystem must perform to deliver novel grains from farm to fork.

3.1.2 Stakeholder Involvement in the Business Ecosystem

The business ecosystem is synonymous with stakeholder interdependencies, which extend beyond the traditional realms of inter-organisational collaboration[92]. Teece[211] articulates this point by observing that the commercialisation of a product is contingent on synergies in complementary technology and assets. As Adner and Kapoor[204] explain, collaborative efforts must be pursued across the network of suppliers and customers embedded within the supply chain, but also with stakeholders that are not explicitly captured by the supply chain, referred to as ‘complementors’. In the context of the agri-food industry, providers of processing equipment (e.g. a grain mill) would constitute an example of a complementor. By including these stakeholders, the business ecosystem can be defined as the broader set of interactions that are required to deliver agricultural produce from farm to fork[206]. For example, the transformation of cereals (or grains) into products that resemble recognisable foods such as bread and pasta is an example of a grain ecosystem that includes growers, bulk grain handlers, flour millers, bakers and commercial retailers which is also reliant on complementors, such as providers of transport infrastructure.

Ultimately, an exploration of the perceptions held by stakeholders towards the incorporation of novel grains into the food supply can reveal the presence of potential sources of value. Moreover, identifying the incumbent stakeholders within the business ecosystem can highlight the pathway to market and the range of interactions that are required to deliver novel grains from farm to fork. These insights are particularly relevant in the context of innovation, which is emerging as a key value creation tool that can assist in differentiation from competitors and appeasement of consumer expectations, particularly in the broader food industry[(66)].

3.1.3 Capturing Value Creation in the Business Ecosystem

The process of value creation is generally depicted as the sequence of activities that must occur in order to deliver a final product to the end-user. In the case of the business ecosystem, the value is created for customers through the collaborative actions of stakeholders[(212)] that share constantly evolving fluid relationships[(203)]. A subtle but important point is that a customer in this context could refer to a stakeholder intermediary (e.g. processor) rather than the traditional depiction of a customer as the end-user (e.g. consumer in a retail setting). Importantly, this value creation is contingent on upstream and downstream entities delivering on their promise, with bottlenecks at upstream or downstream points detrimental to the delivery of the final product to market[(204)].

The underlying value system[(138)] captures the combined efforts of individual stakeholders (and the interplay of firm level value chains) to add value by improving product quality, transforming an input, optimising delivery times or devising innovative solutions[(213)]. Importantly, this can take place from product inception through to the delivery to consumers[(214)]. Mapping the flow of activities that are required to deliver novel grains to the end-user can highlight the process of value creation and enable the development of strategies to capture potential value. In mature industries, the underlying value creation mechanism (that is, the ecosystem) is often latent[(93)]. When an innovation emerges and stimulates a change or reconfiguration in the manner in which value is realised (for instance, through the impact on stakeholder positions, their linkages and new sets of interactions that underpin the relationships), the dynamics of the ecosystem become apparent[93]. By applying the VCA method it is possible to identify the key stakeholders involved in the business ecosystem for novel grains and their ability to contribute to the value creation process.

Taken in isolation, this would appear to constitute an exercise in value stream mapping[130]. In the case of this thesis, however, the research also takes into account the flow of information between stakeholders. In other words, the ecosystem mapping approach argues that the relationships between stakeholders and the transactions between stakeholders contribute to the creation of value[134, 137]. This is particularly relevant in an ecosystem context, where stakeholders are actively coevolving their capabilities to achieve their end goal[135]. Value stream mapping could form the next stage of a deeper economic analysis to quantify the potential returns that could be on offer for key stakeholders.

As a caveat, the extant literature tends to explore the stakeholder interactions that shape the ecosystem for a specific focal firm and the ability to deliver value to the customer[204, 215]. Rather than highlighting the linkages that shape a firm specific ecosystem, the research presented in this thesis presents a process-based ecosystem that captures the sequence of activities that underpin the delivery of novel grains from the farmer to the end-user. In addition, due to the exploratory nature of the research, the scope of the analysis is limited to capturing the interplay of stakeholders directly involved in the business ecosystem, rather than including a complete overview of the entire economic community that underpins the ecosystem (e.g. competitors, advocacy groups)[215]. It is envisaged that by performing this research it will be possible to identify focal firms, laying the foundations to perform a finer-grained analysis of firm level business ecosystems. This could be explored in future research.

3.1.4 Sources of Stakeholder Value

The overarching objective of this research is to explore the sources of value associated with incorporating novel grains into the food supply. Bowman and Ambrosini[216] highlight that value is created through the transformation of resources by labour (stakeholders). Exploring the perceptions that stakeholders within the business ecosystem hold towards novel grains can help to reveal sources of value associated with their incorporation into the food supply. Research of this nature can also inform the diffusion process and assist in the provision of information to guide the development of successful new products[217]. The next section considers the diffusion of novel grains and attributes that are relevant in shaping the pathway to market.

3.1.5 The Diffusion of Novel Grains into the Food Supply

Considerable commercial interest lies in evaluating the potential adoption rate of an innovation due to their tendency to fail. Despite efforts to evaluate future market potential, up to 90% of new product development efforts end in failure[218]. Furthermore, market research has estimated that up to 76% of new products in the fast moving consumer goods category fail to remain in the sales pipeline for more than one year after their introduction[219]. Considering the significant amount of time and money involved in new product development, this figure indicates the level of wasted resources on projects that should never have proceeded[220]. Conducting research prior to innovation is therefore commercially valuable.

By exploring the potential diffusion of an innovation across the business ecosystem, there may be scope to capture the likely pathway to market for novel grains. Waarts *et al.*[221] argue that adoption decisions will change over time as an innovation diffuses (that is, there will be differences between earlier and later adopters). This occurs due to the development of utilisation capabilities[222] and emergence of complementary innovations that allow the true value of the innovation to become apparent[223]. Using this logic to set boundary conditions, this thesis considers the adoption process in the early stages of diffusion. This conceptualisation aligns with the argument that novel grains offer a new avenue to the human food market, which is in its formative stages. Application of the diffusion of innovation theory allows the dissemination of the innovation through communication channels among social systems over time[94] to be explored. In addition, the theory offers the ability to investigate the potential adoption of these grains at an ecosystem, rather than individual end-use level. Specifically, this involves developing an overview of the five attributes that Rogers[94] identified as being critical to the adoption of an innovation; relative advantage, compatability, complexity, trialability and observability.

The combination of research exploring the business ecosystem, sources of stakeholder value and the diffusion of innovation represents Part A of Study 1. Part B of Study 1 centres on the potential innovation risks associated with the incorporation of novel grains into the food supply and the relative position of these risks with respect to individual stakeholders.

3.1.6 Types of Risks and their Relative Position in the Business Ecosystem

Risks are a feature of conducting business that are greatly amplified in the context of innovation, particularly when dependencies across the ecosystem are required to successfully execute the implementation of an innovation[175]. In this situation, success is partially contingent on the success of the partners across the ecosystem. Despite this issue of dependence, the majority of managerial attention has been devoted to the execution of an innovation and the risks involved in delivering a new product to market in a timely and efficient manner. Far less attention has been given to co-innovation risk, where success is contingent on a number of stakeholders across the ecosystem. For example, nutrition research exploring the health effects of novel grains may need to be undertaken to generate awareness of the nutritional properties of these grains or agronomy research that identifies suitable varieties of grain might be necessary before novel grains are planted. Another important area of risk in the innovation ecosystem is adoption chain risk. This refers to the risk that key stakeholders positioned between the farmer and the end consumers will behave in ways that do not support the innovation, perhaps due to perceived cost pressure, risk aversion or long lead times in process execution. Processors, manufacturers, wholesale and retail entities are examples of stakeholders that are required to embrace the novel grain into their systems before end users are able to consume the product[98].

While the delineation of risks into execution, co-innovation and adoption chain captures potential dependencies across the ecosystem, of similar importance are the relative position of these risks within the business ecosystem and the impact they can have on stakeholders. Previous work has evaluated the position of risks in an innovation ecosystem with respect to a focal firm in order to capture the impact on firm performance[204]. By examining sorghum and quinoa as case studies, the planned research will attempt to capture the relative position of risks across the ecosystem for novel grains. The findings are then discussed with respect to the impact on entities upstream and downstream of the farm, where novel grains commence their physical journey to market.

Economists have long recognised the entrepreneur as someone who bears capital risk to bring factors of production together to implement a money-making idea[224]. Despite the importance of ecosystem management[212], economic theory has little to say about the roles that farmers (as innovation managers) play with respect to understanding dependencies and linkages between stakeholders in an innovation ecosystem. This is in part because microeconomics pays little attention to the managerial challenges associated with complex ecosystems where risk is ubiquitous and difficult to model with any useful level of confidence[162]. Therefore, exploring the type and position of risks within the business ecosystem and their potential impact on the creation of value forms Part B of Study 1.

3.1.7 Aims of Stakeholder Interviews

With these considerations in mind, the stakeholder interviews were developed to add empirical evidence to the issues that have been raised. The underlying data collection process for Part A and Part B is shared, and as such, the methods for both parts are outlined together. Following the methods, the research findings and discussion for Part A and Part B are separated to enable the descriptive overview of the ecosystem (perceptions of stakeholders and diffusion pathway for novel grains) to be evaluated independently of the identification of the type and position of risks within the ecosystem.

3.2 Method

A case study approach[110], was implemented to explore the business ecosystem, expose stakeholder perceptions and identify potential risks in the market for novel grains. Sorghum and quinoa were selected as cases. Semi-structured interviews were conducted to collect relevant data for Part A and Part B.

3.2.1 Recruitment of Interview Participants

Purposeful sampling was used to recruit stakeholders with relevant experience[225] in the food industry. While specific emphasis was placed on recruiting individuals from the grains industry, variation in participant background was sought to capture the diversity within the ecosystem[226]. This included individuals engaged in product development, innovation, regulatory oversight, food industry consultancy, R&D and other related activities.

Individuals within the food industry known to the research team were initially approached to participate in the study. It is acknowledged that this approach may have introduced selection bias, as there may be latent attributes that are common among participants that are known by the research team. In addition, recruiting participants known by the research team, (who may share similar viewpoints), may contribute to confirmation bias; the tendency to find evidence that supports a belief, while ignoring evidence that does not[227].

In order to mitigate against these potential biases, the recruitment was expanded to stakeholders outside the direct network of the research team. This had the added advantage of adding a level of richness and depth to the interview data. Therefore, establishing a connection with the initial stakeholder facilitated a snowball approach to participant recruitment. While this does not rule out the influence of all biases, it makes a strong attempt to integrate views from a diverse range of stakeholders[226].

3.2.2 Interview Process

After agreeing to participate, subjects were interviewed in person or by telephone. The purpose of the interview was to explore the underlying research question; to identify potential sources of value associated with the incorporation of novel grains into the food supply. The development and selection of questions was guided by work that had been previously conducted in agri-food value chains, specifically, those that focussed on grains[139, 182, 183]. The interview questions explored considerations related to the incorporation of sorghum and quinoa into the food supply (including the organisation of the business ecosystem and their diffusion into the food supply) and the presence of risks across the business ecosystem. A common set of questions across stakeholders[228] (to minimise the presence of retrospective bias for questions that required recounting key events in the sorghum or quinoa paradigm) were used[229]. The interview guide (topic and questions) are presented in Appendix 3-A.

The interview questions provided a framework to guide discussions. The semi-structured nature of the interviews enabled the discussion to remain flexible and, provided the scope to ask further context specific questions, thus removing constraints on the areas that were explored[230]. Where possible, interviews were audio-recorded and transcribed verbatim. Interviews were completed between February 2016 and June 2016 and were conducted by one researcher (TS) to ensure consistency in participant engagement and data generation. The interviews ranged in duration from 30 minutes to one hour.

In instances where consent for recording was not given, summary notes were made during the interview by the interviewer. Interviews were summarised and returned to the participant for an assessment of authenticity to ensure responses were captured and interpreted correctly[231]. Once this process was completed, and the position of each participant within the business ecosystem was recorded, the interview data were de-identified. All study procedures were approved by the University of Wollongong Human Research Ethics Committee (HE15/259).

3.2.3 Data Analysis

An interpretivist perspective, whereby subjective meaning was applied to the insights presented by interview participants[232] formed the basis behind the analysis. This allowed the data to be explored without having a preconceived idea about potential findings[183]. In line with Creswell[187], interviews were first transcribed, followed by coding, consolidation into themes, presentation and interpretation. Further refinement of the data analysis process was undertaken by drawing on the three-stage process suggested by Pera *et al.*[226]:

1. Pertinent segments within individual interview transcripts were identified, highlighted and coded. Each transcript was evaluated separately, with initial interpretations recorded in the margins. The coding system was unrestricted. A second researcher (EB) independently codified the data in order to improve the reliability of the codes[233].

2. A search for common codes across transcripts was initiated in order to identity emerging patterns and underlying themes[234]. This followed an iterative process of analysing the data in the context of relevant literature to capture relevant theoretical concepts[235].
3. Shared themes were analysed by organising the data into categories, so that meaning could be established at a higher level of abstraction[236]. The overarching research question was used to guide the search for patterns[237]. As patterns emerged, the data was organised into conceptual clusters or closely aligned ideas and grounded in the existing literature to enable a deeper overview of potential sources of value within the business ecosystem to be explored[238].

The discussion of the findings focused on (1) the arrangement of the business ecosystem, (2) potential sources of stakeholder value associated with the incorporation of novel grains into the food supply, (3) the potential diffusion pathway for novel grains, with a particular focus on factors that would influence the likely adoption of novel grains, and (4) the potential risks across the business ecosystem. This was guided by quotes that captured a particular theme and illustrated the underlying idea held by the interview participant. To validate the information, interviewees were asked to comment on the use of the quote and its presentation in context[225].

The data collected through the interviews were divided into two discrete parts. Part A explored the business ecosystem for novel grains, sources of value and the perceptions of stakeholders towards the diffusion of novel grains into the Australian food supply. Part B focussed on the type and position of risks across the business ecosystem.

3.2.4 Part A – The Business Ecosystem, Sources of Stakeholder Value and Potential Diffusion Pathway

The VCA method, as discussed by Howieson *et al.*[145] was applied to engage the chain, understand the market and map the flows. The combination of stakeholder insights and previous research that outlined the flow of value addition within agri-food chains[90, 139-141, 206, 239] informed the development of the truncated business ecosystem for novel grains. Participants were also asked questions relevant to the potential pathway to market for novel grains. The business ecosystem model that was derived from this data and the range of themes that influenced sources of value and the diffusion pathway was disseminated to relevant stakeholders to validate its depiction of reality. Their comments and suggestions were used to further refine the model. Part B explored potential risks across the business ecosystem.

3.2.5 Part B – Types and Position of Risks across the Business Ecosystem

Rather than focussing exclusively on execution risks, the application of a blueprint mapping method enabled co-innovation and adoption chain risk to be explored. This process was qualitative in nature and required the identification of risks from interview transcripts, which followed the same conceptual pathway as outlined in section 3.2.3 Data Analysis. A framework that outlines the value blueprint method is presented in **Table 3.1** and was adapted from Adner(98) and Almeida *et al.*(240). When adopting an ecosystem-as-affiliation view, this approach begins with an identification of actors, the links between them and the potential value propositions that can arise(93). In contrast, the ecosystem-as-structure approach takes a reverse approach, whereby the value proposition is first articulated, followed by the activities needed to bring it to life and finally the actors that require alignment. The questions that underpin the value blueprint method were used to gather relevant data from interview participants. Given that an ecosystem-as-affiliation approach was taken(241), the identification of suppliers and intermediaries was considered prior to the identification of the end customer and potential value propositions. This was followed by the identification of potential risks associated with the realisation of the value proposition.

In line with qualitative research approaches, the findings from Part A and Part B were presented in combination with the discussion(242). In conjunction, Part A and Part B captured the potential sources of value that could be leveraged from the incorporation of novel grains into the food supply.

Table 3.1 Value blueprint framework, adapted from Adner[98] and Almeida *et al.*[240] to reflect an ecosystem-as-affiliation approach

Research Stages	*Questions to be Addressed*	*Organisation of Research*
Identify suppliers and intermediaries	What inputs will be needed to construct the offer? Who does the product pass through on the way to the end customer?	Part A
Identify the end customer	Who ultimately needs to adopt the product for it to be considered a success?	Part B
Identify the value proposition	What is the value proposition of the final product?	Part B
Identify ecosystem risks	What are the execution risks, co-innovation risk and adoption chain risks in the ecosystem associated with the delivery of the value proposition?	Part B

Study 1 Part A – The Business Ecosystem and Potential Diffusion Pathway

3.3 Findings and Discussion

3.3.1 Demographic Data

A total of 45 participants (34 males and 11 females) from across the business ecosystem were interviewed (**Table 3.2**). The average age of these participants was 45.8 years with 85% having completed a university degree. The majority of participants identified as working in the primary industry (16) followed by commercial R&D (10). Management and marketing were equally represented with six participants each, five identified as working in university research/education and two aligned themselves with the field of nutrition and dietetics. A further seven participants were involved in other industries such as consulting, innovation, food manufacturing and retail. The average tenure of participants in their current position was 9.5 years. Detailed information regarding the industry that individual participants were members of are provided in Appendix 3-B.

3.3.2 Business Ecosystem Map for Novel Grains

In the context of the agri-food sector, there is a paucity of research applying an ecosystem view to innovative activities. The research undertaken in this chapter has begun to address this gap by considering the ecosystem for novel grains and the potential sources of value that could be leveraged through their incorporation into the food supply. The insights and perspectives of stakeholders from across the business ecosystem were explored in order to map the flow of transactions and information in order to develop a truncated version of the business ecosystem for novel grains (**Figure 3.1**). The truncation was necessary to constrain the extent of activities and actors engaged in the ecosystem. As Teece[(211)] and Adner[(93)] argue, the ecosystem extends beyond the owners of assets to include the suite of actors beyond suppliers and buyers (for example, suppliers suppliers). In addition, for ease of conceptualisation, other actors such as financial institutions, health practitioners, standard setting bodies, legal institutions and government agencies have been omitted. This is not to say that they do not play a role, but is an acknowledgement that their influence is beyond the scope of the work presented in this thesis. The underlying governance system within this ecosystem is also briefly considered and requires additional attention in future research. Specifically, who should take responsibility for the orchestration of actors to drive coordination and cooperation across the ecosystem remains a critical unanswered question.

Table 3.2 Demographic summary of interview participants

Number of participants, N		45
Gender, N (%)	Males	34 (76%)
	Females	11 (24%)
Age, Mean (Standard Deviation)		45.8 (10.9)
Highest Level of Education, N (%)	Postgraduate Degree	21 (47%)
	Undergraduate Degree	17 (38%)
	Diploma	4 (9%)
	High School	2 (4%)
	Other	1 (2%)
Industry[a], N (%)	Primary	16 (31%)
	Commercial R&D	10 (19%)
	Management	6 (12%)
	Marketing	6 (12%)
	University Research/Education	5 (10%)
	Nutrition & Dietetics	2 (4%)
	Other	7 (13%)
Current Tenure, Mean (Standard Deviation)		9.5 (9.0)

[a] Some participants selected more than one industry that applied to their current position

The business ecosystem is underpinned by the collective activity of stakeholders that leads to the creation of value. In the absence of vertical integration, it may be possible to establish business synergies that span stakeholder groups that seek to deliver innovative products to market[(243)]. This aligned with previous research in food chains which argued that coordination can act as a viable strategy to align the objectives of stakeholders across the ecosystem[(141)]. The mapping of the business ecosystem also uncovered the emergence of small, innovation driven players that have the ability to rapidly react to evolving market trends. The agility possessed by these entities can assist in the development of an innovation-driven culture within the food industry and encourage stakeholders within the ecosystem to explore new avenues for value creation. This can assist industry participants to satisfy consumer demands and differentiate themselves from competitors within the market[(65)].

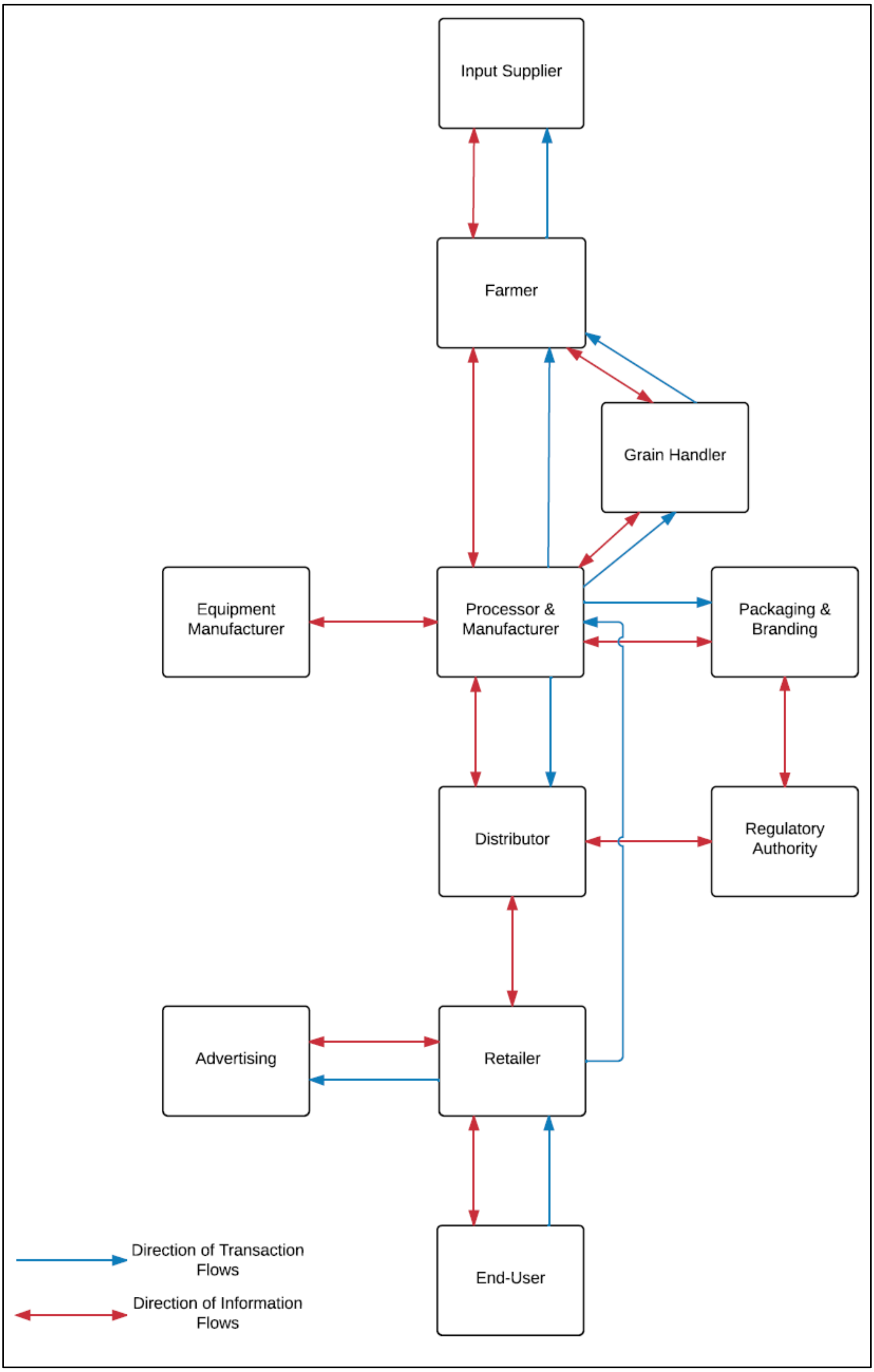

Figure 3.1 The range of activities that underpin the business ecosystem for novel grains

A key assumption of the current model is that the majority of novel grains are processed and consumed domestically. This assumption holds for sorghum where the majority of the grain is processed domestically[244], but potentially less accurate for quinoa, which is sourced primarily from South America[82]. Since the purpose of this research was to evaluate the domestic business ecosystem, the influence of international trade was not considered as part of the analysis. Despite this limitation, the current model does not preclude international trade (export and import) opportunities for novel grains. In line with targeting high value markets[245], it would be desirable to develop and sell value-added sorghum or quinoa products through export distribution channels. The scope to expand into this market could be evaluated in future research.

To anchor the findings in a relevant contextual frame, a brief summary of the key commercial players engaged in the market for novel grains is included in **Table 3.3**. The majority of these stakeholders are based in Australia, reflecting the role that domestic companies have in leveraging value from novel grains. Moreover, the purpose of presenting this brief summary is to offer a snapshot of the characteristics of these players and is intended to act as a guide to stimulate further research into the nature of the market for novel grains. For instance, the potential collaborative, scale and scope opportunities available for incumbent players, room for new players (for example start-up or multi-national firm) as well as the competitive dynamics that shape the industry. In addition, a summary of the value added by key stakeholders is shown in **Table 3.4**. The choice of stakeholders and nature of value addition is based on the ecosystem presented in **Figure 3.1** and informed by previous research focusing on value addition in the agricultural sector[246].

Table 3.3 Stakeholders involved in the market for novel grains

Industry Player	Role	Head Office	Founded
DuPont Pioneer	Seed supplier	Johnston, Iowa, USA	1926
GrainCorp	Grain aggregator and trader	Sydney, NSW Australia	1917
Emerald Grain	Grain aggregator and trader	Melbourne, VIC, Australia	2005
Maralong Milling	Grain miller	Westbrook, QLD, Australia	2000
Kialla Pure Foods	Wholesaler	Greenmount, QLD, Australia	2001
Santos Organics	Wholesaler and retailer	Mullumbimby, NSW, Australia	2000
Kindred Organics	Grower and product seller	Kindred, Tasmania, Australia	2001
Three Farmers Quinoa	Brand/Product Seller	Narrogin, WA, Australia	2011
Woods Foods	Brand/Product Seller	Goondiwindi, QLD, Australia	2012
Freedom Foods	Brand/Product Seller	Sydney, NSW, Australia	1990
Sanitarium	Brand/Product Seller	Melbourne, VIC, Australia	1898
Nestle	Brand/Product Seller	Vevey, Switzerland	1866
Coles	Retailer	Melbournce, VIC, Australia	1914
Woolworths	Retailer	Sydney, NSW, Australia	1924

Table 3.4 Value added within the ecosystem for novel grains

Function	Value-Added
Farm Input Providers	Improve grain yields Reduce disease incidence
Farm Production	Grow grain ready to be processed into value-added products
Handling & Sorting	Sort grain into quality groupings Centralise grain availability
Processing e.g. miller, baker	Transform grain into a consumer product
Packaging	Bundle product into a secure package Project a brand image
Distribution	Move products from distribution centres to sale points i.e. connect supply with demand
Retail	Convenience and access Provide a platform for consumers to purchase products

The ecosystem typology presents an attractive tool for both academic and commercial practitioners to capture market pathways and potential interactions in the agri-food context. Furthermore, exploring other agri-food domains through the application of the business ecosystem approach is potentially feasible due to the shared challenges of perishability[(247)], stochastic production[(166)] and agricultural output price fluctuations[(248)]

that are commonly faced by this sector. The business ecosystem therefore captures the activities that are required to deliver novel grains to the end-user and implies that the sharing of information between stakeholders is necessary to drive value and deliver products to market. By delving into the perspectives of individual stakeholders that participate in the business ecosystem, it was possible to explore perceived sources of value among stakeholder groups, revealing implications for the adoption of these grains into the food system.

3.3.3 Sources of Stakeholder Value for Novel Grains

The interview process revealed nine potential sources of value associated with the incorporation of novel grains into the food supply. **Figure 3.2** provides a summary of these sources of value and categorises them into higher-level concepts. This level of abstraction represents value as strategic, operational or end-user. The ensuing discussion explores these sources of value, outlines the implications for novel grains and offers a potential path forward.

3.3.4 Sources of Strategic Value

An assumption implicit in this research is that the ecosystem for novel grains is driven by market forces. It is anticipated that stakeholders engaged in the ecosystem for novel grains are rational economic agents that have an incentive to participate in the generation of innovative solutions to grow potential economic rents(249). In other words, these stakeholders seek a larger slice of the economic pie. From a strategic perspective, this can be achieved by assembling competitive advantages. Therefore, sources of strategic value are those that can contribute to the formation of competitive advantages.

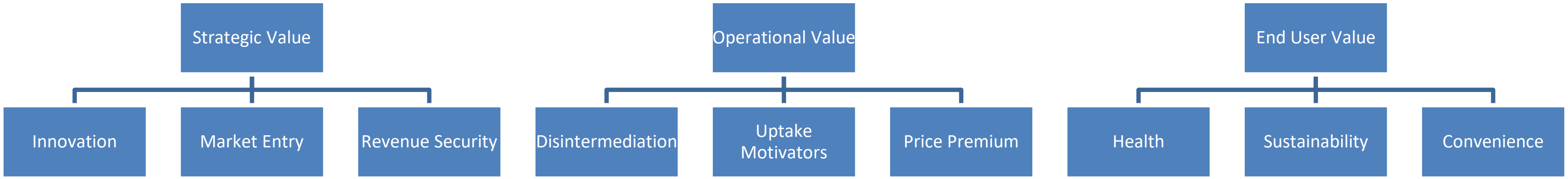

Figure 3.2 Summary of potential sources of value associated with the incorporation of novel grains into the food supply

3.3.4.1 Innovation

Operating in the nascent market for novel grains opens avenues for developing new products from previously underutilised inputs. Stakeholders recognised the potential for sorghum and quinoa to act as an innovative input into production systems.

> *"It needs to be created into some sort of science-reduced form, staple form that can be used as part of an ingredient in the formulations between systems"* Participant 24, Senior Food Science Liaison

Modularising the ingredient offers an attractive approach for its integration into incumbent food architectures. This innovation approach has the added advantage of maintaining the end-users understanding of the final product.

> "*…incorporating I guess new grains into existing formats and the sorghum Weet-Bix is a really good example of that and why it's been so successful is that although it's a different grain, it's been incorporated into a really well-known context that people are comfortable with…"* Participant 8, Director of Research Centre

These findings suggest that linkages between capabilities needed to deliver a product incorporating novel grains to market will remain the same, but the underlying knowledge and capabilities required to integrate components into the final product may change[(250)]. Future work could measure the degree of change that sorghum or quinoa would introduce into product development processes and the resulting impact on linkages between incumbent subsystems. Elucidating these insights could assist in determining the level of change required within incumbent systems to cope with these novel ingredients.

The value associated with innovating in the market for novel grains stems from the unique properties that these grains possess and the applicability for markets that are not currently serviced.

> *"…there are still companies who are trying to look at utilising it one way or another and people are wanting to actually incorporate it into beverages, as a thickening agent in beverages because it's got no gluten. It's got the potential to be able to be used at various levels for people with swallowing disorders, which is an area that people haven't spoken about or thought about"* Participant 24, Senior Food Science Liaison

In addition, innovation was seen as a response to new avenues for value creation within the market. While consumers still want to be satisfied with sweet tasting foods, they are also more conscious of the health implications of sugar.

> *"People are avoiding it [sugar], but they still want to feel satisfied, so the savoury market is exploding"* Participant 7, General Manager

Healthy snack foods were therefore opening avenues to develop innovative products that could meet this market demand. A further advantage that innovation offers is the ability to differentiate from incumbent products. This presents a unique value proposition for stakeholders and the opportunity to develop innovative products that can lead to the establishment of competitive advantages in mature markets.

> *"…if you were launching a product with that [ancient grain] in there, you'd want to differentiate it from, how is this any different, particularly in a breakfast cereal, to a wheat-based breakfast cereal."* Participant 3, CEO

Innovation can therefore act as a strategic tool to bring about elevated levels of value for stakeholders in the broader ecosystem. Rather than focussing on cost leadership and wringing out efficiencies in incumbent systems, stakeholders could pursue a differentiation strategy to bring in unique sources of value(173).

3.3.4.2 Market Entry

While innovation focused on developing new products for new and existing markets, market entry from new players may offer the enabling infrastructure. Specifically, uncertainty associated with operating in a nascent market may deter certain (incumbent) stakeholders from taking an active role.

> *"…it's an ecosystem, you've got the commercial guys, you've got the growers and you've got all the R&D facilities and what have you that are geared up towards these incumbents. How do you build that? The ecosystem needs to be built to provide that sustainability…"* Participant 1, Senior Director

Instead, it may encourage stakeholders with a higher risk tolerance to actively participate and search for value in the market.

> *"The food manufacturers in Australia won't take the risk. Small SME's yes probably…you've got big companies who aren't nimble, who can't change. They've got processes and it takes time and their risk averse"* Participant 14, Company Director

A new entrant may be better positioned to take advantage of bringing sorghum and quinoa to market. They are free from the burdens of existing knowledge that may be partially irrelevant. In other words, they are not tied to legacy systems and existing problem solving strategies that may not be effective in a new architectural environment[(250)].

> *"We just had a conversation about not being able to get the supply and demand. I think people want surety so they go 'show me the supply and demand'. The people that are calling me about quinoa are the leaders, are the risk takers, the front leaders."* Participant 9, Senior Program Manager

This insight aligns with the literature, which suggests that propensity for risk is related to entrepreneurial intentions[(251)] and that on average entrepreneurs tend to be willing to tolerate more risk than managers within incumbent organisations[(252)]. The first movers or market entrants may therefore be more willing to operate in an environment where information is revealed as the enterprise progresses. This approach entails a higher level of risk, but can also lead to significant payoffs through the ability to develop a deeper understanding of the potential application of novel grains into various products and formulations.

Stakeholders recognised that the knowledge and learning generated through the repetition of certain practices led to path dependence[(253)]; the idea that history matters and past decisions and behaviour shape future actions.

> *"It's about breaking those traditional bonds that I'm a beef producer, I don't crop. It's breaking that bond because the potential is to grow it in traditionally beef producing areas. But they are not croppers, so they go 'Oh that's a bit weird for me.'"* Participant 9, Senior Program Manager

This was supported with insights reflecting the perception of upstream stakeholders not actively pursuing market opportunities

> *"…I don't think it's something that the breeders really look at. They're not looking at turning sorghum into a food grain like that. They're more interested in developing it for the current markets"* Participant 5, Grain Merchant

The existing routines and organisational logic can generate inertia that can 'lock in' future outcomes[(254)]. This suggests that the innovation must fit into the existing physical and organisational framework with minimal disruptive negative consequences[(255)].

> *"There's still a reluctance because people don't want to vary their current ingredients and production systems to take it in because there is some R&D*

involved in that. If you're producing large amounts of baked bread or flatbreads and you have to adjust that formulation, it's probably not only adjustment to the formulation but there's an adjustment to the whole process, cooking etc" Participant 24, Senior Food Science Liaison

The implications of these findings are that incorporating a novel grain into the food supply will require stakeholders to identify the degree of change induced by novel grains and simultaneously work together to reconfigure routines in order to incorporate the novel grain into their systems [256, 257].

Stakeholders argued that many incumbent organisations would be willing to let smaller players carve out niches and only react if there was a direct threat to their business.

"…I think the risk aversion of the big ones [companies] is, 'let somebody else, we've got enough on our plate at the moment.' If they saw that their market opportunity was being taken up by somebody else, they'd very quickly want to squeeze them out." Participant 1, Senior Director

Part of the resistance to responding may also be embedded in the fact that the utilisation of novel grains requires behavioural changes and different managerial approaches that do not build on the existing organisational logic[258]. For example, farmers may play a pivotal role in the entry to new markets.

"Typically a farmer has to reinvent themselves and do value add typically on their farm…it's the farmers that actually drive the innovation" Participant 31, Head of Supply Chain

This view is supported by previous research investigating farmer-driven innovation with respect to land management[259]. On-farm value addition through the adoption of novel grains extends the scope of innovation that farmers can pursue and presents an avenue for value creation. Moreover, the tendency to wait for others to canvas the market before making a move highlights the level of due diligence that incumbent stakeholders require before making a decision. Nevertheless, if this market began to show promise, a potential entry strategy for these incumbents was to simply acquire the start-up.

"…I've had discussions with their R&D managers and they are sitting there saying 'well, we kind of own the market – we are aware there is various new packaging that is required, but it is too much CapEx to do anything. So we'll wait, we'll stave it off as much as possible and we'll wait for say somebody who is a little bit more entrepreneurial and has a greater appetite for risk to bring

something to market, and then we'll just go and buy them…" Participant 1, Senior Director

The incumbent organisation recognises the presence of this new market, but does not see value in allocating scare resources in its pursuit. The logic underpinning this approach is that there is more value embedded in refining the existing operation, than investing in an uncertain market where new capabilities may have to be developed. This captures the changing dynamic of the industry where smaller entities may adopt a leadership position in the implementation of an innovation[260]. This contrasts to the more traditional approach whereby brand leaders leverage their capabilities to engage in product innovation as a tool to maintain brand leadership[63].

3.3.4.3 Revenue Security

Establishing competence in utilising novel grains also offered a potential means of securing future revenue streams. Allocating resources to explore novel grains, such as sorghum and quinoa and making them attractive to multiple markets, was seen as a key source of value.

> *"Like a high protein, highly digestible white, that type of thing, that would appeal to probably lots of markets. Then you've got the capability of saying "Well, we've got something – we've got a product here that can go either way. It fits well into that human consumption as well as the animal consumption", so then your whole business model changes altogether"* Participant 22, Sorghum Research Scientist

Upstream stakeholders saw value in having more diverse market entry points, which would ultimately eliminate an over-reliance on revenue streams from one source.

> *"…our interest as producers, I think, are to have the maximum diversity in the marketplace"* Participant 28, Farmer

Diversifying into novel grains could also enhance the ability for stakeholders to withstand fluctuations in exogenous factors that could have a detrimental impact on revenue generation.

> *"…the major issues in the wheat belt with the drought for like five years in about 2005, 2006, 2007, around there. The manufacturers and the farmers were really concerned about the cost of wheat and it's availability and that was a key driver…for the manufacturers to look at it as the potential future to secure their profit lines."* Participant 11, Associate Professor

Establishing the capability to utilise novel grains was therefore seen as a strategic choice that could help to develop competitive advantages as uncertainty began to emerge on the horizon. Moreover, supplying at a smaller-scale was identified as a strategic opportunity for stakeholders that were willing to commit time and effort to establish appropriate market channels.

> *"There's a group of people who are willing to make the effort to supply that because the returns are there, but the hassle is there too. This is not the big supply chain concept"* Participant 28, Farmer

Instead of aiming to displace bulk commodities, a strategic positioning that relied on high value markets, rather than scale, could be considered.

3.3.5 Sources of Operational Value

Operational value encompasses factors that may have an influence on the ability to appropriate profit from the commercialisation of novel grains. This takes into account value associated with a price premium, cost reduction or some combination when taking novel grains to market.

3.3.5.1 Disintermediation

There are a number of stakeholders involved in the commercialisation pathway for a food product. Being an emergent market, a potential source of value (particularly for upstream entities) embedded in the market for novel grains lies in the scope for disintermediation. Put differently, additional value could be retained by excluding members of the ecosystem that tend to take a share of the value on offer and as a result, simply the pathway to market[(261)].

> *"Growers would like to work directly with customers, but the purchasers of grain prefer to go through the bulk handlers because there are less people to deal with and they are able to get all their produce from one source"* Participant 16, Director

Previous research has argued that short supply food chains[(262)] could eliminate a significant portion of the costs incurred in the supply chain by giving farmers the scope to interact directly with end-users. This has the added benefit of increasing economic returns and raising the attractiveness of entering the market[(246)].

"…so I did a thing on supply and demand of feed grain chains and the most profitable supply chain that you could get, not surprisingly, is a grower to a purchaser with no middle person that's local, which is what's happening at the moment for quinoa…" Participant 9, Senior Program Manager

The literature also suggests that implementation costs associated with an innovation can be reduced by simplifying the configuration of interdependencies. Disintermediation would offer once way of achieving this objective and see additional value generated through the incorporation of novel grains into the food supply[233].

Currently, the challenge lies in orchestrating the network. Disintermediation can help to eliminate waste, but there must be someone who can coordinate and lead the ecosystem[263].

"So that's the problem in Australia's innovation system. We've got good universities, we've got good companies, we've got some government policies, we've got some research, we've got universities providing teaching and research, we've got state departments providing some extension and some research. What's missing is the bit that connects it all together" Participant 14, Company Director

Value therefore lies in being able to connect the disparate elements of the ecosystem together. Possessing this capability could drive significant value, particularly as the market begins to grow and expand into new territory. In addition, disintermediation enables stakeholders to have better visibility of the end-user.

"You really have to start at the demand end and go right, who wants this stuff and how do we get it to market" Participant 32, Managing Director

Stakeholders argued that working in reverse order (demand to supply) would enable them to involve the end-user in the product development process. The shift from a supply-orientated to demand-orientated industry aligns with a broader shift in the agri-food sector towards consumer-orientated product development[264]. This highlights the potential for engaging the end user in co-creation activities that positions them as a partner in the process[243]. This can only be achieved with sustained dialogue and a sense of direction within the ecosystem in order to drive the value creation process and coordinate the activities of the key stakeholders required to deliver a product to market[139].

3.3.5.2 Uptake Motivators

From an operational perspective, stakeholders were looking to the market for trends that would give them an incentive to engage in the ecosystem for novel grains. It was identified that the notion of ancient grains could act as a potential motivator to engage the market.

> "*When we look at quinoa, teff, amaranth, farrow and spelt, it's seen as that ancient story. Untouched, non-manipulated through breeding over centuries…that story has done really well aside from the health halo platform that they've been put on."* Participant 3, CEO

The ancient grains category, which sorghum and quinoa are both examples of, are seeing market traction and growth[265]. Moreover, there was a broader recognition that downstream demand and consumer interest was having an influence on the value that could be generated from incorporating novel grains into the food supply.

> *"…the ancient-grain phenomenon has caught on. That has led to people and manufacturers incorporating these grains in their products."* Participant 23, Regional Nutrition & External Manager

Furthermore, the value lay in identifying key trends and being able to act on these to deliver products to market that would meet end-user expectations.

> *"…find out first what consumers want and if the consumers for instance want quinoa or ancient grains in these products the ingredients may be novel in terms of we haven't used it before but it transects what consumers are desiring so we consider that and then we try to very hard to see if we can incorporate quinoa, or kale, or you know whatever it is that is on trend."* Participant 23, Regional Nutrition & External Manager

It was also conceivable that these downstream factors could instigate a feedback loop to producers. In other words, information that was gathered at the position of the end-user could be used to inform upstream processors and facilitate the formation of ongoing partnerships

> *"…one-off things, farmers aren't terribly interested in, but if you can get a processor who will keep coming back because you produce the right product and they tell you how to produce the right sort of product, well then farmers love that. Give them some sort of security over the long term, you're more likely to get them to keep growing sorghum or keep growing a specific hybrid of sorghum for that processor, building that relationship."* Participant 12, Senior Research Fellow

Empirical research suggests that farmers would have strong intentions to scale their operations in line with consumer demand[266]. In essence, aligning stakeholders with a common goal can enhance the efficiency of information transfer, strengthening relationships and encouraging closer collaboration in the development of novel products.

3.3.5.3 Price Premium

The price point resulting from the sale of grain was identified as a clear source of value, specifically among farmers.

> *"So growers from my experience, they're the most kind of price driven customers that you'll ever deal with so they'll do anything for an extra dollar"* Participant 6, Customer Manager

This supports previous research which suggests that the scope to generate potentially lucrative returns from growing specialty crops[267] is a significant source of value. Moreover, the transition of novel grains to high value crops was identified as catalyst for driving engagement with producers.

> *"If the human consumption took off and people were prepared to pay $300/tonne instead of $150 or $200/tonne then you'd see more sorghum being grown because it's a fairly simple crop to grow…"* Participant 38, Managing Director

This was supported by an acknowledgement that downstream stakeholders also saw value in integrating novel grains into product formulations. Their motivation centred on the ability to offer differentiated products that could attract better margins than products that relied on commodity level inputs.

> *"…seeing that there's potential value-add opportunities to move out of some of those commodity grains where we're seeing decline in your standard sweet-based breakfast cereals and move away from your straight forward bread, that are traditionally a wheat-based product. Companies are, therefore identifying some of these opportunities to get better margins and to make more money."* Participant 3, CEO

A market niche was also identified as being able to secure lucrative returns in the market for novel grains. Specifically, stakeholders recognised that novel grains opened the door to unique markets that could see additional returns.

> *"…whenever I'm forced to go to the organic shop…which I don't like going to because everything has an extra zero, you can buy sorghum flour, containers of*

it, but it's extremely expensive. So there's these niche markets that are appearing." Participant 24, Senior Food Science Liaison

Nevertheless, there was an explicit recognition that the domestic (Australian) market should not be the final objective. True value could only be achieved by expanding into international markets, where additional returns could be generated.

"Domestic for sure, you've got to have it so you've got some cash flow, but the eyes and the prize need to be on that export market where you can really make some good big dollars. The high value." Participant 9, Senior Program Manager

Additionally, the positioning of a novel grain may focus on leveraging the presence of some innate characteristic (e.g. being gluten free). The business environment is however dynamic and this may not be feasible in the longer-term.

"If it turns out that gluten free isn't what it's meant to be and you're not gluten free, then 'why the bloody hell am I paying extra for this product? It's not doing anything for me. It doesn't taste any better.' You want to be mainstream…in that well priced product that people are buying every day or every week…" Participant 39, Director

These findings reflect the acknowledgement that while novel grains currently possess a niche in the market, to remain competitive, sufficient volumes must be sold through their incorporation into products that are consumed on a regular basis by consumers.

"…produce a premium product or add value to what we've got so that we drive a sort of high value product. That of course applies to sorghum or wheat or any other grain." Participant 8, Director of Research Centre

3.3.6 Sources of End-User Value

End-user value was defined as attributes that would appeal to the end-user and that could simultaneously be leveraged by stakeholders to encourage the incorporation of novel grains into the food supply.

3.3.6.1 Health

As an extension of the ancient grain phenomenon, the health attributes of food products were also identified as drivers of downstream demand.

"...so I think that audience really, the price aspect, they don't put a price on health. So I wouldn't say price is a bigger driver. Very much for them, it's about the keeping up with the Jones' factor. They're on one of these trendy eating patterns, and that whole health halo is more of a priority to them." Participant 3, CEO

Furthermore, the provision of nutrition information has been shown to increase the willingness of consumers to pay for healthy food options[(268)]. The emergence of a health-conscious consumer demographic may therefore present a potential opportunity to position novel grains with a health orientated value proposition.

*"So this is a product that tastes bloody awful but everyone buys it and it's bloody growing a massive market share. So there is the perception out there that if it tastes s*** it must be good for you."* Participant 14, Director

This insight aligns with the concept of perceived health, with market trends such as 'naturally functional' gaining health credence despite evidence indicating that almost half of products labelled with a natural tag would not fit into a diet considered healthy by the Australian Guide to Healthy Eating[(269)].

"The focus is now health, not skinny, and that it's sort of weight wellness, not about weight. It's about health and nutrition and sickness and that market, predominantly very much in that under-40 category, but we are seeing it in other categories, is very much growing..." Participant 3, CEO

Stakeholders also identified the underlying desire that consumers have for a quick fix that allows them to continue living their lives, making minimal adjustments, but receiving the benefits of foods that are healthy.

"...here's a natural way you can just have a quinoa salad and it will have an effect. That is a massive thing. These natural things we – you can eat 20 Mars bars and – this is what people want. They want to keep doing what they're doing and lose weight. It's the lazy way." Participant 9, Senior Program Manager

Positioning novel grains in this natural category has the added advantage of invoking connotations of health, also shown to be associated with improvements in sensory evaluation[(270)]. Ultimately, this reveals the opportunity to develop products that can leverage the value embedded in the market for healthy food products.

By leveraging these health trends, processors are beginning to see lucrative value in developing products that meet these desires.

> *"So for a processor to include that ingredient – I think there is interest in including new ingredients if they provide a demonstrable health benefit, something that they can actually put a label on…"* Participant 8, Director of Research Centre

While previous research argues that health attributes are more relevant for functional foods[66], these comments reflect the need to be able to inform the end-user of the health properties in order to capture a share of the value.

> *"The amylose:amylopectin ratio in sorghum is more favourable to lower levels of digestibility as compared to wheat, so in other words, the insulin reaction response with wheat is much faster"* Participant 24, Senior Food Science Liaison

It appeared that novel grains possessed certain attractive properties, but to be commercially valuable, nutrition research must identify characteristics of novel grains that will enable product manufacturers to deliver clearly signposted health messages to end-users.

> *"…increasingly food processors are looking for any sort of edge over their competitor to try and compete in the market and I think health properties is one way"* Participant 8, Director of Research Centre

Given the highly competitive nature of the food industry, processors are sensing avenues to differentiate their offering through the health attributes of novel grains. Whether the pursuit of products that offer a health value proposition can contribute to delivering sustainable competitive advantages for stakeholders remains unclear.

3.3.6.2 Sustainability

Stakeholders identified sustainability as an emerging desire from end-users. Grains appear to offer a sustainable solution to future food demand.

> *"I think with the global population ever increasing we're going to have to more and more turn towards grain as a supply of food rather than actual animals. So we're going to hit that point where we're not going to be able to produce enough beef for all the mouths in the world"* Participant 6, Customer Manager

This consideration is connected to a broader recognition that stakeholders must be able to respond to end-user desires.

> *"In the beef industry for example or the chicken industry, animal welfare is a parallel kind of interest that certain consumers have. Food manufacturers,*

suppliers, retailers (that part of the value chain) is starting to respond to what their perception of consumer interest is." Participant 28, Farmer

Trust in particular is seen as a critical aspect of fostering collaboration across the ecosystem[271]. By developing the capabilities to respond to consumer interests, stakeholders are in a position to align their product offerings with specific market segments. This may offer a unique source of value for novel grains.

A further consideration associated with sustainability, was the choice of language used to communicate messages to the end-user.

> *"When marketing at a retail/commercial level, people get a little bit lost with crop rotations…try and market sustainable farming methods, and people get that..."* Participant 43, Manager

This suggests that while end-users are not experts, they have a set of expectations that can be fulfilled by exposure to information that is simple to understand. Specifically, information strategies derived from marketing, behavioural economics and psychology are needed to influence consumer behaviour, particularly towards food choices[272]. The implications are that manufacturers must pay more attention to consumer desires and their need for information, particularly in relation to the origin of their food.

> *"…the best way to take any product to that next level is through that connection that consumers can have back to their food. Knowledge around where products have come from is overtaking organic produce"* Participant 45, Director

The transition to consumer-driven product development[264] has enhanced their level of power and resulted in the emergence of demand for information associated with the traceability of the food system[273] which may be desired by specific market segments[274]. By establishing the capability to meet this desire, stakeholders are well positioned to move their product offerings into a new era of value creation.

3.3.6.3 Convenience

An emerging source of value for the end-user is having access to food choices that are quick and easy to prepare.

> *"I think increasingly convenience is a really important factor for consumers, so being able to purchase something, even if it's more expensive or whatever and*

slightly less quality but offering convenience…" Participant 8, Director of Research Centre

It was also identified that convenient food choices collide with the desire for healthy alternatives, culminating in a unique market that values the ability to prepare food quickly, but also have the security that it is a healthy alternative.

"So give me something that is a snack, easy to use that I can throw in a lunch box that uses grains, or something else that has a proven nutritional value for my child or myself. Absolutely, there is something going on there." Participant 1, Senior Director

Manufacturers are also beginning to recognise this trend and devoting resources to identify strategies that will allow them to take advantage of these trends.

"…one of the people that I talk to, one of the manufacturers, is Sunrice. The majority of their business now is not grain, it's fast food. Convenience food, not fast food. Convenience food." Participant 9, Senior Program Manager

In the context of novel grains, efforts must be devoted to leverage the innate health attributes into a form that will also allow it to be conveniently consumed. Moreover, the evidence suggests that food consumption and purchase behaviour is underpinned by a nexus of price, taste and convenience[(275)]. In combination, these factors represent end-user driven trends that can offer unique sources of value for novel grains.

3.3.7 Elements of Innovation Influencing Diffusion Pathway

An additional aim of interviewing stakeholders for Part A of Study 1 was to explore the potential diffusion pathway for novel grains. The diffusion of innovation theory espouses five elements (relative advantage, compatibility, complexity, trialability and observability) that influence the manner in which an innovation diffuses. The analysis of interview transcripts also revealed a sixth conceptual node (impression), which influenced the diffusion of novel grains. Findings are clustered within these six elements, with sub-constructs and exemplar quotes presented in **Table 3.5**. The discussion of the potential diffusion pathway for novel grains is discussed in the following section.

Table 3.5 Dimensions influencing the diffusion of novel grains into the food supply

Conceptual Node	Sub-Construct	Exemplar Quote
Relative Advantage	Gross Margins	*"So, for growers I think if there's a premium there, if they can get a premium for growing human consumption sorghum and if there's a difference there, whatever it is, then they'll – some of them will take it. Of course they will."* Participant 5, Grain Merchant
	Robustness	*"…during the great drought in the 2000s when I was based out in the region, I noticed it was extremely difficult to grow anything except sorghum. There's not enough water for cotton, it wasn't suitable for wheat, it was just – sorghum was it…"* Participant 24, Senior Food Science Liaison
	Wellbeing	*"… but certainly for humans, in terms of antioxidant properties, potentially anti-cancer properties, so we see sorghum fitting into this sort of super grain category like chia and quinoa. Sorghum would fit within that super high healthy grain"* Participant 12, Senior Research Fellow
	Taste	"*So while it's nice to think that health properties are going to be a big driver, and I think recently it is, at the end of the day they still have to be good quality tasting products with good textures"* Participant 8, Director of Research Centre
Compatibility	Farming Systems	*Rotations are a main driver [of planting decisions], but within those rotations, the flexibility to follow gross margins…"* Participant 45, Director
	Product Requirements	*"…being gluten-free … it makes lousy bread. So they actually use it still as a flour, but it wouldn't go into a normal, fermented baking type product. It could end up in unleavened type breads, or cookies or muffins or anything where you're not looking for rise"* Participant 12, Senior Research Fellow

	Food System Architecture	*"Can it be incorporated into noodle systems, flat noodles, round noodles? The general cereal products we can think about…"* Participant 24, Senior Food Science Liaison
	Eating Patterns	*"…we have to focus on not thinking that consumers have to change into some sort of exotic pattern, but we have to make good nutritious food that is familiar and desired and has the taste that people want…"* Participant 28, Farmer
Complexity	Infrastructure	*"…if you can get a product out like they did using conventional equipment, even if it had to be recertified as gluten free, that's nothing compared to building a whole new factory with all the engineering and everything else"* Participant 11, Associate Professor
	Processing	*"Understanding all those individual steps, what's in the raw material to start with, how the processing is going to affect that, and then how is the animal going to utilise that … Not just animals processing, but anything that's flaked or cooked, anything like that. Our mueslis, cornflakes, noodles, anything that is high pressure or high temperature, things change"* Participant 12, Senior Research Fellow
	Standards	*"so often we'll keep falling back onto the protein standard, even though we know it's not necessarily exactly what we want. But it's just an easier measure which we can relate protein content to starch, and other things, and the farmers can relate to that because they've been getting wheat and barley tested for protein for years and they understand that nitrogen changes protein in the grain, so they have that sort of in-built understanding of nitrogen fertiliser equals grain protein content and it's all linked to yield."* Participant 12, Senior Research Fellow
	Message Delivery	*"…translating science into the meaningful consumer messages, that's something that is difficult and science is complicated and when you need to tweet something in less than twenty characters or*

		something it's really hard to get the message across." Participant 23, Regional Nutrition & External Manager
Trialability	Proactive Behaviour	*"Where I see diversity of agriculture coming from is multi-commodity producers. They're the first ones that'll try something new"* Participant 9, Senior Program Manager
	Additive	*"...fraction may have to be added almost as like a combinant type addition,* rather than as a main *staple type component. Probably at minimum thresholds as well, 5%, 10%, 15% so people might actually perceive something there, but they're not going to be offended or turned off* from buying your *product."* Participant 12, Senior Research Fellow
	Recipes	*"And recipes, people need to know how to use something"* Participant 2
	Culinary Application	*"...the next thing they're going to do is not go and try to cook it from scratch, because you will have that whole education challenge around, well, what do I even use it in? What is it equivalent to? That's a lot of the inquiries you get about quinoa flour, for example"* Participant 3, CEO
Observability	Background	*"...if a show or an article gets out there which goes, 'this is what it is, this is its nutritional profile, it's got high levels of this, this is the form it comes in…' that's essentially what it takes…"* Participant 10, Purchasing Manager and Business Development
	Media Exposure	*"You use good marketing, you use good product development, you use good positioning. With social media it's a lot easier. Tell me, how many people would have known what the hell a chia was?"* Participant 14, Director
	Visual Appearance	*"A lot of mainstream consumers are very influenced by visual appearance. ... What is their interpretation of colour and how that influences their decision on what they buy and how they use it. I*

		guess this is coming from a historical standpoint. Australian and a lot of western diets, they're used to using wheat and other white grains, so seeing components of your food that might look a bit brown or dark, we're not used to that." Participant 12, Senior Research Fellow
	Tangible Benefits	*"But I think that for a non-commercially delivered crop which quinoa is – it's not mainstream commercial. It's emerging commercial. That's how I'd put it. For a crop like that, the growers need to be getting cash return. That's domestic. It's actually local domestic"* Participant 9, Senior Program Manager
Impression	Quality	*"At the moment, for wheat, they get paid a premium for high protein wheat, same for malting barley, they get paid a premium if they get their protein content within a certain window. For sorghum, there's a premium if the grain's not too small, so sorghum is one of those, almost like a poor cousin … nobody really thinks about it too much in terms of quality"* Participant 12, Senior Research Fellow
	Familiarity	*"Where there is a high demographic of African's or Indians, then they're used to eating sorghum and in some cases sorghum two or three times a day in different foods. Like they have sorghum porridge for breakfast, and they might have some sort of flat bread for lunch, you know? It won't be a surprise to them to think, "Oh, there's been some sorghum flour added to some bread", so some sorghum bran added to – again, mainstream Australians are probably going to take time to adjust to this."* Participant 12, Senior Research Fellow
	Historical Paradigm	*"…we've been growing wheat for 200 years. We probably haven't been growing sorghum more than 100 years, so even the first settlers brought bags of wheat with them. When sorghum was being grown, it was just seen, because we've got so much wheat for food, sorghum was seen, "Well, it's just cattle*

		feed, animal feed"…wheat for food, sorghum for feed, and it's been a difficult paradigm to change for a number of industries." Participant 12, Senior Research Fellow
	Engagement	*"…in grain particularly, people say 'it's just not that exciting' when you look at the product it's not like a fresh apple. Grains tend to become different products – maybe that's why people haven't gotten behind it"* Participant 45, Director

3.3.7.1 Relative Advantage

Stakeholders within the ecosystem recognised that the diffusion of novel grains was contingent on there being advantages, or benefits[276] for key stakeholders. At the front-end of production, the dual prospect of generating superior returns and operating with a more environmentally robust grain were identified as being advantageous in comparison to incumbent alternatives. Over time, as more stakeholders observe the innovation and its relative performance, the rate of diffusion is likely to accelerate, following an S-curve[277]. In the short term, however, connecting upstream advantages with downstream advantages, (for example, compelling nutrition messages), could strengthen relationships between ecosystem stakeholders[278] and place novel grains in a superior position with respect to incumbent alternatives. Nevertheless, while advantageous nutritional properties may play a role in facilitating diffusion, this would have to be supplemented with superior sensory properties, such as taste and texture[275]. Ultimately, the final product would need to offer advantages at critical junctures within the ecosystem for successful diffusion to take place.

3.3.7.2 Compatibility

The degree of change that incumbent stakeholders would need to tolerate in order to integrate novel grains into the food supply was identified as a significant compatibility issue. Put differently, the impact that adopting novel grains would have for incumbent stakeholders would be a function of the level of modular or architectural change brought about[250]. The impact of these considerations would also be contingent on the position of stakeholders within the ecosystem. For example, diffusion of novel grains would have different compatibility issues for farmers (i.e. synergies with existing rotations and management of their land for future productivity), manufacturers (scope to leverage existing subsystems) and consumers (awareness of existing food products). The literature suggests that if novel grains were an example of a ‘plug-and-play’ innovation, where they fit into existing systems, it is likely that good product execution will result in good results[279]. However, where novel grains require the reconfiguration of architectural linkages and therefore greater changes in relative compatibility, there would be greater difficulty associated with diffusion.

3.3.7.3 Complexity

The level of complexity associated with incorporating novel grains into the food supply was identified as a key contributor to the relative ease associated with diffusion. A significant portion of relative complexity was embedded in the activities required to transform novel grains into a marketable food. In particular, the degree to which new knowledge and skills would have to be developed. The literature suggests that stakeholders tend to engage in stepwise adoption, which reveals information in a sequential process. Moreover, it has been argued that the quality, rather than quantity of information is more important[280]. If existing capabilities and knowledge could be leveraged, novel grains would stand a far better chance of diffusing. Put differently, if the processes needed to transform novel grains into value-added products could build on existing organisational routines and logics, the prospects for diffusion could be enhanced.

Moreover, the ease of developing quality characteristics for the grain and being able to define criteria that will distinguish high and low quality grain will be important in the potential diffusion process. Specifically, if criteria that incumbent stakeholders are familiar with can be developed, the level of complexity associated with interpreting quality characteristics of novel grains will be reduced. Furthermore, the level of complexity associated with translating insights to consumers has significant implications for potential diffusion. Information is a powerful tool, but complex information can dilute its impact, meaning that additional cognitive effort will have to be devoted to understand certain messages[281]. To build a viable path to market, strategies must focus on eliminating complexities and seek to build synergies with existing knowledge and logic. Transferring existing information into a new venture would be more likely to be successful and enhance the prospects of novel grains diffusing into the market.

3.3.7.4 Trialability

The ability to offer novel grains in a format where they could be trialled prior to full uptake was identified as an element of the innovation that would influence diffusion. Farmers, being at the forefront of the ecosystem would play an instrumental role in the diffusion process. It was suggested that farmers engaged in multi-commodity output activities would be more likely to engage, due to their varied experiences and greater tolerance for change. Previous research has shown that the ability to trial an innovation also improves access to information and the ability to learn, laying the foundations for deeper diffusion[282]. Further downstream, the ability to trial novel grains at low levels in order to explore the impact on taste and sensory properties were identified as an important enabler of diffusion. This was supported by views that there must be scope for end-users to trial novel grains and become comfortable with their application in order for their diffusion to become more widespread. The difficulty lies in integrating each of these components and ensuring that stakeholders across the ecosystem are able to experience the full-scale trial. In other words, the benefits of diffusion accrue after the entire system is in operation, potentially increasing the difficult of trialling novel grains[150].

3.3.7.5 Observability

Having an observable presence was identified as a further element influencing the diffusion of novel grains into the food supply. Communication across multiple stakeholders[148] and engaging with appropriate forms of media, were seen as being crucial for attention in the public eye. Indeed, emerging theory suggests that it is the number of connections, not the strength of these connections that are important in translating the observable benefits of an innovation[156]. For example, celebrity chefs that have mass appeal can access large swathes of the population through their use of social media as an information dissemination tool[283]. At a more practical level, physical attributes of these grains, such as their colour were identified as playing a role in potential diffusion, while observable benefits, such as cash returns were highlighted as driving the front end of diffusion. As the unique attributes of novel grains are demonstrated, the attractiveness of the innovation may spill-over to other participants in the market and further enhance the diffusion potential[284].

3.3.7.6 Impression

The final dimension explored in the context of diffusion of novel grains centred on the perceptions held by key stakeholders. Research suggests that unfamiliar food products can present consumers with significant challenges in incorporating a food into their diet[285]. Stakeholders argued that this may be a result of the historical paradigm underpinning the food system and the psychology of having familiar foods in the diet. In order to facilitate diffusion, the broader attitude towards novel grains would need to undergo a realignment to accept that novel grains can offer superior quality and that grains are the foundation of numerous foods which have undergone transformation. The construct of impression directs attention to the perception of an innovation, before it has been formally evaluated through explicit use[276]. Put differently, the crux of this concept lies in the level of understanding that is displayed towards novel grains and how they are perceived by end-users and stakeholders within the ecosystem.

3.3.8 Summary of Findings

The findings presented thus far have identified several important insights. Firstly, a combination of transactions and information must flow across the ecosystem in order to create value, which are conceptualised as strategic, operational and end-user factors. Furthermore, competitive advantages are on offer for stakeholders that are willing to engage in the market for novel grains and take risks in entering this nascent market. Path dependence suggests that it may be more difficult for an incumbent stakeholder to engage in this market and that an entrepreneur (free of existing organisational shackles) would be better positioned to move the opportunity forward. Secondly, there is an argument that co-creating value with the end-user can enhance the value of the final offering. Specifically, by observing end-user driven trends, stakeholders within the ecosystem can identify pathways to collaborate and develop products with the consumer rather than for the consumer. Further insights suggest that orchestrating the ecosystem is crucial for the operational feasibility of bringing novel grains to market. Finally, the diffusion of innovation theory offers a lens through which to observe the pathway to market for novel grains. By adding the dimension of impression, this research recognises that information and the manner in which it is processed has a critical role to play in facilitating the diffusion of novel grains into the food supply.

By applying a case analysis of sorghum and quinoa, the research presented in Part A has captured the business ecosystem for novel grains, an insight into the potential sources of stakeholder value and diffusion pathway for these grains. Part B scrutinises the type of risks and their respective position in the ecosystem. In combination, this information reveals the potential challenges that may arise across the ecosystem and the influence that the position of risk has on the ability to create value from the incorporation of novel grains into the food supply.

Study 1 Part B –Types and Position of Risks across the Business Ecosystem

3.4 Findings and Discussion

As outlined in the methods section, participants that were interviewed to capture perceptions towards novel grains were also interviewed to explore insights related to potential risks within the business ecosystem. The findings relevant to Part B are presented in the order suggested by the value blueprint framework (**Table 3.1**). This commences with a consideration of the end customer and an overview of potential value propositions that could be linked to the incorporation of novel grains into the food supply.

3.4.1 End Customers and Potential Value Propositions

The overarching aim of applying the value blueprint method to the incremental innovation associated with the incorporation of novel grains into the food supply was twofold. Firstly, it was applied to identify the types of risk associated with the incorporation of novel grains into the food supply. Secondly, it was applied to explore the relative position of these risks with respect to the business ecosystem. In line with the ecosystem-as-affiliation approach, potential end customers and value propositions must be elucidated from the ecosystem before potential risks can be investigated.

By identifying the end customer, the ultimate user of the innovation can be highlighted, which can provide practical insights into attributes that would be deemed as being of value to this market. It is important to note that due to the integrated nature of the ecosystem and the relative position of stakeholders, a customer for a product could have a simultaneous role as a supplier for another stakeholder. For example, the customer for grain produced by a farmer could be a grain miller, who is in turn a supplier for a bakery. Due to the absence of a single focal firm (the analysis considers the ecosystem from farm to fork) it is unlikely that stakeholders across the ecosystem will share the same customer. At the level of the ecosystem however, and for ease of conceptualisation, consumers represent the end customer in the market for novel grains.

Closely related to the identification of the end customer is the value proposition, which is defined as the proposed benefit that the customer will receive from the innovation[241]. Stakeholders, particularly those involved in marketing and sales, recognised the fundamental role of the consumer as the source of demand and ultimate target of the value proposition.

> *"It's all about what can the product do for them [consumer]? At the end of the day they're the buyer, they're number one."* Participant 43, Manager

While value may be created through the activities of the stakeholders across the ecosystem, this value can only be captured if the end-user is satisfied that the net benefit offered by the value proposition is sufficient to outstrip the potential cost. Ritala *et al.*[212] argue that a similar scenario is prevalent across the ecosystem, whereby stakeholders seek to capture the value associated with their participation in the ecosystem. The question of what this value proposition should be was only briefly explored. The findings generated from the scoping process identified three potential value propositions that could be applied to novel grains:

1. Premium quality: e.g. *"…develop an image of it being really high value, high class rather than mass market appeal. It's always about being an aspirational thing."* Participant 27, Food Scientist
2. Nutritional convenience: e.g. *"So give me something that is a snack, easy to use that I can throw in a lunch box that uses grains, or something else that has a proven nutritional value for my child or myself."* Participant 1, Senior Director
3. Environmental sustainability: e.g. *"I think sorghum needs to find a way to position and message itself in that way. It's probably going to be more about environmental, complete grain, nutritional profile, grown in Australia."* Participant 7, General Manager

Establishing the overarching value proposition for the target customer is fundamental to the development of a successful product. Furthermore, Frow and Payne[260] argue that the value proposition reflects the fundamental economics behind business decisions and has an important role to play in aligning objectives and co-creating value. In line with the ecosystem-as-affiliation conceptualisation, these value propositions are a result of having first considered the position of stakeholders in the business ecosystem and their notions of value. While the articulation of potential value propositions can inform the strategic direction the ecosystem should focus on, an investigation of potential risks associated with the incorporation of novel grains into the food supply must first be performed. Identifying the types of risks and their relative position can influence the ability of stakeholders to successfully execute the incorporation of novel grains into their individual systems and ultimately the food supply.

3.4.2 Types and Position of Risks across the Business Ecosystem

Interviews conducted with ecosystem stakeholders enabled a range of risks associated with the incorporation of novel grains into the food supply to be identified. In addition, the relative positions of these risks, with respect to the activities occurring in the ecosystem are identified (**Table 3.6**). Risks associated with the incorporation of novel grains into the food supply are categorised as Execution Risks, Co-Innovation Risks and Adoption Chain Risks (3.4.2.1 to 3.4.2.3). In addition, there are multiple examples of risk within each category and they are present in numerous positions across the business ecosystem.

Table 3.6 The classification of potential risks and their position within the ecosystem, elucidated from interviews with key stakeholders

Risk Type	***Example of Risk***	***Position of Risks***
Execution	Competitors	Product Development
	Price Volatility	Growers
	Agronomy	Growers
	Continuity of Supply	Growers, Processing & Manufacturing
	Expenses	Processing & Manufacturing
	Demand	Retail Sales
Co-Innovation	Quality Standards	Grain Handling & Sales
	Production Capabilities	Processing, Business & Product Development
	R&D capabilities	Business & Product Development
	Nutritional Properties	Marketing and Branding
Adoption Chain	Planting Novel Grains	Growing
	Product Formulation	Business & Product Development
	Product Throughput	Wholesale, Retail Sales
	Consumer Adoption	Retail Sales

3.4.2.1 Execution Risk

In the context of incorporating novel grains into the food supply, the contribution of individual stakeholders to the delivery of the final product was associated with risks related to the execution of their role. Execution can therefore be defined as the ability to complete a task on time, within the allocated budget and to meet the specified requirements. In the agri-food industry, competitive pressures faced by ecosystem stakeholders were identified as an additional component of the execution risk framework. There was an inherent desire to be aware of the competitive environment and the potential innovative behaviour being planned by these competitors that may influence the execution of a new product.

> *"…in food and beverage, they want to be able to see what's coming. They don't necessarily want to be first but if they've got enough confidence in it they want to tie it up immediately…"* Participant 1, Senior Director

As expected, the generation of economic returns were identified as a major contributor to execution risk. For example, the sensitivity to price changes for sorghum was identified as a potential risk influencing the desire of farmers to execute the inclusion of sorghum (and potentially other novel grains) into their production systems.

> *"…the demand profile for sorghum is highly elastic as it competes with wheat and barley into the feed sector domestically…"* Participant 15, Sorghum Trader

This was exacerbated by the behaviour of individual farmers also being shaped by an agronomic rationale.

> *"No matter how much demand there is, the crop that is grown in a certain area has to suit the agronomy of that location"* Participant 45, Director

In the absence of suitable economic returns (influencing willingness) and the presence of appropriate agronomy (influencing ability), the incorporation of a novel grain into the food supply would be unlikely to occur.

Economic returns also influenced downstream stakeholders, with the cost of processing quinoa in Australia identified as a factor that could be detrimental to the economic feasibility of its incorporation into the food supply.

> *"One of the issues is the production and processing of quinoa and the cost of that in Australia versus the cost of that in South America"* Participant 10, Purchasing Manager and Business Development

Processors were also faced with cost pressure associated with the procurement of novel grains for their production systems, particularly when compared to alternatives currently being used by these processors.

> *"…so you look at the procurement cost, and the cost of novel grains per tonne is you know, like 1000 times the price of buying a wheat-based source…"* Participant 3, CEO

In addition, processors acknowledged that manufacturing costs added further pressure to the bottom line and would need to be taken into consideration when determining if a novel grain would offer a cost effective solution.

> *"If you're going to manufacture these things into finished products there's a fair few costs that go on board. Our puffed sorghum is just as expensive if not dearer than some of our puffed pulses".* Participant 39, Director

The general consensus among stakeholders was the tight relationship between risk and reward. At a commercial level, there had to be a clear financial argument in favour of pursuing novel grains as a business opportunity.

> *"…generally the dollar, the cost drives everything and if it's too expensive and they can't see how it can be paid back or where it is going to provide the benefit then they are generally not interested in investing for the feel good benefit. It's all about how can we improve these giant businesses that they've managed to build"* Participant 1, Senior Director

Competition for limited infrastructure, particularly during the mining boom in parts of Queensland and Western Australia was also identified as a critical challenge that faced grain producers bringing their products to market.

> *"They're [mining industry] paying I think $32 a tonne to Brisbane and we can do it by road for $29. So they're sort of paying 32 bucks to just keep the line to themselves and really it should only cost about 10 bucks. It costs at the moment, a tonne of grain from say Dalby to Brisbane is say $29 and the quote we had the other day for a bulk ship to a port in China was, like, $7 a tonne."* Participant 5, Grain Merchant

The flow-on effects for downstream processors may result in the need to search further afield for inputs into products. Sorghum and particularly quinoa are not ubiquitous in farming systems and therefore the location of growing regions for novel grains must fall within the scope of the procurement network of downstream stakeholders. The relevance of strong infrastructure linkages are therefore critical in being able to bring novel grains to market.

"If they want it in Sydney and they can only grow it in North Queensland, then it's just a cost factor, but you've got to have the infrastructure in place to be able to do it" Participant 32, Managing Director

A further element of execution risk, particularly when considering the export market, was the challenge associated with competition that was arising due to cost competition. Specifically, favourable cost pressures that were having a detrimental impact on Australian exports into foreign ports.

"…with freight rates and oil prices the way that they are now at record lows we've got other competing origins which are further away who can price into Asia which is usually our strong point given our geographical proximity…" Participant 6, Customer Manager QLD

Further challenges associated with infrastructure were connected with uncertain elements, such as unfavourable weather at the time of harvest and the implications for supply.

"…if there's a lot of weather during harvest in northern NSW and none of that's suitable, then you have to go a lot further away and that might mean your freight costs double" Participant 35, Technical Services & Quality Manager

This insight captures the fundamental challenge associated with unpredictable weather events(97) and the corresponding implications for production quality(286) encountered in the agri-food industry. The execution of a product containing a novel grain, where supply is uncertain and prone to price volatility presents a key risk that must be considered by stakeholders in product development. Moreover, it was recognised that this can also influence the consistency with which an input is supplied, therefore impacting the potential to develop a product from novel grains.

"It is important to maintain regular supply. You don't want to have shortages of ingredients that are needed as inputs" Participant 33, Co-Founder

A strategy to ameliorate these risks, may involve the implementation of contractual agreements with multiple farmers that are capable of supplying sufficient quantities of the input. While this may contribute to additional costs, adopting a flexible supply base strategy can offset the risk associated with reliance on a small pool of growers(287). In addition, establishing partnerships with these suppliers can help to establish incentives to pursue novel grains as part of the growing system, particularly if economic rewards are on offer(287).

Execution risks also emerged with respect to the approach to selling novel grains through the Australian retail sector. In particular, cost pressures were identified as a significant impediment to successfully executing the adoption of novel grains into the food supply.

> *"The supermarkets are so competitive and a lot of pressure on all the suppliers, they just all want price, price, price"* Participant 39, Director

The core execution risk, however, was developing a product that would possess attributes that would be sought after by the final consumer and encourage repeat purchase behaviour.

> *"It doesn't matter how healthy it is. Doesn't matter how much it hits all of those other drivers. If that whole consumption experience is not what they expect it to be, no one will repeatedly come back to that product."* Participant 3, CEO

The execution of the product must involve the delivery of the offer that is purported through the value proposition. If the consumption of the product delivers the proposed benefits to the consumer and lives up to the consumers expectations, there is likely to be repeat purchase behaviour(288). It is vital to execute this on the first trial, otherwise consumer traction and repeat purchases will be unlikely.

Executing the incorporation of a novel grain into the food supply was also faced with the immense challenge of coordinating stakeholders and developing an understanding of the scale that stakeholders were operating at.

> *"I still don't think that that's going to be able to be done because it's individual farmers that are not delivering to a single receival point. There are as many receival points as there are farmers, which is why you can't get a grasp on supply…There's no coordination"* Participant 9, Senior Program Manager

This lack of coordination extended throughout the ecosystem, where expertise was in abundance, but not appropriately connected.

> *"…it's challenging to coordinate everybody, from the growers all the way through to the consumers…we don't have enough people that are experienced entrepreneurs to be able to try and bring that together. We have people that are great and very informed and knowledgeable in their own areas."* Participant 1, Senior Director

This issue was augmented through the inability of smaller stakeholders to coordinate with key stakeholders that could assist in delivering valuable information.

"But I don't know anything about the wider food industry and I don't know anyone in the research, so it's just about knowing, you know, knowing who has the knowledge or the capabilities that you need to access to be able to do something." Participant 14, Director

It appeared that the ecosystem would benefit from knowledge brokers that were capable of bridging across domains to share critical insights[289]. The fragmented nature of the ecosystem therefore presents novel opportunities for stakeholders with these boundary spanning capabilities[290] to offer innovative solutions that could assist in overcoming the challenge associated with executing the incorporation of novel grains into the food supply. Despite being crucial to understand, execution risks do not consider the broader set of risks that may emerge when an innovation is required to pass through multiple stakeholders across the ecosystem before being delivered to market. Co-innovation risk and adoption chain risk capture the risks faced by ecosystem partners.

3.4.2.2 Co-Innovation Risk

Co-innovation risk captures the requirement for other innovations to be implemented in order for the incorporation of novel grains into the food supply to succeed. As an example, product manufacturers may identify specific attributes of sorghum or quinoa that would enhance the value proposition for a product containing these grains.

"It would be desirable to research specific seed varieties and understand their nutritional composition. This would provide the scope to pursue particular varieties that have particular properties that could be leveraged to generate products with desirable nutritional attributes." Participant 29, Senior Plant Breeder

Grains with these attributes may not currently be in mainstream circulation, requiring collaboration of seed breeders to engage in innovative activity to develop these varieties for farmers to then grow. Without collaboration from stakeholders that have expertise in the breeding of seed varieties, the grain that is produced may not be suitable for the development of products and curtail any path to market.

In addition, co-innovation would be necessary to develop appropriate quality standards that captured the quality traits of these grains that aligned with the desires of product manufacturers.

> *"…get some sorghum and try it out in a whole heap of different recipes and find out exactly what you wanted and then once you've figured out that then you would go back to develop a standard which would say okay well we want sorghum with this sort of grain size, this kind of tannin content…"* Participant 35, Technical Services & Quality Manager

Ideally these quality standards would be developed in consultation with manufacturers and processors in order to correlate the standards with commercially relevant attributes[(291)]. Colour attributes were proposed, however this was identified as being risky for an incumbent player and had a greater likelihood of being pursued by a smaller processor that was looking to differentiate themselves.

> *"…there are objective colour standards. So it's possible, but again, it's a risk that GrainCorp probably wouldn't take, but a smaller processor might be prepared to take to us this subjective colour assessment if that's what they were really interested in and prepared to pay for"* Participant 12, Senior Research Fellow

Once quality standards are established, there would also need to be an incentive for farmers to incorporate them into their growing systems.

> *"…it's highly likely that they won't pay more for that, they'll just pay less if you don't meet that standard. So you're not actually paying a premium, you're actually giving a discount."* Participant 12, Senior Research Fellow

In the absence of price segregation that aligns with quality standards, there is no incentive for farmers to invest resources to produce a crop that would be regarded as higher quality[(140)].

Co-innovation risks were also identified in relation to retaining attributes that were seen as being desirable by downstream stakeholders. For example, in order to leverage the gluten-free status of both sorghum and quinoa, processors must ensure that their factories are not susceptible to contamination from gluten containing ingredients.

> *"The issues for us to use sorghum, are the cross-contact you would have in our factory and the capital that would be required to make a factory. Or we would have to build a whole other section that would guarantee that is not contaminated with bits of wheat flour or barley or whatever…"* Participant 20, R&D Manager

"In order to get it into a flour, most millers are set up to be able to do wheat, which is softer. The other thing that you've got is that you've got the gluten contamination and non-gluten contamination. So you literally have to have a specific system that won't allow you to do anything that's got gluten." Participant 24, Senior Food Science Liaison

In this example, the co-innovation risk corresponds to the ability of these stakeholders to develop an innovative approach to preserve the ability to make gluten-free claims about particular ingredients. Innovative methods to process the grain were also identified as a requirement to overcome challenges associated with their inherent composition.

"It'd [sorghum] be too hard. You can't just put the grain in there because you'd get complaints because of teeth." Participant 39, Director

Without co-innovation in processing methods, it may not be possible to develop feasible products. Furthermore, the lack of R&D capabilities in Australia may form a barrier to effective product development.

"…the big processors mostly have their R&D strength offshore in the US or Switzerland or wherever it might be. So that's where I think we might miss out a little bit in Australia for some of the local innovation in some of those companies…we just don't have the science available to us at the moment and I think there's a big gap in research capacity and people to be able to move that technology forward…the only way to address that is for Australia to build its capacity and produce more food technologists who can solve those problems" Participant 8, Director of Research Centre

The absence of Australian R&D can in part be attributed to the dearth of skilled food technologists(292). Despite the shortage of these individuals and associated R&D capabilities, there may be scope to adopt practices from other industries (for example pharmaceuticals) where the locus of innovation is shifting from in-house R&D to strategic alliances(249) and more broadly, open innovation(210). Empirical evidence also suggests that collaboration between university institutions (capable of doing basic science research) and commercial players can foster the development of capabilities to drive innovation through access to skilled labour, development of networks and associated absorptive capacity(293).

"But for a processor to invest in that, it'd need to be something which is pretty close to market for them to invest" Participant 8, Director of Research Centre

In other words, solutions revolve around deeper engagement with research institutions to leverage their capabilities in order to conduct work that would not be commercially viable for a private company. Moreover, Sarkar and Costa[208] argue that the tendency for firms to engage in R&D may be contingent on the position of their innovation effectiveness curve (an indication of the marginal return on additional R&D investment). If the costs involved in developing a new product were expected to outstrip potential sales revenue, it would be very difficult to justify the investment in such a product. It has also been touted that small and medium-sized enterprises (SMEs) may have a role to play in identifying commercial opportunities in the business ecosystem. The key challenge for these entities is the perceived lack of funding to conduct internal R&D, which could hamper their ability to process novel grains into value-added products, particularly when there are limited connections to better resourced partners[62].

From a product development perspective, it was recommended that innovative strategies would have to be developed to ensure that certain nutritional attributes of a novel grain were retained.

> *"...high temperature, high pressure extrusion cooking, it's really hard not to completely destroy the properties of the sorghum that differentiates it from most other grains."* Participant 11, Assistant Professor

The co-innovation challenge lies in the ability of ecosystem stakeholders to adopt processing methods that can retain the unique properties of the grain. Furthermore, stakeholders revealed that processing was a genuine challenge due to the differences between incumbent grains (such as wheat) and novel grains.

> *"There's a bit of an art to it and a bit of a trade secret around how they do that because this is all part of the – why they're very quiet about it. Whereas if you get a book on how to mill wheat flour, it will probably tell you A to Z how to do it"* Participant 24, Senior Food Science Liaison

Furthermore, stakeholders suggested that data pertaining to the potential substitution of sorghum for incumbent ingredients would be required to facilitate co-innovation in product development.

> *"...trying to come up with some basic classifications as to what is required for bread making and other products using sorghum."* Participant 36

This type of information would provide manufacturers with the agility to tweak their products in line with supply variations and demand variations.

Ultimately, co-innovation risks persist across the ecosystem and tend to be most prominent in the sphere of product development. This may be an artefact of sorghum and quinoa being novel ingredients and as a consequence, a limited degree of expertise being available to transform these grains into value-added products. The identification of co-innovation risks captures an important element of the pathway to market for novel grains and reflects the importance of having an awareness of the requirements of stakeholders across the ecosystem. Several key stages of innovation that commence with the development of suitable grain varieties and proceed through to the processing of the grain into final products have been identified. This has implications for the potential creation of value across the ecosystem.

3.4.2.3 Adoption Chain Risk

Adoption chain risk represents the risk that stakeholders positioned across the ecosystem do not adopt the initial innovation, resulting in the initial innovation not being able to deliver its full value proposition to the end use customer. The fundamental challenge in the market for novel grains is to have farmers adopt these grains into their production systems. Findings from the interviews, however, suggested that demand from downstream stakeholders would be required to motivate the farmer to grow novel grains.

> *"Growers are risk averse to planting varieties that don't have an established market"* Participant 16, Director

An additional element of adoption chain risk was the potential consequences for farmers of adopting unique grain varieties into their production system.

> *"There needs to be decent returns on the sorghum for it to be viable. If the sorghum variety for human foods had lower yields than current varieties, the price differential would have to make up for the difference."* Participant 16, Director

Economic returns remain a clear driver of adoption among farmers as well as downstream product manufacturers.

> *"There's a big cost to reformulating and why reformulate? There's got to be some massive claim"* Participant 39, Director

Consistent with previous work, product development incurs significant cost[264]. Market returns must be able to be secured[294] and there must be a significant benefit for the consumer for a reformulation to take place[295]. In the absence of these factors, the likely adoption of novel grains into production systems remains unclear.

Further challenges associated with incentivising downstream stakeholders to adopt novel grains into their production systems were identified.

> *"…the current paradigm uses certain quantities, certain processes, certain procedures and qualities around current grain. They're not interested in adjusting their grain because there's no driver to do so"* Participant 24, Senior Food Science Liaison

The key point is being able to identify a driver to change their current practices. Rather than developing creative products (e.g. never before seen products)[264], ecosystem stakeholders suggested that a more appropriate strategy might involve incorporating sorghum and quinoa into existing products.

> *"What Sanitarium have done with sorghum and weet-bix is really cool, it looks just like their normal weet-bix just made out of sorghum. The consumer is eating something familiar…"* Participant 39, Director

While this approach still requires changes to production systems, it is more attractive due to the familiarity that consumers have with the product. The risk of consumer adoption is however a significant barrier that is arguably the most important to overcome. Given the novel nature of these grains, the consumer would have to be educated to ensure they are capable of using it.

> *"…there's a lot of that old basic home economics around what's it the equivalent to, and therefore how much do you substitute for what? Is it two cups of sorghum flour to every one normal cup of self-rising flour?"* Participant 3, CEO

While the commoditisation of a novel grain such as sorghum or quinoa is more likely to occur in the latter stages of adoption, without guidance on preparation techniques, end-users may have significant difficulty in adopting the product into their diet.

Adoption chain risk will be most likely to prevail in a wholesale and retail context.

> *"The [supermarket] duopoly means that they have significant market power. If a product doesn't sell or have regular turnover within a given timeframe, it is likely that the product line will be cut…"* Participant 33, Co-Founder

In the Australian context, the retail grocery industry is dominated by two supermarket chains[296]. Being completely reliant on these retailers to stock the final product is a significant adoption chain risk that must be addressed. This is particularly relevant if the value proposition is based on attributes such as health or environmental sustainability, which tends to attract a premium price.

> *"...people that wander down the health food aisles and choose things primarily on health benefits, but if the quality is not up to standard, those guys still aren't going to be impressed"* Participant 12, Senior Research Fellow

Despite the emerging support for health trends, adoption of novel grains and their product derivatives into the diet must deliver a high quality consumption experience. Relying solely on the health attributes, or the sustainability aspect may see initial uptake, but in the absence of meeting consumer expectations for taste and quality, it cannot guarantee repeat purchase behaviour and ultimately adoption(288).

A further challenge lies in the coordination of objectives across the ecosystem.

> *"...you've got breeding companies who are breeding the particular things but drivers for breeding companies are largely around what most farmers want which usually involve improving yield and improving disease resistance. So largely there's a disconnect between what the processors might want and what the breeders are trying to deliver."* Participant 8, Director of Research Centre

This insight highlights the need to match supply with demand, which Simatupang and Sridharan(297) argue can be achieved through collaboration across the ecosystem. The deeper issue however, is the need for leadership to drive the innovation adoption process, potentially through the actions of a stakeholder with the conviction that there was value embedded in an idea.

> *"So we need people, patient investors, we need more skills, more people who can coordinate it all and we need the individual players in those industries to be able to take a punt and really buy into that opportunity for the future of their particular part of the ecosystem."* Participant 1, Senior Director

This highlights the interdependencies that innovation introduces and speaks to the notion that product innovation may also require changes to organisational processes(298). Stakeholders must be convinced that there is value in pursuing the adoption of novel grains into their systems

> *"The key thing is getting manufacturers on board. They need to be convinced that the product's going to be a winner and even then it's got to be a winner for a long time"* Participant 39, Director

This implies that an organisation may have to make changes to support an innovation, and there must be a strong enough incentive for them to do so[299].

While adoption chain risks were noted across the ecosystem, they tended to centre on the retail sector. It is conceivable that the risk incurred at this position would have the greatest impact on the market for novel grains. Without a retail market, this potential sales channel would not exist. This recognises the importance of establishing robust supply relationships that can be leveraged to distribute products containing novel grains to a large audience. The dynamics of any supply arrangement would however be contingent on broader adoption across the ecosystem, which is ultimately a function of the relative attractiveness of the innovation to stakeholders in the ecosystem.

3.5 Limitations of Research

A key limitation of the research performed across both parts of this study is the reliance on the subjective insights of interview participants to guide the analysis. To minimise the possibility of themes being missed, a wide variety of stakeholders were consulted with care taken to gain representation across the business ecosystem including crossover between areas. The primary motivation behind this work was to explore the business ecosystem for novel grains and develop an insight into the potential sources of value that could be derived. The findings that were captured could form the foundation of future empirical work to deliver additional insights into the market for novel grains. In the interim though, this work captures important perspectives into the potential value that could be created from incorporating novel grains into the food supply and the attributes of the business ecosystem that would enable this process to commence.

An additional limitation is the static nature of the exploration of the adoption pathway for novel grains. Research suggests that adoption decisions evolve as the diffusion process unfolds[221] and therefore the factors influencing early adoption may differ from those influencing later adoption. Novel grains such as sorghum and quinoa are in their relative infancy in the human food system and therefore this research sought to capture a snapshot of the diffusion process at a single point in time. Future work could extend this model to capture dynamic changes in adoption decisions over time and investigate the interplay of strategic and practical considerations when making the adoption decision.

Further limitations of this research relate to the absence of an analysis of the ecosystem governance structure. This aspect is briefly explored by identifying the farmer as a potential manager of the innovation ecosystem, but remains open to further analysis. In addition, the shifting dynamic of the business ecosystem may lead to a transition in the governance structure, whereby focal firms emerge and can take additional control of orchestrating the stakeholders across the ecosystem. The identification of a focal firm may also motivate further research that can extend the platform established in this thesis by investigating the business ecosystem shaping the activities of this focal firm.

Finally, this research is limited by the choice of case study. It is acknowledged that the selection of sorghum and quinoa as case studies captures elements specific to these grains and this may therefore limit the generalisability of the results. Despite this limitation, there appear to be similarities between other grains and those assessed here. For example, lupins have experienced a similar paradigm to sorghum while chia is more closely aligned with the experiences of quinoa. This suggests that the findings may be applicable to other novel grains in the Australian context. Future research could however further scrutinise these findings by evaluating the ecosystem for other novel grains and determining the degree to which this aligns with the case studies examined in this research.

3.6 Conclusions

The research presented in this chapter has considered the insights of stakeholders with exposure to sorghum and quinoa to inform a generalised pathway to market for novel grains. At the centre of the findings was the conceptualisation of the business ecosystem for novel grains and the range of activities that are required to transform a grain into a value-added final product. This process was underpinned by the recognition that collaboration and coordination are required to orchestrate the ecosystem in order to enable viable value propositions to materialise. A number of challenges were identified, the most intriguing being the level of change that novel grains would introduce into incumbent production systems. While the pathway to market was explored in the context of the diffusion of innovation, more research is needed to elucidate whether novel grains are accurately depicted as an incremental innovation, or whether their impact would be more disruptive to incumbent systems than first anticipated.

The scope to generate economic returns was identified as a fundamental incentive for participation in the business ecosystem. This was particularly relevant for farmers, who hold ultimate responsibility for the growing of novel grains. This positions the farmer as a vital cog in the business ecosystem. With the appropriate incentives (financial and non-financial) farmers may be motivated to take a leadership role in the ecosystem to manage the diffusion process of novel grains into the food supply. Collaborative partnerships that focus on aligning the objectives of downstream entities with the primary upstream production were identified as being part of the strategy that could deliver value and enhance the potential for broader uptake of novel grains in the business ecosystem.

Value propositions that could potentially be communicated to end customers (retail consumers) were briefly explored. These sources of value centred on the nutritional attributes, environmental sustainability and premium quality of novel grains. In addition, sources of execution, co-innovation and adoption chain risk associated with the incorporation of novel grains into the food supply were identified. The tendency for these risks to appear across the business ecosystem suggests that coordination and collaboration are required to encourage these stakeholders to pursue the adoption of novel grains into their production systems. In the absence of supportive behaviour, the successful incorporation of novel grains into the food supply is in doubt and the potential for value creation is severely hampered.

The analysis that is outlined in this Chapter sets the scene for novel grains and provides an exploratory insight into the business ecosystem that underpins their adoption into the food supply. The findings from this chapter suggest that it is clear that economic incentives must be present for farmers to consider adopting novel grains into their production systems. These incentives can be the result of consumer support and willingness to pay for a novel grain-based product filtering through to the farm-gate. One of the sources of value that consumers increasingly take notice of are the health attributes of the food they consume. There may therefore be potential value in leveraging the health attributes of novel grains and applying them into a promotional context. The important questions that arise relate to the presence of health attributes that are possessed by sorghum and quinoa and how these could be leveraged to generate a health related value proposition. This can assist in identifying potential sources of value associated with the incorporation of novel grains into the food supply.

Chapter 4: Nutritional Attributes of Sorghum and Quinoa

The majority of Part A of this chapter is the substantive content of the work, Simnadis, TG, Tapsell, LC & Beck, EJ, 2016, Effect of sorghum consumption on health outcomes: a systematic review, **Nutrition Reviews**, vol.74, no.11, pp690-707

The majority of Part B of this chapter is the substantive content of the work, Simnadis, TG, Tapsell, LC & Beck, EJ, 2015, Physiological effects associated with quinoa consumption and implications for research involving humans, **Plant Foods for Human Nutrition**, vol.70, no.3, pp238-249

Discussion relating to the comparative health effects of sorghum and quinoa was included in Simnadis, TG, Tapsell, LC & Beck, EJ, 2016, Sorghum and quinoa: health benefits and implications for future research, **American Association of Cereal Chemists Annual Meeting**, *Savannah, USA*, (603-O, Oct 24–26)

4.1 Introduction

The exploration of sources of value associated with the incorporation of novel grains into the food supply commenced in Study 1 with the application of the business ecosystem approach to conceptualise the pathway from farm to fork. Study 1 focussed on elements of strategic planning and highlighted a range of themes that may influence the scope for novel grains to diffuse across the business ecosystem. In addition, potential risks associated with the incorporation of novel grains into the food supply were identified in accordance with the value blueprint framework as execution, co-innovation or adoption chain risk. Collaboration was identified as a fundamental element of the value creation process, with economic drivers also playing a significant role in the uptake of novel grains. The research presented in Study 1 also identified the presence of an emerging value proposition related to nutritional convenience. In the context of this thesis, by exploring the nutritional attributes of novel grains and their health effects, it may be possible to identify properties that would be attractive for an end-use customer as well as stakeholders across the business ecosystem.

The research presented as part of Study 2 (Chapter 4) adopts a case study approach to systematically review the nutritional impact of sorghum and quinoa consumption. A significant body of work has investigated the effect of sorghum consumption in humans (Part A). A limited body of work has investigated the effect of quinoa consumption in humans, and as such, the effect of quinoa was limited to those studies performed with animal models (Part B). The evidence-base underpinning the reviews are critically appraised, which informs the development of conclusions regarding the nutritional properties of these two novel grains. For the purposes of this thesis, potential sources of value that can be derived from the nutritional attributes of these novel grains are discussed. This has implications for the direction of future nutrition research that is seeking to uncover health attributes that would have commercial relevance for ecosystem stakeholders. In addition, properties that align with an end-users innate concept of health may encourage the incorporation of novel grains into product formulations.

4.1.1 Evidence for Health Benefits of Grain Consumption

There is a growing body of evidence linking the consumption of grains with positive health outcomes. Recent meta-analyses have identified that the risk of coronary heart disease[300], cardiovascular disease[301] and Type 2 diabetes[302] is significantly reduced among individuals who consume at least two servings of whole grains per day compared to those that consume none. In addition, the consumption of cereal fibre has been identified as being associated with a significant reduction in total mortality[303].

While these studies present an argument in favour of incorporating more cereals and whole grains into the diet, they do not explore the nutritional efficacy associated with specific types of grain. Elucidating the nutritional attributes of specific grains may encourage stakeholders to adopt them into product formulations, particularly if they are seeking to enhance the innate nutritional capital of a food product. Moreover, processors and manufacturers are increasingly aware of the need to innovate in their product offerings to meet consumer demands and establish competitive advantages[66]. Exploring the nutritional attributes of specific novel grains may therefore contribute to the generation of a health related value proposition and enhance the value associated with their incorporation into the food supply.

4.1.2 Nutritional Properties Possessed by Sorghum and Quinoa

Sorghum and quinoa both possess a range of unique bioactive compounds that may have positive health implications. Certain varieties of sorghum are rich in proanthocyanidins, 3-deoxyanthocyanidins, and flavones[304], which have been purported to inhibit the growth of cancer cells *in vitro*[305-308] and induce anti-inflammatory effects[309] in animal models. The protein present in quinoa is considered a complete source, since unlike most other grains, it is not limited by the amino acid lysine[310-312]. In addition, the presence of saponins in quinoa has been implicated as being responsible for generating anti-inflammatory effects[313]. The attributes possessed by sorghum and quinoa may therefore provide a point of difference to other grains, which can be exploited.

While these nutritional attributes are of interest to researchers, the underlying commercial question relates to the value that these properties can impart on a food product. As outlined in Chapter 3, the pathway to market involves a complex set of interactions that are heavily influenced by economic factors. It is therefore unrealistic to expect the nutritional attributes of a grain to be the primary driver for stakeholders to incorporate them into the food supply. Nonetheless, evaluating the nutritional attributes of novel grains can still provide value, particularly in the context of this thesis, which conceptualises the incorporation of a novel grain into the food supply as an example of incremental innovation. For example, the substitution of a novel grain for an incumbent ingredient in an existing formulation may be motivated by the superior nutritional attributes possessed by the novel grain[314]. Rather than designing a study that explores a specific health attribute, the purpose of the research presented in this Chapter is to review the current evidence-base in order to identify potentially valuable nutritional attributes.

4.1.3 Previous Research Investigating Sorghum and Quinoa

Previous literature reviews that have focussed their attention on sorghum have directed their efforts to the exploration of specific compounds, such as phytochemicals[315, 316], the effect of processing on grain composition[317] and the nutritional implications of specific compounds[71, 318]. Similarly, reviews synthesising the literature surrounding quinoa have focussed on the nutrient composition[319, 320], and the functional potential of quinoa in the human diet[52]. There is therefore a paucity of systematic research investigating the nutritional attributes of sorghum and quinoa and the potential implications this has for value creation in the food supply.

4.1.4 Organisation of Research Pertaining to Study 2

Two separate systematic literature reviews that explore the nutritional attributes of sorghum and quinoa will be performed in Part A and Part B respectively. The nutritional attributes will be evaluated in the context of the health effects they impart upon their respective study populations. The impact of sorghum consumption will be reviewed among human participants. Due to the paucity of human studies investigating the health effects of quinoa, the impact of quinoa consumption will be reviewed within animal studies. By exploring the nutritional attributes of sorghum and quinoa, this research can highlight the functional characteristics of these grains and outline the nutritional attributes that may be appealing to stakeholders in the food industry.

Study 2 Part A – Systematic Review of Nutritional Attributes of Sorghum

4.2 Method to Review Nutritional Attributes of Sorghum

The systematic literature review of sorghum studies was performed according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines[191]. The protocol, including search strategies, inclusion criteria, quality assessment and method of analysis were registered with the International Prospective Register of Systematic Reviews (PROSPERO) (http://www.crd.york.ac.uk/PROSPERO), registration number CRD42015024024 prior to commencement.

4.2.1 Inclusion and Exclusion Criteria

The eligibility criteria were determined prior to the commencement of the search so as to minimise any bias in inclusion and exclusion of studies. Studies that explored an association between sorghum consumption and health outcomes in humans were considered. A health outcome was defined as a measurable effect on a biologically or physiologically relevant parameter in humans. This could include (but was not limited to) the impact of sorghum consumption on disease biomarkers, anthropometric measures, mortality and morbidity. The definition did not include bioavailability or digestibility of nutrients from sorghum. Studies investigating these characteristics were excluded from the review. A summary of the participants, interventions, comparisons, outcomes and study design (PICOS) criteria is presented in **Box 4.1**.

Original research published in the English language after January 1985 was included. Articles were excluded if they did not appear in a peer-reviewed journal or if they were review articles or conference abstracts. A single author (TS) conducted the search and selected the articles.

Box 4.1 PICOS criteria for inclusion and exclusion of studies

Parameter	***Description***
Population	Males and females of any age, health status, socioeconomic status and geographic location
Intervention/exposure	Consumption of sorghum in its raw form (grain sorghum), processed form (refined, milled, cooked etc), extracted form (such as the germ or endosperm), or included as an ingredient in a food product
Comparison	Control/comparison groups that did not consume sorghum. If the control/comparison group was exposed to an alternative source of nutrients (e.g. in an intervention study), these nutrients must have been in the form of a 'food' to enable valid comparisons to be made
Outcomes	Effect of sorghum on health outcomes
Study Design	No restrictions on the study design

4.2.1.1 Intervention/Exposure

To be eligible for inclusion, at least one group of participants within the study must have been consuming sorghum as part of the diet. The sorghum could be present in native form (grain sorghum), processed form (refined, milled, cooked etc.), or extracted form (such as the germ or endosperm), or included as an ingredient in a food product. Studies were excluded if a range of foods (including sorghum) were included as part of the intervention diet, unless the effect of sorghum could be separated from the effect of the other factors in the diet.

4.2.1.2 Comparison Group

The study was excluded if the control group was also exposed to sorghum, unless one of the following was applicable:

1) The study had a crossover design with 2 distinct periods (1 in which sorghum was included in the diet and 1 in which it was absent from the participants' diet); or
2) The study was an observational study that made between-group comparisons on the basis of the frequency of and/or the quantity of sorghum consumption or

compared a pre-test (prior to sorghum consumption) period with a post-test (after sorghum consumption) period.

If the control/comparison group was exposed to an alternative source of nutrients (for example in an intervention study), these nutrients had to be in the form of a 'food' to enable valid comparisons between control group and the intervention/sorghum group.

4.2.1.3 Study Design

Experimental and observational studies conducted over all time frames were considered.

4.2.2 Search Terms and Strategy

The following search terms were used: "sorghum", "human", "health", "diet", "benefit", "subject" and "intervention". Combinations of these terms were joined with the Boolean operator 'AND' to identify relevant articles during the search phase, performed in October and November 2015. The same set of search terms was used to identify relevant articles in the following databases: Agricola, Cambridge Journals Online, Cochrane Library, CINAHL, MEDLINE, PubMed, SAGE Journals Online, Science-Direct, Scopus, SPORTDiscus, Springer Link, Web of Science and Wiley Online.

Initially, one author screened the titles of the articles for inclusion. The abstracts of potentially suitable articles were then reviewed. The full text of each potentially eligible article was retrieved and saved for further analysis. After two authors assessed the full text independently, articles were either included in the review or excluded on the basis of the predefined criteria. The reference lists of the articles included for review were also examined for additional articles, which assessed using the same eligibility criteria.

4.2.3 Data Extraction

Intervention and observational studies were summarised separately. Study design, participant characteristics, country in which the study was performed, health outcomes, main findings and study quality were included in the summary tables. Both the control diet and the intervention diet were reported for intervention studies. Inclusion criteria and the method used to assess dietary intake were reported for observational studies. For studies that met all eligibility criteria, the necessary data were extracted into one of the aforementioned tables by one author (TS) and then verified by a second author (EB).

4.2.4 Quality Assessment

Two approaches were used for quality assessment. First, the design of each included study (e.g. randomised control trial, case-control study, or cohort study) was identified and recorded. The National Health and Medical Research Council levels of evidence criteria[190] were then used to assign a ranking to each of these studies. Next, the internal validity and the risk of bias among individual studies were assessed using the Health Canada quality appraisal tool[192].

This tool enables intervention and observational studies to be assessed separately, with a possible score of 0 to 15 generated for intervention studies and 0 to 12 for observational studies. A point was scored for each 'yes' response to the equally weighted questions that comprise the tool. Studies that scored at least 8 of 15 and 7 of 12 for intervention and observational studies, respectively, were high quality, while those scoring below these thresholds were low quality. Intervention studies were assessed on the basis of inclusion/exclusion criteria, group allocation, blinding, attrition, exposure/intervention, health effects, statistical analysis and potential confounders. The same set of criteria, apart from group allocation and randomisation, was assessed for observational studies. Instead, the quality appraisal tool for observational studies assessed the comparability of study groups at baseline.

The criteria included in the Health Canada tool were grouped together under the broad categories of "reporting" and "internal validity". The categorisation of criteria as either reporting or internal validity was guided by existing quality rating tools, such as the study quality checklist developed by Downs and Black[321], which provides clear guidance about which criteria should be incorporated into these categories. Furthermore, the distinction between reporting and internal validity provided a transparent overview of the key elements that underpin the quality of individual studies and enabled comparisons to be made across studies and, more broadly, across the body of literature.

Finally, the composition of sorghum was considered. Plant foods are known to differ in their nutritional composition because of genetic and environmental factors[(322)]. This may result in different health outcomes because of the varying composition of sorghum used in each individual study. Additionally, the degree of processing and the consumption of certain components of the grain may also have varying effects on health outcomes[(317)]. Thus, the variety of sorghum used in the study, the type of processing (if any) of the grain, and whether a chemical analysis of the grain (to determine nutritional composition) was performed were all reported. These factors provide a means of exploring the quality of the reporting in relation to the composition of sorghum used in each study (**Table 4.1**).

Table 4.1 Questions and potential responses to assess reporting of the composition of sorghum

Category	***Question***	***Response***
Sorghum Variety	Was the variety specified?	Yes/No
	If yes, what was the variety?	Variety
Processing	Was the sorghum processed?	Yes/No/Not reported
	If yes, how?	Processing technique
Chemical Analysis	Was a chemical analysis performed?	Yes/No/Not reported
	If yes, are the results reported?	Yes/No/Not applicable

4.2.5 Method of Analysis

Because of the range of health outcomes being assessed, it was not possible to perform a meta-analysis. Instead, broad patterns were observed and used to group together specific health outcomes associated with the consumption of sorghum, such as chronic disease prevention. The data generated from studies investigating similar outcomes were synthesised at a group level rather than an individual level. These results were examined from a qualitative perspective, although the analysis incorporated quantitative estimates for studies that reported estimated effect sizes. Characteristics of the sorghum product that may have influenced health outcomes (such as processing), as well as compounds that may have been potentially responsible for generating these effects, were also explored in detail. Studies that were rated of higher quality (on the basis of the Health Canada appraisal tool) guided the discussion and underpinned the formulation of recommendations for future research.

4.3 Results

4.3.1 Article Identification Process

The systematic searches of the scientific databases resulted in the retrieval of 1782 articles. After screening and eliminating articles that did not meet the eligibility criteria, 15 articles were included in the final review (**Figure 4.1**). The reference lists of included articles were searched manually, resulting in 4 additional articles that met the eligibility criteria. The combination of electronic and manual searches led to the inclusion of 13 intervention studies and 6 observational studies.

4.3.2 Quality Assessment

Using the Health Canada Quality Appraisal tool, the quality of the intervention and observational studies was summarised in descending order (**Table 4.2** and **Table 4.3** respectively). The overall scores for intervention studies ranged from 4 (low) to 12 (high), with the average being 7.5 (low). The overall scores for observational studies ranged from 3 (low) to 9 (high), with the average score being 7 (high). More broadly, 11 studies were classified as high quality, with the remaining 8 being of low quality. Among intervention studies, the scores obtained in the reporting component were generally superior to the internal validity scores, while the scores for these components among the observational studies were equivalent.

Information relevant to the composition of sorghum was poorly reported, with fewer than one-quarter of the studies stating the variety of sorghum used in the study and fewer than one-third performing an analysis of the composition of the grain (**Table 4.4**). Processing of sorghum was reported in 12 of the 19 studies, with all but 1 of these 12 also stating the processing method.

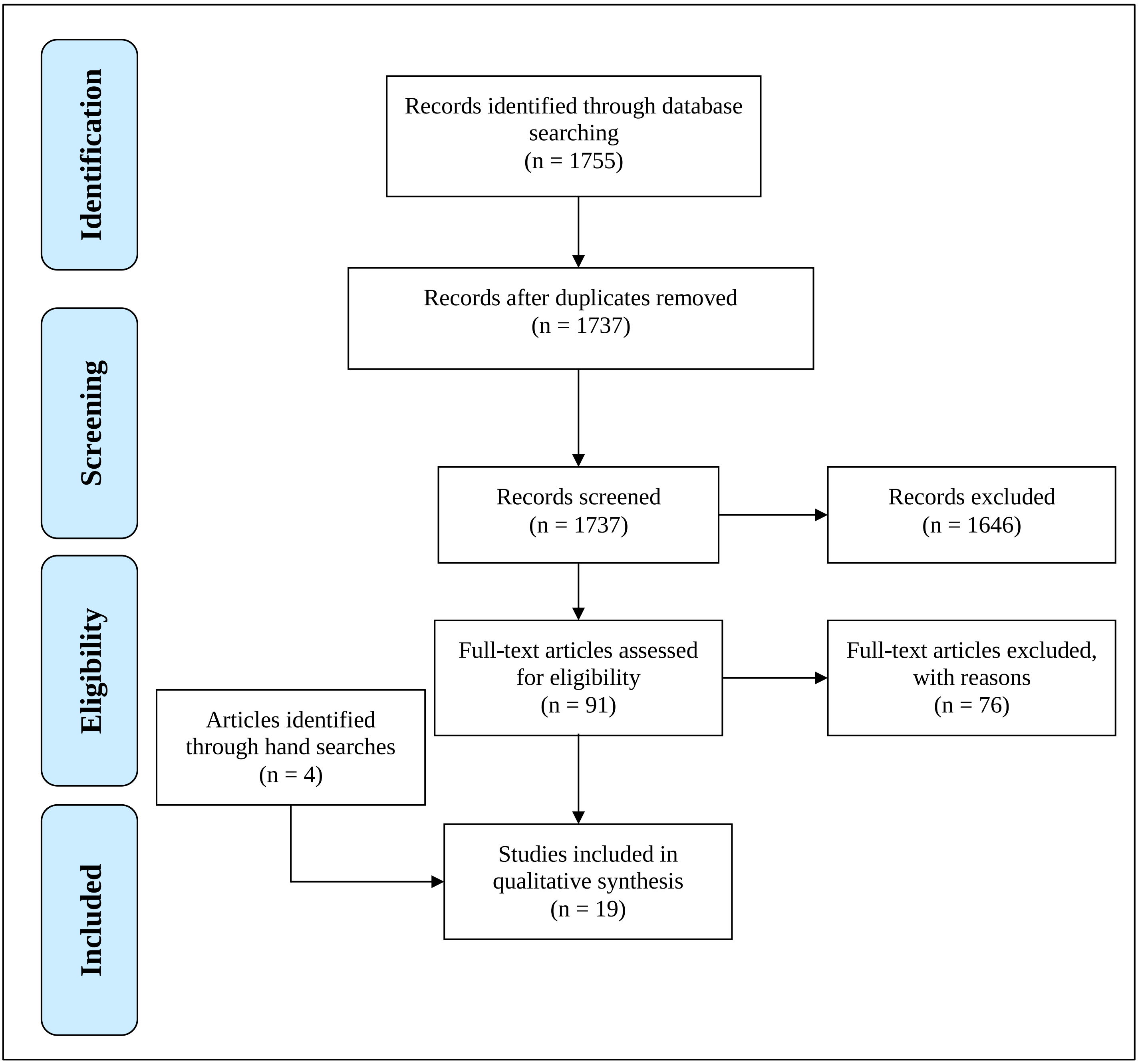

Figure 4.1 PRISMA Flowchart

Table 4.2 Summary of the overall quality of intervention studies (high or low), classification of study design as per National Health and Medical Research Council (NHMRC) level of evidence guidelines, and the scores associated with reporting, internal validity and overall study quality. The average scores for these components across all intervention studies are provided for comparison.

Reference	***Quality***	***NHMRC Level of Evidence***	***Reporting score (n/8)***	***Reporting (%)***	***Internal validity score (n/7)***	***Internal validity (%)***	***Total Score (n/15)***
Khan *et al.*[323]	High	II	8	100	4	57	12
Molla *et al.*[324]	High	II	7	88	3	43	10
Kenya *et al.*[325]	High	II	7	88	2	29	9
Mustafa *et al.*[326]	High	II	6	75	2	29	8
Abdelgadir *et al.*[327]	High	III-2	5	63	3	43	8
Poquette *et al.*[328]	High	III-2	5	63	3	43	8
Prasad *et al.*[329]	High	III-2	5	63	3	43	8
Lepage *et al.*[330]	Low	II	5	63	2	29	7
Pelleboer *et al.*[331]	Low	III-2	6	75	1	14	7
Mani *et al.*[332]	Low	III-2	4	50	2	29	6
Ayuba *et al.*[333]	Low	II	3	38	2	29	5
Prasad *et al.*[334]	Low	II	5	63	0	0	5
Lakshmi and Vimala[335]	Low	III-2	2	25	2	29	4
Average	**Low**	**-**	**5.2**	**65**	**2.2**	**32**	**7.5**

Table 4.3 Summary of the overall quality of observational studies (high or low), classification of study design as per National Health and Medical Research Council (NHMRC) level of evidence guidelines and the scores associated with reporting, internal validity and overall study quality. The average scores for these components across all observational studies are provided for comparison.

Reference	***Quality***	***NHMRC Level of Evidence***	***Reporting score (n/6)***	***Reporting (%)***	***Internal validity score (n/6)***	***Internal validity (%)***	***Total Score (n/12)***
Zheng *et al.*[336]	High	III-2	4	67	5	83	9
Sewram *et al.*[337]	High	III-2	5	83	4	67	9
Gao *et al.*[338]	High	III-2	4	67	4	67	8
Foltz *et al.*[339]	High	III-2	4	67	4	67	8
Ciacci *et al.*[340]	Low	IV	2	33	3	50	5
Tumwine *et al.*[341]	Low	III-2	2	33	1	17	3
Average	**High**	**-**	**3.5**	**58**	**3.5**	**58**	**7**

Table 4.4 Summary of the frequency with which included studies reported information pertinent to the composition of sorghum

Reporting criteria	*Number of studies that reported (n/19)*	*Proportion of studies that reported (%)*
Sorghum variety[a]	4	21
Grain processed (method of processing[b])	12 (11)	73 (92)
Performance of a chemical analysis[c]	6	32

[a] Varieties included: red, red (tannin free), white (tannin free), narango, serena, bari, diri and M35-1
[b] Refers to the number of studies that reported the processing method (e.g. milling, boiling etc) among those that reported that the sorghum had been processed
[c] All studies that reported performing a chemical analysis also published the results from these analyses

4.3.3 Data Extraction

The range of health outcomes assessed included the effect of sorghum consumption on blood glucose responses (5 studies), oral rehydration (5 studies), cancer (3 studies), a condition known as 'nodding syndrome' that affects children (2 studies), growth (1 study), immune function (1 study), oxidative stress (1 study) and coeliac disease (1 study). These studies were categorised dichotomously (**Table 4.5**) as studies investigating:

a) Health outcomes associated with chronic diseases, such as type 2 diabetes and cancer, and
b) Other health outcomes associated with sorghum consumption e.g. treatments for conditions such as dehydration

Table 4.5 Categorisation of outcomes identified through the systematic review

Chronic Disease Prevention	*Other Health Outcomes Associated with Sorghum*
Blood Glucose Responses	Oral Rehydration
Cancer	Nodding Syndrome
Oxidative Stress	Immune Function
	Growth
	Coeliac Disease

4.3.3.1 Health Outcomes Associated with Chronic Disease

Of the studies that investigated the effect of sorghum consumption on blood glucose responses, three were of high quality and two of low quality. After consumption of sorghum, glucose and insulin responses were decreased by up to 26% and 55% respectively[(328)], compared with responses after consuming control foods such as wheat, maize or rice. In addition, the glycaemic index and glycaemic load of sorghum-based foods (apart from sorghum roti) were lower than those of equivalent wheat-based foods[(329)].

Three high-quality case-control studies investigated the risk of oesophageal, oral and gastric cancers associated with dietary and lifestyle factors. The purpose of these studies was to identify factors that appeared to impart risk or protection, with the findings proving to be highly inconsistent. The results corresponding to sorghum consumption (after adjusting for potential confounders such as age, tobacco use and alcohol use), suggested that individuals consuming the highest quantity in a cohort from Shanxi province in China were up to 5% less likely to develop oesophageal cancer[(338)], while individuals in the Eastern Cape of South Africa were 54% more likely to experience this outcome[(337)]. Risk of gastric cardia cancer increased by 1% for those consuming sorghum, while risk of gastric noncardia cancer decreased by 12% (gastric cardia cancer occurs at the point where the oesophagus connects to the stomach [cardia], while gastric noncardia cancer is found in all other areas of the stomach)[(338)]. Finally, sorghum consumption was associated with a 65% increased risk of oral cancer among hospitalised patients in Beijing[(336)].

Another study of high quality explored the impact of tannin free sorghum on markers of oxidative stress. Two hours after the consumption of pasta containing 30% red sorghum, a 24% increase (compared with baseline) in the level of plasma polyphenols was recorded[(323)]. In contrast, the consumption of wheat pasta generated a 1% decrease in plasma polyphenols over this same time period[(323)]. In addition, a 34% increase in superoxide dismutase activity was recorded after the consumption of red sorghum pasta, compared with an increase of 0.7% after the consumption of wheat pasta. Finally, a marker of protein oxidation, protein carbonyl, decreased by 26% after red sorghum consumption, but increased by 8% after wheat pasta consumption.

4.3.3.2 Other Health Outcomes

Three high quality and two low quality studies assessed the efficacy of using sorghum as part of an oral rehydration solution (ORS) for children with acute diarrhoea. Compared with children treated with the standard World Health Organisation (WHO) ORS, children treated with sorghum ORS consumed between 16%[(330)] and 42%[(324)] less ORS in the first

24 hours. This relative decrease in intake persisted over the entire period that children were treated with ORS. Treatment with sorghum ORS also decreased stool output by up to 40%[330] in comparison with the WHO ORS treatment and decreased the average duration of diarrhoea.

A high quality case-control study conducted in Uganda[339] and three separate low-quality case-control studies (results were pooled) conducted in South Sudan[341] attempted to identify underlying risk factors for the onset of nodding syndrome; a rare condition that affects the physical and neurological development of children and is characterised by paroxysmal episodes of 'head nodding'[339]. In Uganda, the consumption of red sorghum was associated with a 40% increased risk of nodding syndrome, but this was not statistically significant[339]. The consumption of the serena variety of sorghum in South Sudan was associated with a statistically significant five-fold increased risk of nodding syndrome[341]. There did not appear to be a statistically significant effect of consuming any other variety of sorghum in the same population group[341].

Immune function in HIV-positive patients, growth among children and safety for individuals with coeliac disease were assessed in three separate low quality studies. The consumption of a traditional preparation of sorghum (Jobelyn) in conjunction with antiretroviral therapy augmented the increase in CD4+ T-cell counts beyond the increase seen with antiretroviral therapy alone[333]. The supplementation of traditional diets with sorghum was associated with an increase in height and weight among female children but no discernible differences among male children[334]. Finally, it was established that sorghum was a safe alternative for patients with coeliac disease, with no gastrointestinal or non-gastrointestinal symptoms observed after consumption[340].

4.3.4 Data Presentation

A summary of intervention and observational studies exploring the effect of sorghum consumption on outcomes associated with chronic disease is presented in Appendix 4-A. Appendix 4-B presents a summary of intervention and observational studies that explore other health outcomes associated with the consumption of sorghum in the human diet.

4.4 Discussion

4.4.1 Health Outcomes Associated with Chronic Disease

The review of the literature suggests sorghum possesses nutritional properties that could facilitate a role in the management of chronic diseases. The favourable glycaemic responses induced by the consumption of sorghum were similar in magnitude to the relative glucose attenuation induced by grains rich in β-glucan, such as oats and barley(342). This has implications for food manufacturers and their choice of ingredients when products are developed for consumers who display health conscious behaviours. In contrast, evidence from studies investigating a relationship between sorghum consumption and the risk of gastric and oesophageal cancer, estimated to be responsible for 14% of global cancer deaths annually(343) is ambiguous. There appeared to be a stronger relationship between the consumption of sorghum and a reduction in the expression of markers of oxidative stress. Similar effects have been noted after the consumption of plant foods, such as fruit and vegetables(344) suggesting that sorghum may possess functional bioactive compounds that can impart health benefits.

The mix of research described in this review was further scrutinised to identify the manner in which health benefits from consumption of sorghum appear to be maximised. In particular, factors that may have influenced outcomes, such as degree of processing, food composition, dose, and exposure time, need to be explored, as these variables have implications for manufacturing and for generation of health benefits.

4.4.1.1 Blood Glucose Responses

4.4.1.1.1 Food Type, Nutritional Composition and Processing

The consumption of sorghum, irrespective of whether it was consumed as part of traditional foods, such as flat bread, porridge, dhokla and roti, or as foods more commonly consumed in the Western diet, such as pasta, biscuits and muffins, consistently attenuated blood glucose responses. This suggests that the matrix of nutrients present within sorghum remains active even after the grain is processed.

The favourable glycaemic responses may have been facilitated by the presence and digestibility of starch. Previous *in vitro* research showed a reduction in starch digestibility of flat breads prepared from sorghum[345] and an inverse correlation between starch digestibility and the sorghum content of pasta[346]. Levels of slowly digestible and resistant starch were higher in muffins prepared from sorghum than in wheat muffins and may have contributed to the attenuation of blood glucose and insulin responses[328]. Assessments of the starch content were absent from other reviewed studies. This should be addressed in future research in order to establish how starch present within the matrix of the grain may affect glycaemic responses.

The elevated dietary fibre content of sorghum (compared with that of wheat[329, 335], rice[329, 335] and maize[327]) may also have contributed to the observed glucose and insulin responses. An inverse relationship between dietary fibre content and glycaemic response was apparent in 2 studies[329, 335]. This association was absent when sorghum was compared with millet (*Panicum miliaceum*), which had less dietary fibre than sorghum but induced more significant improvements in blood glucose and insulin responses[327]. This suggests that other compounds present in the grain, such as polyphenols, (found in high concentrations in millet and sorghum[347]), and protein, may have affected glycaemic outcomes[348]. Despite this, the presence of these compounds was not evaluated in any studies investigating glycaemic responses and should be explored in future research.

Factors such as the ratio of amylose to amylopectin, the degree of starch gelatinisation, and particle size are known to influence glycaemic responses and have been shown to vary between whole and refined grains[349]. This was reflected by the consumption of whole grain sorghum generating smaller net changes in blood glucose responses than products made from dehulled sorghum, wheat or rice[335]. Similarly, muffins prepared from whole grain sorghum significantly decreased the glucose and insulin responses compared with whole grain wheat muffins[328]. It would be advisable for future studies investigating glycaemic responses to report the degree of processing the grain has undergone in order to evaluate the effect of processing on glycaemic responses.

The favourable glycaemic responses attributed to the consumption of sorghum suggests that the release of glucose into the bloodstream is more gradual. This is supported by the glycaemic index of sorghum-based foods which ranges from 45 for sorghum poha[329] (a dish of flattened, flaked grain) to 77 for roasted sorghum bread[332]. These values were superior to those of the corresponding control meal and provide further evidence that the matrix of nutrients present within the grain may play a synergistic role in generating positive outcomes. Future research should build on this evidence by focussing on the effect of sorghum consumption on satiety, which has been articulated by traditional sorghum consumers in Africa[(315)], but has yet to be scientifically validated.

4.4.1.1.2 Study Designs

Means of determining the serving size of sorghum-based and control meals varied from matching on the basis of carbohydrate content[(327, 332, 335)] to matching on a mass basis[(329)]. Although the comparison of the glycemic responses to foods with an equivalent carbohydrate load provides more robust scientific evidence at the population level, it is conceivable that individuals would be more likely to consume or substitute foods on a mass basis. Sorghum appeared to generate superior glycemic responses to wheat when equivalent serving sizes were consumed[(329)]. This has implications for future research methods and the translation of results to a broader population level.

An absence of standardisation in the number of time intervals and overall timeframe used to calculate the incremental area under the curve values is likely to explain part of the variability in the magnitude of blood glucose responses seen across the literature. Despite this heterogeneity, the results consistently showed that the consumption of sorghum induced smaller peaks[(327, 328, 332, 335)] and smaller overall changes[(327, 328)] in blood glucose responses than did the consumption of control foods.

4.4.1.1.3 Study Populations

The attenuation of blood glucose responses was observed in healthy subjects[(328)] as well as in those with Type 2 Diabetes[(327, 332, 335)]. The observation of these positive outcomes across these population groups suggests the consumption of sorghum could contribute to health benefits for a wide range of individuals. Specifically, substituting sorghum for currently popular dietary grains such as wheat, rice and maize may lead to more favourable control of blood glucose and insulin. This has implications for researchers and food manufacturers alike.

4.4.1.2 Cancer

4.4.1.2.1 Compounds Relating to Cancer

Research in animal and *in vitro* models has shown that polyphenolic compounds present in whole grain sorghum can inhibit the proliferation of breast cancer cells[307, 308] and gastrointestinal cancer cells[350]. The three case-control studies investigating gastric, oral and oesophageal cancer did not specify whether whole or refined sorghum was consumed[336-338]. This may have contributed to the variability in cancer outcomes, particularly if some patients consumed whole grain sorghum, potentially rich in polyphenols while others consumed refined sorghum, devoid of such compounds.

The relative abundance of these polyphenols also depends on both environmental and genetic factors[315], which varies depending on the geographical origin of sorghum. The case-control studies were conducted in China[336, 338], and South Africa[337], which suggests that different varieties of sorghum with unique nutritional compositions were consumed by the populations under study. Without a detailed chemical analysis, it is impossible to know the nutritional composition and associated phytochemical content of the specific sorghum consumed. Future work should endeavour to characterise the phytochemical composition of the sorghum used in a study in order to gain insight into the potential role of the specific compounds present.

4.4.1.2.2 Study Designs

There appeared to be an inverse relationship between frequency of sorghum consumption and risk of oral[336] and oesophageal cancer[337], particularly among females[337]. It is not possible to ascertain the quantity of sorghum needed to achieve a reduction in risk, since these studies focussed on the frequency of sorghum intake, rather than the quantity. Despite this, frequency was not measured in a uniform manner, ranging from daily, monthly or 'staple' consumption[338]. A definition of 'staple' was not provided, and thus it is conceivable that the ambiguity associated with this term led to inconsistent interpretations by study participants. This may have resulted in vastly different sorghum consumption levels being combined, decreasing the precision of estimates linking sorghum consumption to cancer outcomes.

A potential weakness of the case-control studies, as well as a potential reason behind the ambiguous results, was the reliance on self-reported dietary consumption and time lag between actual consumption and data collection (up to 15 years)[338]. Dietary intake was collected through a food frequency questionnaire[336], validated by the Chinese Institute of Nutrition, or estimated through interviews conducted by nursing staff[337, 338]. Since the cancer had already been diagnosed, retrospective questionnaires provided the solitary means of ascertaining dietary consumption prior to the onset of the cancer. Although the interviews were structured to allow nursing staff to conduct them, it is conceivable that employing trained dietitians would have generated richer information, such as the consumption method (porridge, flat bread etc) and quantity of sorghum consumed. This information would have provided insight into historical food consumption, which has particular relevance for sites such as the stomach, mouth and oesophagus, which are directly exposed to food and the associated nutrients on a regular basis.

The adjustment for confounders such as tobacco smoking and alcohol consumption provides a degree of assurance that the resulting empirical results were robust. However, because of the observational, rather than experimental design of these studies, it is impossible to infer a cause and effect relationship between sorghum consumption and cancer outcomes. Moreover, the consumption of other grains such as wheat, rice or millet was not associated with a change in cancer risk[337], suggesting that grains may not play a significant role in the aetiology of cancers of the stomach and oesophagus. Instead, it was shown that a healthy dietary pattern comprised of sorghum, green leafy vegetables, green legumes, fruit and meat had a protective effect against oesophageal cancer, particularly in females[337]. This reflects the importance of understanding that dietary risk factors are more appropriately analysed in the context of whole diets rather than individual foods.

4.4.1.2.3 Study Populations

The relatively large samples recruited for entry into these case-control studies suggest that the findings would be quite robust. However, the total number of individuals consuming sorghum within these studies was quite small when compared with the size of the overall sample. This may explain the wide confidence intervals in these studies. It also reflects the challenge in assessing the effect of sorghum consumption on cancer outcomes, namely the difficulty in finding population groups that have consumed the grain on a regular basis.

The role of sorghum in the aetiology of stomach, oral and oesophageal cancer is remains unclear. Further understanding could be gained through research that explores the mechanistic basis behind purported effects in both animal and *in vitro* models. Concurrently, the incidence of cancer in population groups known to consume sorghum should be monitored over time (longitudinal studies) to provide insight into potential protective effects.

4.4.1.3 Oxidative Stress

4.4.1.3.1 Bioactive Compounds

Elevated levels of free radicals in the human body contribute to oxidative stress, which has been implicated in the onset of cancer, arthritis and degenerative diseases[344]. Compounds with antioxidant activity properties provide protection against these free radicals, with whole grain sorghum, particularly the red, brown and black varieties, being rich sources of phytochemicals that have antioxidant activity[315]. Pasta with a red sorghum content of 30% was shown to have a phenolic content approximately four-fold higher than pasta prepared from wheat. Consumption of this pasta generated a significant reduction in oxidative stress, which is likely attributable to this elevated phenolic content[323]. Future research should focus on identifying these phenolic compounds in order to gain a deeper understanding of their bioactivity and potential functionality when incorporated into food products.

4.4.1.3.2 Study Design

The randomised control trial of Khan *et al.*[323] provided compelling evidence that the consumption of tannin free red sorghum decreased the expression of markers of oxidative stress. Moreover, the crossover design facilitated comparison of results among the same set of individuals, providing a robust framework for comparing outcomes. Furthermore, the acute reduction in markers of oxidative stress within a healthy cohort suggests that the compounds responsible for this effect are potent antioxidants. Future work should attempt to replicate and extend these findings by observing the effect of sorghum consumption over longer time periods and among unhealthy cohorts. These results would have broader implications for manufacturers of sorghum-based products and for the potential marketing strategies that could be used to engage consumers.

4.4.2 Other Health Outcomes

While the majority of commercial interest is focused on the impact of sorghum consumption on outcomes related to chronic disease, there is a parallel body of literature that investigates health outcomes among population groups that consume sorghum on a regular basis. The majority of this research focuses on individuals in the developing world and the effect of sorghum consumption on acute infant dehydration and diarrhoea, nodding syndrome, immune function among HIV-positive patients, and adolescent growth and development. The safety of sorghum as a gluten-free food is also explored.

4.4.2.1 Oral Rehydration

4.4.2.1.1 Concentration and Quantity Consumed

Dehydration among infants living in developing countries, commonly induced by diarrhoea, is a significant public health issue, particularly since diarrhoea is the second most common cause of death among children aged 1 to 59 months[351]. Treatment methods are improving, with water and electrolyte ORS advocated by the WHO as an effective means of assisting recovery. Difficulties in accessing WHO ORS for remote communities, however, is concerning. This has spawned research exploring the efficacy of using grains, such as sorghum, for preparation of ORS.

The WHO has articulated an optimal osmolarity for ORS that was adjusted in 2003 to align with clinical best practice. The 5 studies investigating the role of sorghum as a potential component of ORS were all performed prior to this amendment, meaning that the efficacy of sorghum-containing ORS in comparison with that of the current WHO ORS is difficult to ascertain. Nonetheless, when compared with the previous WHO ORS, the sorghum ORS appeared to be at least as effective (and often superior) at facilitating rehydration.

There appeared to be a tendency for a smaller volume of sorghum ORS than WHO ORS to be consumed[324-326, 330]. This may partially explain the decrease in overall output of stools observed in this group[324-326, 330]. Furthermore, it was postulated that the presence of starch in the sorghum preparation resulted in a smaller osmotic penalty in the intestinal lumen than did the glucose molecules in the glucose-based solution[352]. This enables more water molecules to be transported across the intestinal lumen, providing enhanced opportunities to recover water and leading to improved recovery outcomes.

4.4.2.1.2 Definition of Recovery

The range of definitions used by individual studies to define recovery from diarrhoea may have contributed to the variation in results. Half of the studies showed that sorghum ORS significantly decreased the average duration of diarrhoea by at least 12 hours[326, 330], while the other half noted a non-significant increase in the average duration of diarrhoea up to a maximum of 11 hours[325, 331]. In addition, recovery time appeared to vary widely, with standard deviations of over 20 hours across the sorghum and WHO ORS groups. These findings reflect the complex interactions involved in recovery from diarrhoea and the need to implement a clear and consistent definition for what constitutes recovery.

4.4.2.1.3 Study Populations

Differences in participant recruitment may provide an additional explanation for the range of findings. To be eligible for inclusion, the duration of diarrhoea prior to study commencement was capped at 72 hours by four of the five studies. In contrast, Pelleboer *et al.*[331] allowed participants to have experienced diarrhoea for up to 14 days prior to entry. The findings suggest that sorghum ORS is less effective at inducing recovery from chronic diarrhoea than from acute diarrhoea. This should be further investigated in clinical settings.

4.4.2.1.4 Grain Processing

The premise behind investigating sorghum as a potential ORS component was to identify its efficacy in assisting recovery from dehydration in communities that may not have reliable access to WHO ORS. Additionally, these communities may not have access to equipment that can be used to refine grain, meaning that they would be reliant on whole grain sorghum. The absence of reporting on both the type of sorghum and the degree of processing among studies investigating the efficacy of food-based ORS is therefore a limitation. This shortcoming should be rectified in future work, particularly since sorghum is readily available in large areas of sub-Saharan Africa, where diarrhoea is responsible for over 20% of infant deaths in certain areas[351]. The inclusion of sorghum in ORS preparations is therefore a sensible alternative that should be further explored to ensure sorghum-based ORS is at least as efficacious as the current WHO ORS preparation.

4.4.2.2 Nodding Syndrome

4.4.2.2.1 Grain Variety

The underlying cause of nodding syndrome is currently unclear, although various lifestyle, dietary and environmental factors have been identified as possible aetiological factors. Populations native to Uganda and South Sudan who have shown susceptibility to this illness, are known to consume sorghum on a regular basis. Despite this, there was no evidence to suggest that the consumption of red sorghum[341] or three varieties of sorghum native to South Sudan had a significant impact on the number of individuals who experienced nodding syndrome[339]. In contrast, there appeared to be an increased risk of developing nodding syndrome among individuals who consumed the 'serena' variety of sorghum, which was introduced as emergency food aid by the World Food Programme[341], but not was well accepted by local farmers because of its colour and bitter taste[353]. This suggests the presence of undesirable compounds that could be evaluated in future research. The findings could provide insight into compounds that may be implicated in the aetiology of nodding syndrome.

4.4.2.2.2 Study Designs

The difficulty in designing a study to determine the cause of nodding syndrome stems from the multifaceted aetiology of this illness. The use of case-control studies was therefore a valuable method for gaining insight into the influence of potential causes. Furthermore, the matching of cases with appropriate controls enabled risk factors such as consumption of serena sorghum to be identified and explored. The exploratory nature of this research, however, did not provide sufficient scope to identify the effect of consuming different quantities of sorghum on nodding syndrome outcomes. This, along with other risk factors, such as the presence of the parasitic nematode Onchocerca volvulus and exposure to wartime chemicals[339] should be further investigated in future research.

4.4.2.3 Immune Function

4.4.2.3.1 Traditional Preparations

The practice of using traditional preparations for medicinal purposes is gaining increased support from the WHO, particularly for conditions such as HIV infection, usually treated with antiretroviral therapy. Antiretroviral therapy is available to only about 37% of HIV-positive patients living in Africa[354], providing impetus for the identification of easily accessible traditional preparations with similar levels of efficacy. Jobelyn, a commercially available dietary supplement prepared from sorghum, is one such example, but it requires rigorous scientific examination before it can be approved as a medicinal compound.

Over a 12 week intervention period, the consumption of Jobelyn significantly increased the CD4+ T-cell count in HIV-positive patients[333]. The results showed that Jobelyn augmented the effect of antiretroviral therapy alone. Although the mechanism of action is unclear, previous *in vitro* research showed that Jobelyn triggers antiviral immune responses by stimulating the production of natural killer cells and chemokines[333]. These promising findings should be explored across a larger sample to elucidate the efficacy of Jobelyn. This has implications for the management of illnesses such as HIV infection in geographic locations where there is limited access to medications available in more affluent countries.

4.4.2.4 Growth

4.4.2.4.1 Study Subjects

Although sorghum is used as a dietary staple in parts of Africa and Asia, only 1 study has investigated the impact of sorghum consumption on outcomes related to growth and weight gain in children. Over an 8 month intervention period, the female group consuming sorghum exhibited an increased rate of growth and weight gain in comparison with the control group. In contrast, the male control group showed an increased rate of growth and weight gain compared with the group consuming sorghum[334]. These results may simply have been indicative of a ‘catch-up’ effect caused by differences in baseline height and weight of the respective female and male study populations[334]. It is therefore difficult to attribute the height and weight outcomes in these children to the consumption of sorghum.

Future studies should investigate the effect of sorghum consumption in children considered overweight or obese. If the results from this type of study were favourable, they could provide a unique marketing point and act as an incentive for food manufacturers to develop sorghum-based products. This would have broader implications for public health advocates and consumer adoption of sorghum into the diet.

4.4.2.5 Coeliac Disease

4.4.2.5.1 Study Design

Sorghum was considered safe for individuals with coeliac disease, although the methodology on which this outcome was based was not clearly presented. The levels of anti-transglutaminase antibodies (generated in response to the presence of gluten) were not reported as frequently as was stated in the method. Although the reported levels of these antibodies were within a normal range, they were not measured immediately after the sorghum consumption period. If antibody levels remained within a normal range immediately after the consumption of sorghum, there would be compelling evidence that it is safe for individuals with coeliac disease. In future work, these measurements must be reported in a clear and transparent manner. In addition, the gold standard for determining negative consequences associated with food consumption and coeliac disease is gastroscopic examination for the presence of villous atrophy, but this was not performed at any stage.

The use of pre and post intervention measures to determine outcomes related to coeliac disease represents the lowest form of scientific evidence. Intervention studies are generally performed when very little is known about the possible outcomes. They are used to gain insight into possible relationships. Therefore, to ensure sorghum is safe for patients with coeliac disease, long-term studies should be conducted. Additionally, research should focus on identifying and characterising the types of protein present in sorghum.

The small sample (n=2) showed the exploratory nature of the research and a weakness of the study. This study provides a foundation from which to work, particularly since these two individuals were known to have coeliac disease, and as such, it is likely that sorghum would be safe for other individuals with similar conditions. Further work should investigate the protein composition of sorghum so that it can be compared with that of other grains regarded as safe for individuals who cannot tolerate gluten.

4.4.3 Limitations of the Review

The majority of studies included in the review focus on traditional foods that are not commonly consumed as part of the diet in regions such as Australia, Europe, and the United States. The effect of sorghum consumption on outcomes relevant to chronic disease in the developed world, where grains are commonly consumed as bread, pasta, and breakfast cereals, is difficult to infer. Without a clear understanding of the health effects of sorghum processed into such foods, conclusions about the efficacy of sorghum as a potential health food will be limited.

The studies included in this literature review explore the nutritional attributes of sorghum in isolation. Many foods, however, are not eaten individually but are consumed as part of a broader diet. The external validity of these studies is therefore questionable because the effect of consuming sorghum as part of a broader diet was not considered. It is not known how the consumption of sorghum within the context of a diet will affect health outcomes or whether the health effects identified in this review will still persist.

A key limitation identified in this review is the absence of clear reporting of the physiochemical and nutritional composition of the food under study. Without knowing the nutrients contained in a food, it is very difficult to pinpoint the compound responsible for generating a particular effect. Although this is a simplistic view, it is often ignored in many quality-rating tools, which seek to categorise the overall quality of a study. When there is an absence of understanding of how particular compounds interact to generate a particular health outcome, it would be valuable to know the nutritional composition of the food to gain insight into the compounds potentially responsible for this outcome. This is often ignored in studies of food, despite the need to characterise the ingredient or food prior to submitting health claims.

4.4.4 Summary of Part A

The systematic literature review performed in Part A has highlighted a range of nutritional attributes possessed by sorghum. These attributes were explored in the context of outcomes relevant to chronic disease (e.g. blood glucose responses, cancer and oxidative stress) and other health outcomes (e.g. ORS, nodding syndrome, immune function, growth and coeliac disease). The presence of potentially desirable nutritional properties may motivate stakeholders to consider the incorporation of sorghum into the food supply. In particular, it may encourage stakeholders to leverage these attributes in order to formulate products that can deliver potential nutritional benefits. Part B will now present a systematic literature review of the nutritional attributes of quinoa. Due to the paucity of literature investigating the consumption of quinoa in human populations, the systematic review presented in Part B explored the nutritional attributes associated with the consumption of quinoa in animals.

Study 2 Part B – Systematic Review of Nutritional Attributes of Quinoa

4.5 Method to Review Nutritional Attributes of Quinoa

The systematic literature review of quinoa studies was performed according to the guidelines outlined by Sena *et al.*[(193)], which makes explicit reference to the importance of critically appraising the body of animal studies that form the basis of the literature review.

4.5.1 Inclusion and Exclusion Criteria

The eligibility criteria were determined prior to the commencement of the search so as to minimise any bias in inclusion and exclusion of studies. All animal studies that investigated the impact of quinoa consumption on physiological outcomes were considered for inclusion. Included papers were limited to original research published since 1975 in peer reviewed journals and published in the English language. Studies were excluded if they did not include quinoa as part of an experimental diet. Previously conducted reviews were also excluded.

4.5.2 Search Terms and Strategy

The following search terms were used: “quinoa”, “animal”, “health” and “feeding”. Combinations of these terms were joined with the Boolean operator ‘AND’ to identify relevant articles. The search encompassed the time period from 1975 onwards and involved seeking relevant articles from the following electronic databases: Agricola, Cambridge Journals Online, Cochrane Library, CINAHL, MEDLINE, PubMed, SAGE Journals Online, Science-Direct, Scopus, SPORTDiscus, Springer Link, Web of Science and Wiley Online. The same set of search terms were used in each database during the search phase, performed in February 2015.

Initially, one author screened the titles of the articles for inclusion. Potentially suitable articles were further reviewed through their abstract. The full text of potentially eligible articles were retrieved and assessed for inclusion. The reference lists of the articles included for review were also examined for additional articles, which assessed using the same eligibility criteria.

4.5.3 Data Extraction

Animal species, animal age, sample size, duration of the experiment, the control and intervention diet/s, quinoa content in the intervention diet/s, main findings and the quality of the article were included in the summary table. The sample size reported in the summary table was restricted to animals that were fed either the control or intervention diet/s and was not necessarily equal to the sample size for the overall experiment. Instances where significant findings were presented in graphs (without an explicit presentation of the effect size in a table or text) had their results summarised in the summary table as being significantly different to their respective control.

4.5.4 Methodological Quality Assessment

The methodological design and validity of included studies were assessed by using a modified version of the Quality Index (QI), developed by Downs and Black(321) and adjusted for use among animal studies by Ainge *et al.*(194). This modified tool, known as the Methodological Quality Assessment (MQA), was refined further for this systematic review to include all animal studies, rather than just studies utilising rats (**Figure 4.2**). The MQA provides a quantitative measure of study quality, enabling an assessment of the rigour of individual studies to be made.

Of the 19 review questions, 12 assess the reporting quality, 6 the internal validity and 1 the power of the studies. A ‘yes’ or ‘no’ response was reported as a one or zero for each question respectively, with the total score determined by summing together the answers to each of the 19 equally weighted questions. There were two possible ways for a study to fulfil the criteria regarding power. Either an explicit power calculation was provided within the article, or the study identified a significant effect of the treatment with respect to the primary outcome. Reporting and internal validity scores were determined separately and reported(194). In a similar manner to previous work(355), individual study quality was categorised into four discrete quality levels based on the overall score: excellent (17-19), good (14-16), fair (10-13) and poor (less than 10). Furthermore, responses to individual quality questions across the included studies were summed in

Reporting

General

1. Were the hypothesis/aims/objectives of the study clearly described within the introduction?
2. Were the main outcomes to be measured clearly described in the introduction or methods section?

Animal characteristics

3. Was animal species/strain identified?
4. Was the animal age at commencement of the study or at conception specified?
5. Have the animal weights at commencement or at conception of the study been specified?
6. Have the animal starting numbers, including litter number and sizes been specified?
7. Have the housing details been specified?

Design and outcomes

8. Were the interventions of interest clearly described?
9. Were the main findings of the study clearly described?
10. Were estimates of the random variability in the data for the main outcomes provided?
11. Have all important adverse events that may be consequences of the intervention been reported?
12. Have the actual probability values been reported for the main outcomes except where probability value is less than 0.0001?

Internal validity

Bias

13. Was an attempt made to blind those measuring the main outcomes of the intervention?
14. Were the statistical tests used to assess the main outcomes appropriate?
15. Were the main outcomes measures used accurate (valid and reliable)?

Confounding

16. Was it stated in the text that the animals were randomised to intervention groups?
17. Was there adequate adjustment for confounding in the analyses from which the main findings were drawn?
18. Were loses of animals explained?

Power

19. Was the paper of sufficient power to detect a clinical important effect where the probability value for a difference being due to chance is less than 5%?

Figure 4.2 Methodological Quality Assessment questions[194], modified from Downs and Black[321] Quality Index order to show general strengths and weaknesses across the literature.

4.6 Results

4.6.1 Article Identification Process

The systematic search of the scientific databases resulted in the identification of 888 articles. After eliminating articles that did not fit the eligibility criteria, a total of 17 articles were included in the final review. Hand searching of the reference lists of the included articles yielded an additional 2 articles, of which 1 met the necessary inclusion criteria (**Figure 4.3**). The combination of electronic and hand searching resulted in 18 articles being included for review.

4.6.2 Quality Assessment

The results from the MQA as well as the quality of the included studies were summarised in descending order (**Table 4.6**). The overall scores ranged from 6 (poor) to 14 (good), with the average total score being 10.9 (fair). The vast majority of studies (12) were classified as fair quality. 4 were classified as being of poor quality, 2 as good and none as excellent quality.

A summary of the reporting and internal validity scores for each study is also provided in **Table 4.6**. Generally, the scores in the reporting component of the MQA were superior to the scores generated for the internal validity component across all studies. Furthermore, the low internal validity scores were generally responsible for the low overall scores generated among all the studies. An overview of the responses to the MQA questions across the body of literature is depicted in **Table 4.7**.

Reporting factors that were poorly assessed included adverse impacts that could result from the intervention as well as exact probability values. A lack of blinding and randomisation as well as inadequate adjustment for confounding factors and an absence of explanations for the loss of animals were consistently noted across the majority of studies reviewed. This reflected a poor level of internal validity across the literature.

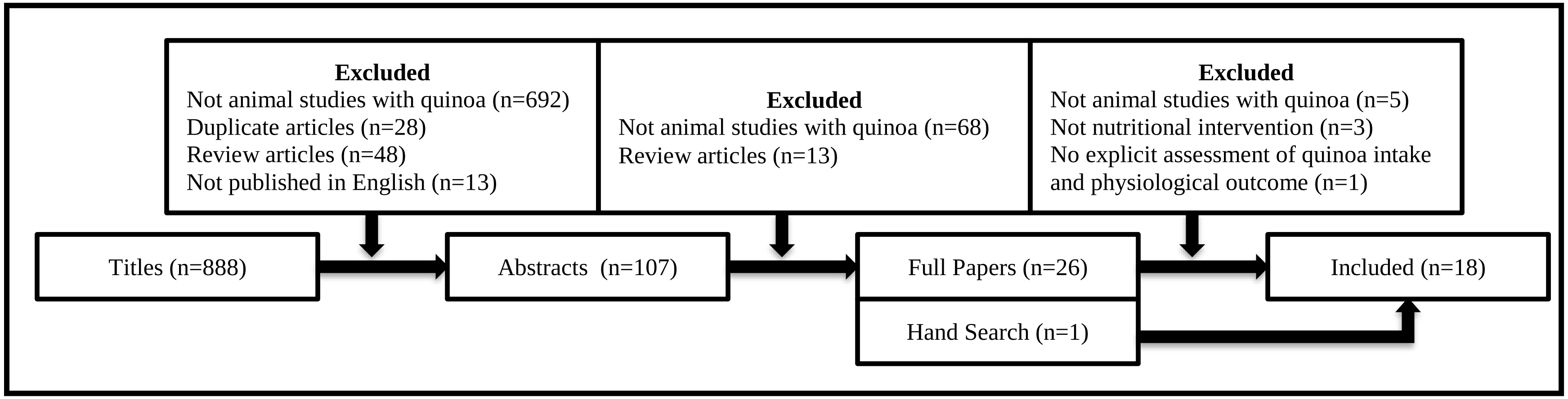

Figure 4.3 Flow chart of literature screening process, with combinations of “quinoa”, “animal”, “health” and “feeding” identifying a total of 888 titles that would then be screened based on their titles, abstracts and full text

Table 4.6 A summary of the reporting, internal validity, total Methodological Quality Assessment scores and study quality (excellent, good, fair or poor) attained by each study as well as the average for these components across the body of literature

Reference	***Quality***	***Reporting Score (n/12)***	***Reporting (%)***	***Internal Validity Score (n/7)***	***Internal Validity (%)***	***Total Score (n/19)***
Jacobsen *et al.*[356]	Good	9	75	5	71	14
Carlson *et al.*[357]	Good	11	92	3	43	14
Meneguetti *et al.*[358]	Fair	9	75	4	57	13
Foucault *et al.*[359]	Fair	10	83	3	43	13
Pasko *et al.*[360]	Fair	9	75	3	43	12
Paśko *et al.*[361]	Fair	9	75	3	43	12
Mahoney *et al.*[312]	Fair	8	67	3	43	11
Improta and Kellems[362]	Fair	8	67	3	43	11
Matsuo[363]	Fair	8	67	3	43	11
Takao *et al.*[364]	Fair	8	67	3	43	11
Mithila and Khanum[365]	Fair	9	75	2	29	11
Gee *et al.*[366]	Fair	9	75	1	14	10
Diaz *et al.*[367]	Fair	7	58	3	43	10
Foucault *et al.*[368]	Fair	8	67	2	29	10
Ranhotra *et al.*[311]	Poor	7	58	2	29	9
Grant *et al.*[369]	Poor	7	58	2	29	9
Ruales *et al.*[370]	Poor	8	67	1	14	9
Ruales and Nair[310]	Poor	5	42	1	14	6
Average	**Fair**	**8.3**	**69**	**2.6**	**37**	**10.9**

Table 4.7 A summary of the number and proportion of positive (yes) responses to each MQA[a] question for the 18 studies that were reviewed

	Reporting Quality												***Internal Validity (Indication of Bias, Confounding & Power)***						
Item	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**
Positive Response	14	15	17	10	10	15	17	15	17	18	0	1	0	15	15	5	0	3	9
Proportion of Positive Responses (%)	78	83	94	56	56	83	94	83	94	100	0	6	0	83	83	28	0	17	50

[a] Methodological Quality Assessment

4.6.3 Data Extraction

Health outcomes that were comparatively assessed between animals consuming quinoa and a control diet included weight gain and metabolic outcomes (16 studies), lipid profiles (6 studies) and antioxidant effects (2 studies). Several studies examined a combination of these outcomes, thus explaining the discrepancy between the number of articles reviewed (18) and the number of studies purported to show health effects (24).

Of the studies pertaining to weight gain, two were of good quality, ten of fair and four of poor quality. The vast majority of studies showed a positive association between quinoa consumption and decreased weight gain among animals. The largest effect was a comparative decrease of 89% between the control and quinoa group[369]. The studies that showed a comparative increase (of up to 10%) in weight gain among animals fed quinoa were unable to show statistical significance. A general trend was for relative differences in weight gain between the quinoa and control group to narrow as study quality declined.

Three studies investigating weight gain also analysed the concentration of hormones involved in the regulation of appetite. The consumption of quinoa in the diet was associated with a decrease in the concentration of plasma leptin by between 14% and 35%[359, 368]. Post-prandial ghrelin and cholecystokinin differences among the quinoa group were respectively 5.4% lower and 45.5% higher than levels among the control group[365]. In addition, one of these studies investigated differences in the release of cytokines (such as monocyte chemoattractant protein-1, interleukin-1β and plasminogen activator inhibitor-1) from adipose tissue (adipokines) among mice fed high fat diets[359]. The addition of quinoa to the diet decreased the mass of adipose tissue and significantly reduced the expression of inflammatory adipokines[359].

Six studies, all of fair quality, investigated the impact of quinoa consumption on lipids. Across the body of literature, the consumption of quinoa was associated with decreases in cholesterol, triglycerides, low-density lipoprotein (LDL) and high-density lipoprotein (HDL). The largest decreases in cholesterol, triglycerides and HDL were 25.5%, 46.5% and 9.6% respectively[364]. It was not possible to accurately quantify the relative decreases in LDL levels because none of the studies reported the level of this biomarker in a tabular format. It did however appear that as the concentration of quinoa in the diet rose above

50g/kg so too did the efficacy of reductions in cholesterol, HDL and LDL. This apparent relationship between dose and effect did not appear to persist for decreases in triglyceride levels.

Finally, the two studies investigating the antioxidant effects of quinoa were both of fair quality. These studies measured the concentration of antioxidant compounds such as glutathione peroxidase, catalase and superoxide dismutase as well as markers of oxidative damage such as malondialdehyde. The expression of these antioxidant compounds showed a vast degree of variability between organs and between animals subjected to varying degrees of oxidative stress. Measures of lipid peroxidation between the two studies were in complete contrast. The inclusion of quinoa in the diet resulted in a decrease in lipid peroxidation by between 29.6% and 66.1%[(360)] but also a 21% to 50% increase in peroxidation compared to the control group[(363)].

4.6.4 Data Presentation

A summary of the animal species animal age, sample size, duration of study, control and intervention diet, quinoa concentration in the diet as well as the main findings of each included study is depicted in **Appendix 4-C**. The majority of studies were performed in rats (11), while mice, chickens and piglets were also used to conduct experiments.

4.7 Discussion

Among the included animal studies, weight gain, lipid profiles and antioxidant responses were the main physiological outcomes affected by quinoa consumption. However, the body of literature supporting these effects showed wide variation in terms of rigour and quality. The value of conducting a defined quality assessment for an evidence-based review was therefore demonstrated here. Specifically, the MQA tool showed that the quality of animal studies could be improved by incorporating design aspects such as blinding, randomisation and power calculations. These methodological tools would help minimise the impact of bias and improve the corresponding MQA score.

4.7.1 Weight Gain

4.7.1.1 Presence of Saponins

Animal feeding experiments investigating quinoa as a potential food source have identified the presence of saponins, which have been implicated in the reduction of weight gain and feed consumption among animals(362). There is however potential for saponins to play a role in human nutrition, particularly in developed countries, where over nutrition is more widespread than under nutrition.

Across the body of literature, it appeared that the presence of saponins in quinoa was connected to decreased weight gain. This association was replicated in rats, mice and chickens and was achieved using a range of different dietary concentrations of quinoa. It was however not replicated in two piglet studies(357, 367), with speculation that the concentration of saponins in the diet was too low to induce a significant change in weight gain. More generally, it became apparent that as the methodological quality of the studies decreased, so too did the detection of differences in weight gain between treatment and control groups.

Despite the underlying tendency to induce weight loss, the magnitude of the effect varied across studies, possibly due to the different concentration of saponins present in quinoa seeds. Each variety of quinoa has a slightly different composition of saponins and each study used processing techniques to prepare the intervention diet, which may have resulted in the loss of saponin fractions. Evidence of these contrasting effects was seen in the two good quality studies where saponins appeared to inhibit weight gain among chickens(356) but had no effect among piglets(357). Both studies used large sample sizes, randomisation and employed a similar time period for the intervention to be performed. The saponin content was however markedly lower in the latter study with piglets.

It was postulated that the mechanism through which saponins operate revolves around their ability to interfere with intestinal function(366). Studies in an Ussing chamber showed that the presence of saponins derived from quinoa resulted in an increased conductance of pig jejunum(357). This result suggests that there was an increase in the permeability of the intestinal lining, resulting in a decreased capacity to actively absorb nutrients for animal growth and development.

The bitter taste associated with saponins has been implicated in reducing the palatability of certain varieties of quinoa. This was shown to decrease food intake[356, 358, 365, 366] and provided an additional explanation for the incidence of decreased weight gain. A further rationale for the decreased food intake may be due to changes in the expression of gut hormones upon the consumption of quinoa. In particular, post-prandial cholecystokinin levels were elevated after the consumption of quinoa[365], resulting in a feeling of satiety. Although most commercially available quinoa has been processed to remove the bitter tasting saponins, the presence of protein, dietary fibre and phenolics within the seed may be capable of inducing feelings of satiety, assisting in the reduction of food intake and weight gain.

4.7.1.2 Potential Mechanism Influencing Weight Loss

The ability of quinoa to induce decreased weight gain was unable to be replicated among mice fed a high fat diet with added quinoa[359]. Despite the null finding, the mice fed quinoa showed a slight decrease in adipose tissue mass as well as a decrease in the expression of lipid storage genes such as lipoprotein lipase and peroxisome proliferator-activated receptor-γ[359]. The quinoa extract used in this study was rich in the naturally occurring steroid hormone, 20-hydroxyecdysone. This compound is structurally similar to Vitamin D, which has been shown to affect lipid accumulation in adipose tissue[359]. It was postulated that Vitamin D receptors formed suitable binding sites for 20-hydroxyecdysone, enabling it to influence the expression of genes responsible for lipid storage, however this mechanism requires further elucidation.

A recent follow up study suggested that the presence of 20-hydroxyecdysone in quinoa was responsible for an increase in glucose oxidation and respiratory quotient (RQ) among mice[368]. However, the explanation for the change in the RQ appears to be counterintuitive. It was suggested that this was indicative of a decrease in fat oxidation and decreased rate of de novo lipogenesis[368]. These both seem unlikely since levels of lipid oxidation among the quinoa and the control diet did not differ[368] and furthermore, increased, rather than decreased de novo lipogensis from carbohydrate would lead to an increase in the RQ value[371].

4.7.1.3 Biochemical Findings

A high fat diet fed to mice was shown to increase the expression of inflammatory cytokines released from adipose tissue[359]. This agrees with findings among overweight and obese individuals that display elevated levels of inflammation due to the release of cytokines from adipose tissue[372]. The addition of a quinoa extract rich in 20-hydroxyecdysone to the high fat diet reversed the expression of inflammatory cytokines to levels associated with a low fat diet. This effect may be due to a decrease in adipose tissue mass among the quinoa group and therefore less capacity to release adipokines. It may also be due to the action of 20-hydroxyecdysone and its metabolites binding membrane receptors and influencing signal transduction and the expression of adipokines. Future research should aim to identify the underlying cause, which is likely to involve a complex interplay between these factors.

4.7.1.4 Variables Requiring Control

The concentration of quinoa needed to induce weight loss effects in a human cohort must be explored in order to determine if the amount needed to achieve these effects is attainable in the context of a regular diet. In addition, further studies investigating the action of quinoa on weight gain should control the energy density by using isoenergetic diets or calculate average energy intake by measuring the quantity of food consumed in order to ascertain the effect of quinoa on weight gain independent of energy intake.

Identifying the potential for quinoa to influence weight gain is of such interest due to the unacceptably high incidence of overweight and obesity; estimated to be 39% and 13% of the global population respectively[373]. This represents a significant public health burden, particularly since overweight and obesity are known risk factors for a chronic diseases such as cardiovascular disease, Type 2 diabetes and some cancers[373].

4.7.2 Effects on Lipid Profile

4.7.2.1 Study Design

The studies investigating lipids were all of fair quality, and showed similarities in terms of their weaknesses. Baseline measures were not explicitly reported, which is a basic limitation of the findings. It could be argued that baseline measures among the animals would not show significant variability due to the similarity in their age and species. However, providing baseline measures would enable a comparison of changes in lipid biomarkers between intervention and treatment diets to be performed. This would be more informative than a comparison of levels at the completion of the study. Heterogeneity in study design is also likely to have played a part in the observation of variable outcomes. This heterogeneity included differences in animal species, animal ages, quinoa content in the diet and duration of the intervention period. In addition, it was not clear which bioactive compound/s were responsible for the underlying effects observed in these studies.

4.7.2.2 Potential Mechanism Influencing Lipid Profile

Despite these limitations, it was shown that the inclusion of quinoa in the diet had a significant effect on cholesterol levels in as little as 15 days[(365)]. A similar acute cholesterol lowering effect has been previously reported among humans consuming β-glucan, where favourable outcomes were noted in as little as two weeks[(374)]. It was proposed that proteins present within the quinoa seed facilitated a reduction in the re-absorption of bile acids and a reduction in hepatic cholesterol synthesis. This was supported by findings that bile acid excretion was elevated and the expression of hepatic HMG-CoA reductase was decreased among mice fed a quinoa diet[(364)]. This is a similar mechanism to that indicated in other food components such as β-glucans[(375)], which are effective at decreasing cholesterol[(374)].

The presence of 20-hydroxyecdysone in the outer coating of the quinoa seed has also shown potential lipid lowering properties. In particular, it was associated with altering lipid absorption, which caused significantly higher levels of lipids to be excreted in the faeces of mice fed a high fat diet supplemented with quinoa[(368)]. Additionally, the cholesterol lowering properties of quinoa were sustained when hypercholesterolemia[(364)] and oxidative stress[(361)] were induced through the addition of cholesterol and fructose to the diet respectively. Collectively, this suggests that quinoa may play an active role in the metabolism of cholesterol.

4.7.2.3 Quinoa Dose

Based on the literature, it appears that the cholesterol lowering properties of quinoa only become significant when at least 2.5% of the diet (2.5 grams per 100 grams) contains quinoa[364]. In contrast, there is very little evidence to suggest that the concentration of quinoa has an obvious impact on triglyceride levels. It appears that significant changes in triglycerides are not observed until quinoa is consumed in the diet for at least 30 days[358]. A greater understanding of the process occurring is therefore necessary before firm conclusions can be drawn regarding quinoa and the impact on triglycerides.

None of the included studies were able to demonstrate that quinoa had a significant impact on HDL, while only one study showed that a diet containing quinoa was able to significantly lower LDL levels[361]. Interestingly, this study also had the highest dose of quinoa and was performed over the longest time period. The tentative conclusions of these findings are that consuming quinoa can reduce LDL over a longer time frame. Extending the intervention period (beyond four or five weeks) may therefore lead to additional improvements in the lipid profile. However, without the guidance of previous work investigating quinoa consumption over a longer duration, it is difficult to determine the optimum intervention period.

Animal studies should further investigate the lipid lowering effects imparted by quinoa and attempt to refine the possible mechanisms that are in operation. It is well established that high cholesterol levels are a risk factor for developing cardiovascular disease[374]. Therefore, food products that can assist in improving the lipid profile in the human body, without radically altering the diet are extremely desirable from a functional and nutritional perspective.

4.7.3 Antioxidant Effects

4.7.3.1 Study Design

The antioxidant properties of quinoa were most prominent during periods of oxidative stress. Plasma lipid peroxidation was decreased while the expression of antioxidant compounds such as glutathione peroxidase and catalase were elevated in several organs[360]. This suggests that quinoa has the ability to regenerate antioxidant species that can then attack free radicals and therefore protect tissues against oxidative damage.

However, these antioxidant properties were less clear when oxidative stress was not intentionally induced in the diet. Since similar analytical methods were used to determine lipid peroxidation, differences in study design are more likely to explain the contrasting results. This includes the use of quinoa extracts that did not possess antioxidant properties, short intervention periods and the use of vitamin supplements in the control diet, which may have acted as antioxidants and nullified any advantageous effects that were generated by consuming quinoa(363).

4.7.3.2 Bioactive Compounds

A limitation of both studies investigating the antioxidant potential of quinoa was the absence of a detailed analysis (identification and quantification) of the main (bioactive) compounds. Quinoa is known to possess compounds with strong antioxidant activity, such as flavonoids and phenolic acids(376), however the presence of these compounds was not assessed in either study despite the phytochemical composition of quinoa known to vary due to genetic and environmental factors. Additionally, there was no attempt to determine the presence of potential *in vivo* metabolites in the blood, urine or faeces of animals, which is crucial in understanding the *in vivo* bioactivity of compounds found in plant foods such as quinoa. As a first step, future studies should determine the presence of bioactive compounds followed by an assessment of the bioactivity of these compounds.

It is well established that the consumption of foods rich in phytochemicals is associated with a decrease in oxidative stress(344) and risk of mortality from cardiovascular disease(377). However, it is necessary to identify the specific phytochemicals present in the quinoa seed and their relative bioactivity in order to begin to understand the potential physiological benefits that they could impart upon consumption. This will provide a more thorough understanding of their action and could be used to design experiments that test their efficacy in human populations.

4.7.4 Limitations of Review

Throughout the design and completion of this literature review, steps were taken to minimise the level of bias in the generation of the results. Despite these efforts, there are several limitations that have been identified. Firstly, studies were included regardless of their overall quality and as such, possible associations between dietary consumption and physiological effects may have been under or overestimated. This was mitigated to a certain degree by using a quality-rating tool, which provided a transparent guide to ranking studies within the body of literature.

The second limitation refers to the doses consumed by animals in the respective studies. It is difficult to infer the dose that would be appropriate in a human context and whether dose dependency would persist, however, this is the critical issue and needs to be addressed in any future human study. Additionally, this review treats studies that use isolated extracts, processed forms and raw forms of the quinoa seed as equally valid dietary interventions. The weakness of this assumption is that humans eat foods and not food extracts. Therefore, it is difficult to predict the efficacy with which specific compounds present in the quinoa seed would impact human health when consumed as part of the diet. This is a limitation inherent in research exploring the effect of specific compounds or nutrients. Exploring the efficacy of quinoa in the whole diet would be an appropriate procedure once these initial outcomes are identified.

4.7.5 Summary of Part B

The systematic literature review performed in Part B has highlighted a range of nutritional attributes possessed by quinoa. These attributes were explored in the context of weight gain, lipid profile and antioxidant effects among animal models. Despite the presence of potentially desirable nutritional properties, these were observed in animal models and therefore require further elucidation in human populations. The following section considers the potential sources of value associated with the nutritional attributes possessed by sorghum and quinoa. These implications are extended to consider the relevance of nutritional attributes in the pathway to market for novel grains and their potential incorporation into the food supply.

4.8 Discussion of Nutritional Attributes of Sorghum and Quinoa and the Implications for Sources of Value

Reviewing the nutritional attributes of sorghum and quinoa has added a valuable contribution to the scientific literature surrounding the health effects of these grains. It may be possible for this research to inform the design of future studies seeking to further elucidate the role that bioactive compounds play in delivering novel health outcomes. The commercial application of these findings will, however, be contingent on the ability to translate the science into a clear value driver and coupling it with other desirable attributes. For example, Maehle *et al.*[378] identified that price and taste were the most important attributes of food choices while O'Neill *et al.*[379] demonstrated that food preferences are influenced by taste, convenience and healthfulness. These results indicate the importance of considering a range of factors, other than just nutritional attributes when developing food products.

Despite taste and price being a significant driver of food choices, nutritional attributes were considered the second most important attribute (after price) for health conscious consumers[378]. In addition, it is conceivable that perceived health benefits can influence consumer adoption of a product. For example, foods positioned as 'superfoods' are associated with being good for your health[380]. Specifically, value may lie in identifying specific compounds that are present within novel grains and linking their functionality to health attributes. This generates an opportunity to link a food, such as sorghum or quinoa, which possess specific compounds (e.g. polyphenols) with the notion of health.

A further implication of exploring the nutritional attributes of novel grains is the potential to identify specific compounds that could have valuable properties when incorporated into a final product. For example, the desire among consumes for foods with anti-inflammatory properties[381], may encourage manufacturers to identify ingredients that can deliver these benefits upon consumption. This may spawn high value market niches that motivates stakeholders from across the business ecosystem to align their objectives and co-create value[382]. As an example, manufacturers may partner with farmers who grow a specific variety of grain that possesses high levels of naturally occurring anti-inflammatory compounds. The collaborative activity to ensure this grain is used in the production process can therefore act as a potential source of value for stakeholders across the ecosystem.

At a population level, the body of scientific evidence supporting the nutritional value of whole grains continues to mount. By delving into the nutritional attributes of specific grains, such as sorghum and quinoa, it is possible to evaluate their potential health effects. Conducting this form of research adds a further element to the analytical framework that can be applied to the evaluation of a novel grain for the food supply. Ultimately, nutrition research is necessary, but not sufficient to guarantee the development of products from particular ingredients.

4.9 Conclusions

Systematically reviewing the nutritional attributes of sorghum and quinoa and their effect on a range of health outcomes has revealed potential sources of value associated with their nutritional composition. This suggests that conducting research that investigates the nutritional attributes of novel ingredients may have an important role in generating an awareness of these attributes for stakeholders across the ecosystem and end-use consumers. Establishing these insights and considering them in conjunction with other attributes such as taste and price may enhance the prospect of incorporating novel grains into the food supply.

While the identification of nutritional attributes associated with the consumption of these grains may deliver health benefits, their consumption becomes redundant (to public health outcomes or commercially) if a sustainable supply of the grain cannot be secured. By exploring the empirical influence of a range of variables on the area of grain planted, Chapter 5 highlights the potential impact of these variables on the supply of novel grains to market. This will have important implications for the pathway to market and potential sources of value that underpins the incorporation of novel grains into the food supply.

Chapter 5: Supply and Acreage of Novel Grains: Empirical Modelling

5.1 Introduction

This thesis has thus far identified sorghum and quinoa as novel grains and conceptualised their potential incorporation into the Australian food supply as an example of incremental innovation. The argument that unique sources of value can be realised through the incorporation of these grains into the food supply has been supported through research spanning strategic planning and nutrition science. The findings from stakeholder interviews suggested that collaboration across the business ecosystem would enable value co-creation (Study 1 Part A). This was augmented with an identification of the types of risk associated with the incorporation of novel grains into the food supply and their position within the business ecosystem (Study 1 Part B). The nutritional attributes possessed by these grains were also identified as a potential source of value (Study 2). The final element of this thesis, presented as Study 3, recognises the farmer as crucial to the growing of the grain and ultimately the initiator of supply.

Evaluating the supply of these novel grains on the basis of cultivated land area can reveal the potential ability to maintain a consistent supply to downstream ecosystem stakeholders. While the agricultural economics literature has spent considerable time exploring planting decisions influencing staple commodities (such as wheat, corn and soybeans), it has little to say about the area of land planted to grains that are underutilised in the food supply. The research presented in this chapter attempts to fill this gap by conducting a case analysis of land area planted to sorghum. Specifically, the research reported in this Chapter highlights the magnitude of the impact of a range of variables on the area of land planted to sorghum, by Australian farmers, over time. Exposing these variables can contribute to the identification of strategies that could be considered within the policy environment to ensure that the supply of novel grains is capable of meeting the requirement of stakeholders across the business ecosystem. Readers interested in gaining an insight into the volume of sorghum production in Australia are encouraged to look at Appendix 5-B, which summarises the production of major crops (including sorghum) across key Australian agricultural regions between 2010 and 2016.

While the analysis focuses on sorghum, the development of this model may be applicable to the exploration of supply scenarios for other novel grains. The implications of the findings are discussed with respect to the potential sources of value associated with the incorporation of novel grains into the food supply.

5.1.1 Supply of Food

The traditional conceptualisation of the food industry as a supply-orientated market driven by agricultural production has undergone a chain reversal process whereby product development is being increasingly driven by consumer demands(264). Despite the transition to a more consumer centric model, farmers are still responsible for carrying out production related activities to supply inputs to downstream stakeholders(383). To ensure that the development of products containing novel grains have the greatest probability of success, their production must be underpinned by a stable supply of raw inputs(2). By focussing on factors that influence the area of land that is planted to a novel grain over time, it is possible to explore the implications for the consistency of supply to market(384). The selection of sorghum as a case study provides this capability.

An empirical analysis of the area of land planted to a grain requires data that spans a sufficiently long period of time to enable the capture of fluctuations in planting behaviour. Sorghum is an example of a grain that has a long history of use in Australia and has been the subject of data collection activities since at least 1972(3). The availability of data coupled with its position as an underutilised grain in the Australian food supply provides support for selecting sorghum as an appropriate case study to conduct the analysis. Specifically, the analysis of sorghum will enable the aggregate outcome of the planting actions carried out by individual farmers to be highlighted. Furthermore, it may be possible to extend the coverage of this model to include acreage decisions by Australian farmers relevant to other novel grains. Before this can occur however, it is important to explore existing crop acreage models in order to leverage insights and generate a model that is empirically sound.

5.1.2 Crop Acreage Models

Before considering the existing agricultural economics literature, a subtle, but important distinction between acreage and allocation, as explained by Dury *et al.*(385) must be clarified. Acreage refers to the area of land planted to crops in a given year, while allocation refers to specific tracts of land and the crops that have been planted in these areas. Crop allocation captures spatial intricacies of the planting decision, while crop acreage enables aggregate planting behaviour to be evaluated. The evaluation of aggregate sorghum planting activities is the focus of this research.

The agricultural economics literature has devoted considerable efforts to explore the drivers of crop acreage and the implications for farm policy. The majority of these models assume that farmers are rational economic agents that are seeking to maximise their profits[103, 105, 197, 386, 387]. Other behavioural drivers, such as agronomic considerations, have been captured through variables representing soil attributes[102, 198], while innate heuristics have been modelled through the application of the Nerlovian partial adjustment model[104, 387]. Briefly, partial adjustment captures the influence of previous farming decisions (e.g. investment in machinery for particular crops) on present ones by considering current acreage decisions as an adaptive response to acreage and prices in the previous period[201]. This is a seminal concept in the agricultural economics literature and a widely used tool to capture the impact of switching costs between crops.

More generally, the vast majority of crop acreage models have tended to focus on acreage decisions as a choice between crops. For example, empirical models have explored the impact of the price of water[197, 387], emergence of genetically modified crops[388], farm insurance programs[103, 198], risk preferences[105], income stabilisation programs[389] and climate influences[200] on crop planting behaviour by the farmer. The model to be presented in this chapter represents a critical departure from this body of literature in that farmers can effectively choose to use their land for the growing of sorghum or use it for some other purpose. Rather than identifying the allocation of land to all its possible uses, the analytical approach presented in this chapter focuses purely on the empirical influences of sorghum acreage in Australia. While this does not explicitly analyse the acreage of other crops, it does allow the impact of price changes in substitute crops to have an impact on sorghum acreage. This may provide an insight into the responsiveness of sorghum acreage to price changes and the potential implications for value creation.

The explanatory scope of models exploring crop acreage is continually improving with variables capturing diverse elements such as the influence of price expectations (derived from the futures market), weather expectations (from historical patterns) and yield expectations (from previous years) being developed. The application of these models tends to be focussed on the major grain commodities such as wheat, corn and soybeans. This has however not been replicated to the same extent in grains such as sorghum, with only a small body of literature providing an empirical analysis of sorghum acreage[196, 197, 390, 391]. This gap in the literature coupled with a complete absence of empirical work evaluating sorghum acreage in Australia presents an important research avenue that is explored in this Chapter.

5.1.2.1 Acreage Research Conducted in Australia

Of the recent acreage research that has been performed in Australia, Agbola and Evans[387] focussed on rice and cotton planting in the Murray Darling basin, while Oczkowski and Bandara[390] applied an innovative approach to evaluate land use across Australia. Although sorghum was captured in the latter analysis, the primary aim of their modelling was to explore whether land use across geographic clusters responded to variation in a series of pertinent variables. The magnitude of the effect on acreage was not evaluated. There is therefore a unique opportunity to specify an empirical model that can explore sorghum acreage in Australia.

5.1.2.2 Model Specification to Guide the Planned Work on Sorghum Acreage

Early approaches to evaluate crop acreage were undertaken through time-series models that explored the area of land planted to specific crops over a number of years. While this approach captured changes over time, the results centred on a distinct spatial location. This limited the ability to generalise the findings beyond specific geographies. More recently however, panel data models have been proposed as a solution to overcome this limitation. The ability to capture variation across time and space enables the generation of robust findings that are more favourable to being generalised across different settings[103, 106, 196, 199, 200].

The panel data approach involves analysing acreage across locations over a series of time points. An advantage of this approach is that unobserved heterogeneity that is time-invariant can be captured through a fixed-effects estimator. An example is soil type, which is likely to differ across geographic regions, but remain the same (within these regions) over time. The influence of soil type (and any other time-invariant factors), which may influence sorghum planting behaviour, can be controlled for and won't contribute to omitted variable bias that would be introduced in a time-series model specification. The combination of this background enables the underlying aim of this Chapter to be articulated.

5.1.3 Aim of the Sorghum Acreage Model

The aim of the research presented in this chapter is to explore the magnitude of the impact of variables that may influence the area of land planted to sorghum over time. The empirical modelling of sorghum acreage introduces a quantitative element to this thesis, which complements the qualitative findings and contributes to the exploration of sources of value associated with the incorporation of sorghum into the food supply. More generally, the approach taken in this Chapter may also have applicability to the supply of other novel grains. This may reveal sources of value associated with the incorporation of novel grains into the food supply and generate a deeper insight into the potential pathway to market. The theory behind the planned research approach and relevant assumptions are now outlined.

5.1.4 Theoretical Model

For any given grain, such as sorghum, farmers seek to maximise the amount of profit that can be generated from its production and sale. The grain level profit is defined in (5-1) as:

$$\pi_{Sorghum} = (P \times A \times Y) - (C \times A + F) \quad (5\text{-}1)$$

Profit (π) is expressed as revenue minus costs. Revenue is defined as the price (P) of sorghum in $ per tonne, multiplied by the product of the area (A) of land (in hectares) planted to sorghum and the yield (Y) achieved in tonnes per hectare. The cost function is a combination of fixed (F) and variable costs. These variable costs are defined as the cost (C) per hectare of land multiplied by the area of land planted to sorghum. The optimum area of land planted to sorghum (A*) is obtained as the solution to the profit maximisation problem (5-2) and will be a function of expected prices, yields and costs.

$$A^{*} = f(P, Y, C) \quad (5\text{-}2)$$

The lag between planting and harvest means that actual prices and yields are not known and farmers must base their decisions on previous observations and anticipated future expectations[196]. This is captured in (5-3).

$$A^{*} = SP, SB, E(SP), LY, W, F, LA \qquad (5\text{-}3)$$

Current prices and expected future prices influence the decisions of farmers[102] and as such, prices are divided into previously observed and expected future prices [E(SP)]. Historical observations are based on the spot price (SP) and basis price (SB) of sorghum. Basis captures the difference between the spot price and the futures price at a given point in time. Expected yields are a combination of one year lagged yields (LY) and observed weather (W) in the lead up to planting. Variable costs are captured as the observed fertiliser prices (F), while the one year lagged area (LA) is a proxy for fixed costs. and costs associated with switching planting away from sorghum. This variable represents a combination of the learning costs (diminishing over time) incurred in growing sorghum along with the extensive capital costs that make switching between crops unfeasible.

Implicit in this model is that planting decisions are based on an assessment of potential returns that can be earned by planting grains other than sorghum. The substitution effect relies on these grains being suitable for sorghum farmers and in addition, farmers having knowledge of the price of these substitutes and expectations about their prices at harvest. These elements are added in (5-4) as the observed prices of substitutes (SuP) and the expected prices of substitutes [E(SuP)].

$$A^{*} = SP, SuP, SB, E(SP), E(SuP), LY, W, F, LA \qquad (5\text{-}4)$$

A panel data approach is used to estimate the empirical impact of these variables on the land area devoted to sorghum. Region specific land area (where regions represent statistical divisions), A_{it}, planted to sorghum in region i and in year t is outlined in (5-5).

$$\begin{aligned} A_{it} = \gamma A_{i,t-1} + \beta_{i1} SP_{it} + \beta_{i2} \Gamma_{it} + \beta_{i3} \mathrm{SB}_{it} + \beta_{i4} FP_{it} + \beta_{i5} \Delta_{it} + \beta_{i6} F_{it} \\ + \beta_{i7} LY_{i,t-1} + \beta_{i8} \mathrm{W}_{it} + \nu_{i} + \varepsilon_{it} \end{aligned} \qquad (5\text{-}5)$$

Where A_{it} is region level sorghum area, $A_{i,t-1}$ represents one year lagged area and accounts for producer inertia and is indicative of the adjustment costs faced by farmers when switching between grains. *SP* is the average sorghum spot price in the lead up to planting (planting times and relevant time periods used for the calculation of spot and futures prices are discussed in the methods section), Γ is a vector of spot prices of substitute grains, *SB* is the sorghum basis price, *FP* is the sorghum futures price, Δ is a vector of futures prices of substitute crops, *F* is the fertiliser price, *LY* is the one year lagged yield and *W* is rainfall in the lead up to planting. To control for time-invariant heterogeneity across regions, fixed effects, denoted by ν_i are included, while ε_{it} is the idiosyncratic error term. The limited cross-sectional variation in futures prices and fertiliser prices warrant the exclusion of time fixed effects from the model[106] since these would be captured by the time parameter[198]. Boussios and Barkley[196] apply a similar modelling approach where time fixed effects are omitted from the model, due to the lack of cross-sectional variation in prices.

I use Driscoll and Kraay standard errors to correct for autocorrelation and heteroscedasticity[392]. These standard errors are heteroscedasticity consistent and robust to cross-sectional (spatial) correlation. The fixed effects specification with lagged dependent variables can generate biased results since the lagged dependent variable is correlated with the error term[106, 196]. A standard approach to this problem is to apply an Arellano-Bond dynamic panel data model[393]. This model uses $y_{i,t-2}$ as an instrument in the first differences model. The instrument is correlated with the transformed dependent variable ($y_{i,t} - y_{i,t-1}$) but uncorrelated with the transformed error term ($e_{i,t} - e_{i,t-1}$). In what follows, the results obtained using the Arellano-Bond approach are consistent with those of the main specification.

The presentation of the theoretical model and the underpinning assumptions presents an overview of the approach that will be taken to capture the influence of variables on sorghum acreage. In order to develop this model, the source of relevant data and transformations that must be undertaken to conduct the regression analysis will now be outlined.

5.2 Method and Data

A time series of cross sections[103, 106, 196] forms the panel data approach to analyse the area of land planted to sorghum. This model adapts the fixed effects panel models developed by Boussios and Barkley[196] and Hausman[106] to the case of sorghum acreage in Australia. The dependent variable in this model is the area of land (in hectares) planted to sorghum. The selection of independent variables was based on theoretical considerations presented above and previous empirical models. The source of these variables and their derivation will now be outlined.

5.2.1 Sorghum Land Area

Over 99% of sorghum production in Australia occurs in the adjacent states of New South Wales and Queensland [394]. GrainGrowers Ltd provided data for the total area of land planted to sorghum across statistical divisions (SD) (geographical spatial units used to divide Australia[395]) between 1983 and 2011. Sorghum producing areas were defined as an SD that had an average production volume greater than 1000 tonnes for the period between 1983 and 2011. Fourteen SDs met these criteria (**Figure 5.1**).

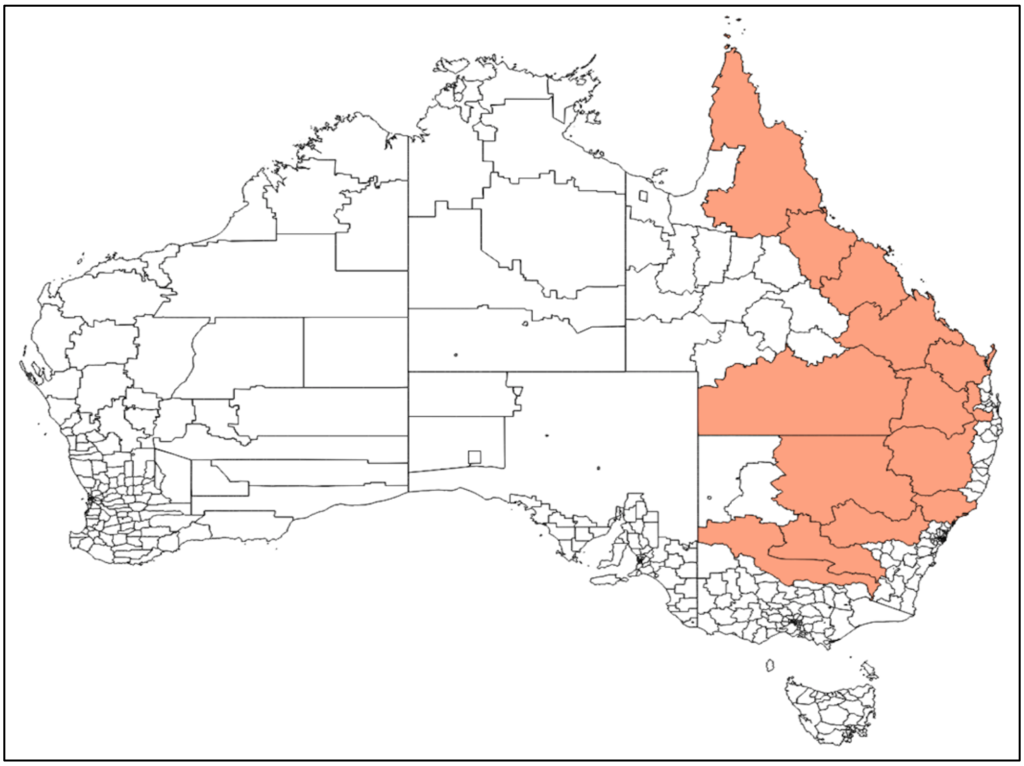

Figure 5.1 Australian Statistical Divisions (SD's) where the average production volume of sorghum exceeded 1000 tonnes between 1983 and 2011

Local government areas (LGAs) (legally designated geographical areas of a state that are administered by local governments[395]) within these SDs that showed regular and significant production (greater than 100 tonnes per year) between 1983 and 2011 were identified. Regular production was determined as a minimum of 15 years (between 1983 and 2011) where at least 100 tonnes of sorghum was produced. A total of 47 LGAs met this criterion (**Figure 5.2**).

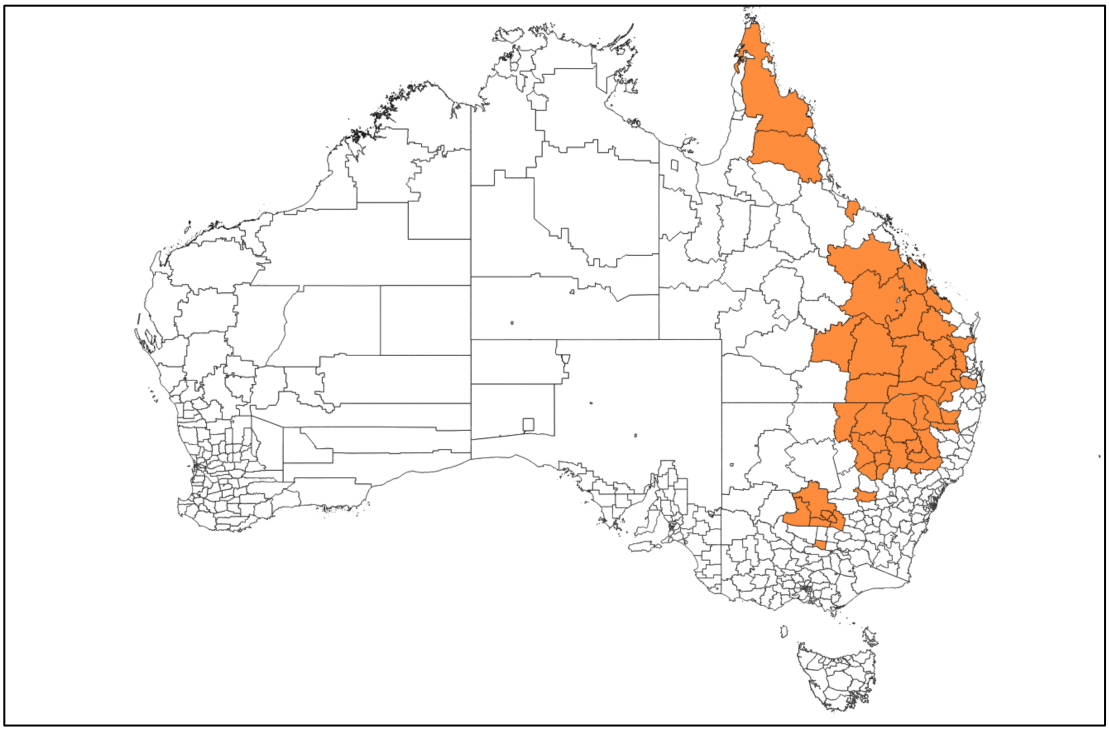

Figure 5.2 Local Government Areas (LGA's) that produced more than 100 tonnes of sorghum in at least 15 years between 1983 and 2011

SDs formed part of the Australian Standard Geographical Classification (ASGC), which was superseded by the Australian Statistical Geography Standard (ASGS) in 2011. Sorghum land area between 2011/12 and 2014/15 was sourced from the Australian Bureau of Statistics (ABS) annual Agricultural Commodities, Australia publication series. This data was aggregated at Statistical Area Level 4 (SA4) (largest sub-state regions in the main structure of the ASGS[396]). The geographical positioning of SA4 and SD areas are not identical (**Figure 5.3**), and accurate correspondence factors to translate from SA4 into SD are not currently available. This was overcome by triangulating values published at the ASGC and ASGS level in the relevant ABS publications, enabling conversion factors to be estimated (**Table 5.1**). These were applied to SA4 data (2011 onwards) to derive values that were equivalent to the SD values.

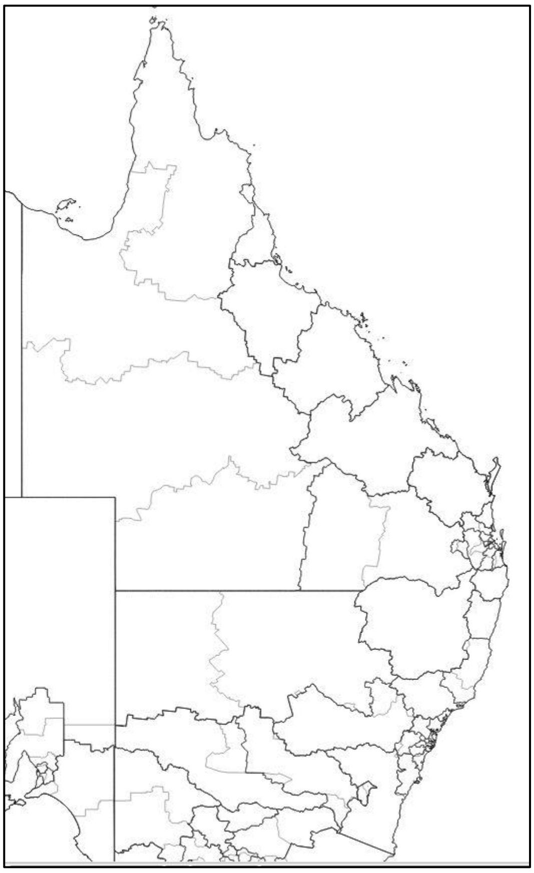

Figure 5.3 Statistical Divisions (SD's) (lighter lines) and Statistical Area Level 4 (SA4) (darker lines) superimposed on the east coast of Australia

5.2.2 Own Price

Commercial seed breeding company representatives supplied data pertaining to planting times for sorghum across agro-ecological regions (**Table 5.2**). The differences in planting times enabled a degree of cross-sectional variation in the price level observed by farmers in the lead up to planting to be introduced. Sorghum spot prices were defined as the average real price of Australian sorghum in the four months leading up to planting for any given year, which is information that farmers would have access to prior to their planting decisions. In certain regions, there were two possible planting periods (**Table 5.2**). The data pertaining to sorghum land area was captured at an aggregate level (over an entire growing season) and therefore did not differentiate between land planted in a specific planting period. To select the appropriate time periods for the calculation of the spot price (across regions), two approaches were taken.

Table 5.1 Summary of conversion factors from Statistical Area Level 4 (SA4) to Statistical Division (SD)

Statistical Division	***Conversion factor from SA4***[a,b]
Northern	Townsville
Fitzroy	Fitzroy
Mackay	Mackay
Wide Bay-Burnett	Wide Bay
Far North	Cairns + (0.0747 ∗ Outback)
West Moreton	(0.9484 ∗ Ipswich) + Logan Beaudesert + (0.0529 ∗ Toowoomba)
South West	(0.9092 ∗ Outback) + (0.1264 ∗ Darling Downs Maranoa)
Darling Downs	(0.8736 ∗ Darling Downs Maranoa) + (0.9471 ∗ Toowoomba)
Hunter	Hunter Valley excluding Newcastle
Murray	0.9838 ∗ Murray
Murrumbidgee	Riverina + (0.0162 ∗ Murray)
Central West	0.7770 ∗ Central West
North Western	(0.7988 ∗ Far West & Orana) + (0.2230 ∗ Central West)
Northern	New England & North West + (0.2012 ∗ Far West & Orana)

[a] SA4 regions without a numeric conversion factor (e.g. Townsville) indicate that the area of land in that given SA4 is equivalent to the corresponding SD
[b] Numerical values represent the proportion of land in an SA4 region that was also present in an SD. These values were derived by comparing ASGC and ASGS values in Agricultural Commodities, Australia, 2010-11 [(397)]

5.2.2.1 Approach 1: Simple Estimation Process

To account for planting in multiple time periods, observed prices were calculated as the average of prices in the four months leading up to the earlier planting period. Under this scenario, price data would have been available to all farmers in the lead up to planting, irrespective of whether they planted sorghum in the earlier or later period.

Table 5.2 Sorghum planting periods outlined by seed breeding representatives and optimal sorghum planting times (as determined by regression models) across regions

Region	***Crop Planting Periods***	***Selection of Planting Period Based on Regression***
Northern (NSW)	Start of October Start of December	Start of October
Hunter	Start of October Start of December	Start of December
North Western	Mid September Start of December	Start of December
Murray	Mid October	Mid October
Murrumbidgee	Mid October	Mid October
Central West	Mid October	Mid October
South West	Late September	Late September
Darling Downs	Late September Start of December	Start of December
West Moreton	Start of September Start of December	Start of December
Wide Bay Burnett	Start of September Start of December	Start of December
Fitzroy	Start of September Start of December	Start of December
Northern (QLD)	Start of September Start of December	Start of December
Mackay	Start of September Start of December	Start of September
Far North	Mid November	Mid November

5.2.2.2 Approach 2: Linear Regression Process

To account for planting in multiple timer periods, a time-series linear regression model (5-6) for each region was applied to determine a single planting window.

$$A_t = \beta_0 + \beta_1 SP_{it} + u_t \quad (5\text{-}6)$$

A_t represents the area of land planted to sorghum in a specific region, SP_{it} represents the real spot price of sorghum in the four months leading up to one of the two planting periods and u_t represents the error term. Regression output is provided in Appendix 5-B. The selection of the planting period (**Table 5.2**) was based on the model that produced a better fit and produced appropriate signs on the spot price coefficient.

Price data was taken from the Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES). These prices were deflated by the index of prices received for sorghum (ABARES publications), which is a better representation of prices received by agricultural producers than the Consumer Price Index (CPI)[(387)].

5.2.3 Prices of Substitute Crops

The major crops that compete with sorghum are cotton and corn[(3)]. Substitute prices were defined as the average spot price of corn and cotton in the four months leading up to planting. Ideal planting times were derived in an equivalent manner to the approach taken for sorghum planting times (this allows for direct competition) across geographic regions. Due to a paucity of reliable price data for Australian corn and cotton, monthly US No.2 yellow corn (Gulf of Mexico) was sourced from the International Monetary Fund (IMF) and the Cotlook A Index (published by Cotlook Limited) provided the spot price of cotton. These values were converted from United States Dollars (USD) into Australian Dollars (AUD) using the nominal USD-AUD exchange rate. Corn prices were deflated by the Index of Prices Received for Total Grains (ABARES) and cotton prices were deflated by the Index of Prices Received for Cotton (ABARES). All crop price indexes set 1997-98 as the baseline (100) year.

5.2.4 Basis Price

The basis price was calculated as the real spot price at the previous harvest minus the real planting futures price for the futures contract that matured at that harvest (5-7).

$$\begin{aligned} Basis\ Price_t = {} & Harvest\ Time\ Spot\ Price_{t-1} \\ & - Planting\ Time\ Futures\ Price\ Maturing\ at\ Harvest_{t-1} \end{aligned} \tag{5-7}$$

This variable enables divergences between actual prices and expected prices (derived from the futures market) to be captured, which may influence the manner in which farmers form their price expectations[196].

5.2.5 Expected Own Price

Expected sorghum prices are defined as the average futures prices maturing in March (the month of harvest) of the year following the current planting period. Variation across regions was introduced through the range of optimal planting times across geographic areas (outlined previously). For example, the expected sorghum price in a given year for the Darling Downs region (under the regression approach to optimal planting time) would be equivalent to the average December (planting month) price of the futures contract that matures in March of the following year.

Futures price data was taken from the Australian Securities Exchange (ASX). In years prior to 2008, where ASX sorghum futures were not traded and US futures for sorghum were not traded, expected prices were derived by dividing the nominal corn cash price (US No.2 yellow) at planting by the nominal sorghum cash price and then multiplying that figure by the nominal corn futures price derived from the Chicago Mercantile Exchange (CME)[196]. Given the high degree of substitutability of corn and sorghum in feed rations, producers often use corn prices to estimate sorghum prices[196]. These values were then deflated by the Index of Prices Received for Sorghum (ABARES).

5.2.6 Expected Substitute Prices

Expected prices were determined as the average harvest time futures prices at the time of planting. This was taken as the average futures price in the month of August, September, October or November prior to planting for futures that were due to mature in March the following year. Corn futures were sourced from the CME, while cotton futures were sourced from the Intercontinental Exchange (ICE). Prices were converted into AUD using the nominal USD-AUD exchange rate. Corn prices were deflated by the Index of Prices Received for Total Grains (ABARES) and cotton prices were deflated by the Index of Prices Received for Cotton (ABARES).

5.2.7 Winter Rainfall

While the futures market supplies expectations about future prices, there is no market for expected weather patterns. Instead, observed weather in the lead up to planting provides valuable information when making planting decisions[(200)]. Rainfall during the winter months leading up to the planting of the summer crop provides an indication of the amount of moisture available in the soil and may influence planting decisions.

Total monthly precipitation for the three months leading up to planting in a given region was sourced from the Bureau of Meteorology (BOM). The selection of weather stations followed the approach of Weersink *et al.*[(104)] where selections were based on geographical proximity to LGAs where significant sorghum production occurred. In instances where monthly rainfall amounts for specific weather stations were missing, the data was imputed from a nearby weather station where the average rainfall for the month in question was within 10% of the average rainfall for the original weather station. Both linear and quadratic specifications[(196)] were explored, with the linear approach preferred.

5.2.8 Fertiliser Price

Average annual prices of ammonia fertiliser were sourced from ABARES and deflated by the Index of Prices Paid for Fertiliser. 1997-98 was set as the baseline year (100) for this data. The combination of these variables formed the basis behind this empirical model. The approach to generate the regression data will now be outlined.

5.2.9 Regression Approach

Each variable was imported into a new Stata (an econometrics software package)[(398)] workfile and given an appropriate title. The area of sorghum was regressed against the explanatory variables using a panel data approach. Four models were specified. Model 1 (5-8) and Model 2 (5-9) utilised spot prices that would have been available to all farmers prior to planting, irrespective of whether they planted sorghum in the earlier or later period. The price variables and rainfall variable in these models are denoted with de (default planting model). Model 3 (5-10) and Model 4 (5-11) utilised spot prices that were based on the output of the optimal planting time regressions. The price variables and rainfall variable in these models are denoted with re (regression planting model). These models are summarised in **Table 5.3** with the interpretation of the variables outlined previously in section 5.1.4.

Table 5.3 Summary of models applying a default planting approach (de) and regression planting approach (re)

Model 1	
$A_{it} = \gamma A_{i,t-1} + \beta_{i1}SPde_{it} + \beta_{i2}\Gamma\mathrm{de}_{it} + \beta_{i3}\mathrm{SBde}_{it} + \beta_{i4}F_{it} + \beta_{i5}LY_{i,t-1} + \beta_{i6}\mathrm{Wde}_{it} + \nu_i + \varepsilon_{it}$	(5-8)
Model 2	
$A_{it} = \gamma A_{i,t-1} + \beta_{i1}SPde_{it} + \beta_{i2}\Gamma\mathrm{de}_{it} + \beta_{i3}\mathrm{SBde}_{it} + +\beta_{i4}F_{it} + \beta_{i5}LY_{i,t-1} + \beta_{i6}\mathrm{Wde}_{it} + \beta_{i7}FPde_{it} + \beta_{i8}\Delta\mathrm{de}_{it} + \nu_i + \varepsilon_{it}$	(5-9)
Model 3	
$A_{it} = \gamma A_{i,t-1} + \beta_{i1}SPre_{it} + \beta_{i2}\Gamma\mathrm{re}_{it} + \beta_{i3}\mathrm{SBre}_{it} + \beta_{i4}F_{it} + \beta_{i5}LY_{i,t-1} + \beta_{i6}\mathrm{Wre}_{it} + \nu_i + \varepsilon_{it}$	(5-10)
Model 4	
$A_{it} = \gamma A_{i,t-1} + \beta_{i1}SPre_{it} + \beta_{i2}\Gamma\mathrm{re}_{it} + \beta_{i3}\mathrm{SBre}_{it} + +\beta_{i4}F_{it} + \beta_{i5}LY_{i,t-1} + \beta_{i6}\mathrm{Wre}_{it} + \beta_{i7}FPre_{it} + \beta_{i8}\Delta\mathrm{re}_{it} + \nu_i + \varepsilon_{it}$	(5-11)

The models were estimated using Driskoll-Kraay standard errors to account for the presence of autocorrelation and heteroscedasticity. The explanatory variables were tested at the 5% level of significance against the null hypothesis that they had no effect on the dependent variable. The impact of a one unit change in a variable that was identified as being statistically significant was reported. Elasticity estimates of price variables on sorghum acreage were also generated. The results of the regression model are presented in the next section.

5.3 Results

5.3.1 Regression Results

A total of 448 observations generated from 14 SDs over 32 years (1984-2015) underpinned the model. **Table 5.4** presents the summary statistics for the variables included in the acreage models. A Hausman test suggested a fixed effects specification was more appropriate than a random effects specification. Autocorrelation and heteroscedasticity were both detected and as a consequence Driscoll-Kraay standard errors were applied. The results from the empirical models are presented in **Table 5.5** and **Table 5.6**.

Table 5.4 Summary statistics for variables included in the empirical models

Variable	***Observations***	***Mean***	***Std. Dev.***	***Min.***	***Max.***
Area ('000 hectares)	448	46.16	75.93	0.00	374.65
Lagged Area ('000 hectares)	448	46.09	75.85	0.00	374.65
Lagged Yield (tonnes/hectare)	448	2.36	1.30	0.00	7.52
Fertiliser Price ($/tonne)	448	288.06	94.37	87.99	450.99
Sorghum Spot Price Default Planting ($/tonne)	448	187.92	19.99	144.92	230.75
Corn Spot Price Default Planting ($/tonne)	448	159.68	29.14	98.30	244.70
Cotton Spot Price Default Planting ($/bale)	448	495.21	100.57	314.95	825.42
Sorghum Basis Price Default Planting ($)	448	30.92	56.89	-104.54	157.85
Expected Sorghum Price Default Planting ($/tonne)	448	149.52	44.28	43.10	249.80
Expected Corn Price Default Planting ($/tonne)	448	145.33	30.17	88.02	245.94
Expected Cotton Price Default Planting ($/bale)	448	479.67	104.11	336.47	780.59
Rainfall Default Planting (mm)	448	100.08	62.71	0.00	435.2
Sorghum Spot Price Regression Planting ($/tonne)	448	189.92	22.34	144.92	248.79
Corn Spot Price Regression Planting ($/tonne)	448	156.91	29.31	98.30	244.70
Cotton Spot Price Regression Planting ($/bale)	448	494.44	99.23	314.95	825.42
Sorghum Basis Price Regression Planting ($)	448	35.67	56.71	-104.54	157.85
Expected Sorghum Price Regression Planting ($/tonne)	448	145.25	44.30	43.10	249.80
Expected Corn Price Regression Planting ($/tonne)	448	144.00	28.94	88.02	245.94
Expected Cotton Price Regression Planting ($/bale)	448	478.15	106.04	321.04	810.66
Rainfall Regression Planting (mm)	448	126.11	80.21	0.00	417.60

Table 5.5 Results from regression model using Driscoll-Kraay standard errors. The calculation period for spot prices (in Model 1 and Model 2) was based on the earlier planting period (in regions where two planting periods existed)

Parameter	***Model 1***				***Model 2***			
	Coefficient	***Standard Error***	***t-statistic***	***p Value***	***Coefficient***	***Standard Error***	***t-statistic***	***p Value***
Lagged Area	0.40***	0.07	5.43	0.000	0.40***	0.07	5.40	0.000
Lagged Yield	481.31	463.68	1.04	0.307	502.79	494.90	1.02	0.318
Sorghum Spot Price Default Planting	123.90	71.59	1.73	0.093	111.87	83.83	1.33	0.192
Corn Spot Price Default Planting	-145.51**	39.73	-3.66	0.001	-161.28**	47.43	-3.40	0.002
Cotton Spot Price Default Planting	-1.87	8.45	-0.22	0.826	-8.84	13.54	-0.65	0.519
Sorghum Basis Price Default Planting	-15.16	25.97	-0.58	0.564	-13.69	25.50	-0.54	0.595
Fertiliser Price	39.53***	10.03	3.94	0.000	40.24**	12.58	3.20	0.003
Rainfall Default Planting	30.16	19.49	1.55	0.132	27.00	18.76	1.44	0.160
Expected Sorghum Price Default Planting	37.43	32.75	1.14	0.262	30.04	49.32	0.61	0.547
Expected Corn Price Default Planting					25.32	99.04	0.26	0.800
Expected Cotton Price Default Planting					9.06	12.26	0.74	0.466
R-Square	0.2380				0.2388			
F Statistic	23.18				24.82			
Observations	448				448			

* p<0.05, ** p<0.01, *** p<0.001

Table 5.6 Results from regression model using Driscoll-Kraay standard errors. The calculation period for spot prices (in Model 3 and Model 4) was informed through a time-series regression that identified favourable planting periods (in regions where more than two planting periods existed)

Parameter	*Model 3*				*Model 4*			
	Coefficient	*Standard Error*	*t-statistic*	*p Value*	*Coefficient*	*Standard Error*	*t-statistic*	*p Value*
Lagged Area	0.40***	0.07	5.76	0.000	0.40***	0.07	5.66	0.000
Lagged Yield	358.61	483.455	0.74	0.464	335.89	521.24	0.64	0.524
Sorghum Spot Price Regression Planting	148.87*	58.02	2.57	0.015	134.09	73.43	1.83	0.077
Corn Spot Price Regression Planting	-158.55**	43.66	-3.63	0.001	-184.81**	49.60	-3.73	0.001
Cotton Spot Price Regression Planting	-6.78	6.29	-1.08	0.290	-12.60	10.79	-1.17	0.252
Sorghum Basis Price Regression Planting	-30.56	21.36	-1.43	0.163	-29.17	21.13	-1.38	0.177
Fertiliser Price	39.81***	8.51	4.68	0.000	41.42***	10.17	4.07	0.000
Rainfall Regression Planting	44.09**	11.90	3.70	0.001	41.38**	13.49	3.07	0.004
Expected Sorghum Price Regression Planting	45.58	27.19	1.68	0.104	31.22	41.46	0.75	0.457
Expected Corn Price Regression Planting					46.59	99.08	0.47	0.641
Expected Cotton Price Regression Planting					7.15	10.07	0.71	0.483
R-Square	0.2518				0.2527			
F Statistic	26.88				23.05			
Observations	448				448			

* p<0.05, ** p<0.01, *** p<0.001

The results from the regression models produced broadly similar results. To assess potential multicolinearity, pairwise correlations are presented in **Table 5.7** and **Table 5.8**. Strong correlations (>0.70) between expected prices and spot prices coupled with the limited additional value they bring when included in the regression model, motivate us to focus the remainder of Chapter 5 on Model 3. The results from the regression identified that the lagged area of land, real spot price of sorghum, real spot price of corn, real fertiliser price and rainfall had a statistically significant impact ($p<0.05$) on sorghum acreage. None of the other variables had a statistically significant impact on the area of land planted to sorghum. The coefficients on all variables (except for fertiliser price) had the expected signs and can be directly interpreted from **Table 5.6**. For example, a one unit increase in the real price of corn (*ceteris paribus*) was anticipated to decrease the area of land planted to sorghum by 159 hectares.

Alternate specifications of the model that included additional explanatory variables were also explored. These models included a price risk variable and a quadratic specification for rainfall. The addition of these variables did not appear to contribute to the explanatory power of the model and were therefore not included in the primary model (Model 3). The description of these variables and a summary of this additional model is presented in Appendix 5-C. In addition, to account for the bias that can be introduced through the lagged dependent variable, the Model 3 was also run with the Arellano Bond specification (**Table 5.9**). Following a similar approach to Boussios and Barkley(196) the results from this model were broadly in line with the primary model (Model 3).

Table 5.7 Correlation matrix for price variables in Model 1 and Model 2

	Sorghum Spot Price	Sorghum Basis	Corn Spot Price	Cotton Spot Price	Expected Sorghum Price	Expected Corn Price	Expected Cotton Price
Sorghum Spot Price	1						
Sorghum Basis	0.5370*	1					
Corn Spot Price	0.0658	-0.2071*	1				
Cotton Spot Price	-0.3946*	-0.2820*	-0.081	1			
Expected Sorghum Price	-0.1151*	-0.2871*	0.6557*	0.0457	1		
Expected Corn Price	0.1647*	-0.1286*	0.8393*	-0.1750*	0.7422*	1	
Expected Cotton Price	-0.2817*	-0.2624*	0.0252	0.8287*	0.1425*	0.018	1

* p<0.05

Table 5.8 Correlation matrix for price variables in Model 3 and Model 4

	Sorghum Spot Price	**Sorghum Basis**	**Corn Spot Price**	**Cotton Spot Price**	**Expected Sorghum Price**	**Expected Corn Price**	**Expected Cotton Price**
Sorghum Spot Price	1						
Sorghum Basis	0.4433*	1					
Corn Spot Price	0.017	-0.1237*	1				
Cotton Spot Price	-0.3241*	-0.2522*	-0.0147	1			
Expected Sorghum Price	-0.3072*	-0.2704*	0.6388*	0.1301*	1		
Expected Corn Price	0.0652	-0.1246*	0.8748*	-0.0289	0.7328*	1	
Expected Cotton Price	-0.2815*	-0.2625*	0.032	0.8484*	0.2413*	0.1088*	1

* p<0.05

5.3.2 Elasticity Estimations

Taking the natural logarithm of the dependent variable and relevant explanatory variables allows elasticity interpretations to be made. However, across the dataset, several regions had zero acreage planted to sorghum in certain time periods. Rather than taking logarithmic transformations and dropping these observations from the analysis, elasticities were estimated at the mean of the variable of interest, in line with Oczkowski and Bandara[390]. Using data in **Table 5.10**, the following equation (5-12) was used to calculate elasticities.

$$\frac{P}{A} \times \frac{\Delta A}{\Delta P} \tag{5-12}$$

Where *P* represents the mean value of a price variable, *A* represents the mean sorghum acreage and *ΔA/ΔP* represents the calculated regression coefficient associated with the price variable. Point elasticities for all price variables are shown in **Table 5.11**. The calculations are also provided in Appendix 5-D.

Table 5.9 Results using an Arellano Bond regression specification

Parameter	*Coefficient*	*Standard Error*	*z statistic*	*p Value*
Lagged Area	0.37***	0.04	8.51	0.000
Lagged Yield	-30.97	936.17	-0.03	0.974
Sorghum Spot Price Regression Planting	167.77**	54.53	3.08	0.002
Corn Spot Price Regression Planting	-156.83**	45.87	-3.42	0.001
Cotton Spot Price Regression Planting	-4.53	12.42	-0.36	0.715
Sorghum Basis Price Regression Planting	-34.82	20.63	-1.69	0.091
Fertiliser Price	51.24***	12.23	4.19	0.000
Rainfall Regression Planting	50.74*	17.74	2.86	0.004
Expected Sorghum Price Regression Planting	53.40	34.77	1.54	0.125
Wald χ^2		132.61		
Observations		434		

* $p<0.05$, ** $p<0.01$, *** $p<0.001$

Table 5.10 Summary of data to calculate point elasticities

Variable	***β***	***Mean***
Area		46162.52 ha
Sorghum Spot Price Regression Planting	148.87	$189.92
Corn Spot Price Regression Planting	-158.55	$156.91
Cotton Spot Price Regression Planting	-6.78	$494.44
Expected Sorghum Price Regression Planting	45.58	$145.25

Table 5.11 Point elasticities of sorghum acreage with respect to real and expected own or substitute prices

$\varepsilon_{A,\ PSorghum}$	$\varepsilon_{A,\ PCorn}$	$\varepsilon_{A,\ PCotton}$	$\varepsilon_{A,\ EPSorghum}$
0.612	-0.539	-0.073	0.143

A = Area of sorghum, P = Real Spot Price, EP = Expected Price

All acreage elasticities are inelastic with respect to prices. The negative coefficients for the corn and cotton elasticities are in line with expectations for substitutes in production. Briefly, an increase in the price of a grain that is a substitute for sorghum (holding other variables constant) would be expected to result in that grain becoming relatively more attractive for farmers to grow. The positive coefficient for the acreage elasticity of sorghum price also follows expectations. As the price of sorghum increases, it becomes more attractive for farmers to grow and therefore would be expected to have additional land area planted. Equivalent reasoning can be applied to explain the positive coefficients for the acreage elasticities with respect to expected prices. These findings are further discussed in the following section and considered in the context of the supply of sorghum and the broader question surrounding the incorporation of novel grains into the food supply.

5.4 Discussion

The results from the empirical model produce signs on the coefficients that are broadly in line with economic theory. Specifically, the model provides evidence that the lagged area of sorghum, the spot price of sorghum and corn, the average fertiliser price and rainfall in the lead up to planting have a statistically significant effect on the area of land planted to sorghum. The following section presents a detailed discussion of these findings and the potential implications for the supply of novel grains into the food supply.

5.4.1 Potential Empirical Influence on Supply

The identification of heterogeneity in planting periods across geographic regions was an important theoretical consideration that is often ignored in acreage research. Although it is unclear when farmers consider spot prices to form their acreage decisions, the research presented in this thesis (Model 3) suggests that prices tend to be observed in time periods closer to planting. In the absence of detailed agricultural census data, deriving planting periods on the basis of a time-series regression presents a potentially valuable analytical tool to identify time points when price expectations are formed by farmers. This should be explored in future empirical work by considering additional explanatory variables that could explain the variation in planting periods. For example, farmers must account for agronomic considerations and switching costs between crops when determining their planting decisions.

The statistical significance of the lagged area of sorghum reflects the influence that acreage in previous years exerts over future planting decisions. This supports the results of previous sorghum acreage models, which have noted a statistically significant impact of previous land area on current land area(196, 391). Boussios and Barkley(196) argue that personal preferences and capital investment may explain the inability or unwillingness of farmers to change their crop mix. Moreover, Alexander *et al.*(388) identified that there was an increased likelihood that a specific crop would continue to be grown if it had been grown frequently in the past, indicative of farmers utilising their accumulated experience and knowledge. Given that sorghum is the major summer crop in Australia(3), it is conceivable that the majority of farmers in the regions being explored would have experience growing sorghum and therefore be influenced by their previous acreage decisions.

The variable representing the price of sorghum has the anticipated sign and is also statistically significant. This contrasts with the findings of Boussios and Barkley(196) (in the US), but supports Oczkowski and Bandara(390) who identified that in over 60% of geographical clusters across Australia, the own price of sorghum had a statistically significant impact on acreage. This may suggest that Australian farmers are particularly responsive to changes in the price of sorghum. Furthermore, the calculated elasticity of supply indicated that a 10% price increase was estimated to increase acreage by 6.12%, which is larger in magnitude than other studies investigating sorghum in the US(196) and

Zimbabwe[391]. Generating returns from the growing of sorghum are therefore a significant component of the planting decision and will have an influence on the supply of grain to market.

The negative signs associated with the spot price of corn and cotton provides evidence that they are both substitutes for sorghum. Assuming that the area of land available to the farmer is fixed, an increase in the price of a substitute crop (holding all other variables constant) would encourage farmers to plant more of their land to the crop that can generate superior returns. The relatively larger coefficient (and associated statistical significance) of the corn price when compared to the cotton price suggests that it is easier for farmers to substitute between sorghum and corn than sorghum and cotton. Evidence from the US also suggests that sorghum is often substituted for corn (and vice-versa) in feed rations, reflecting their net substitutability[196]. The smaller impact of cotton price on sorghum acreage may be able to be explained by the greater water demands for cotton and the associated implications for soil moisture in current and future periods. Moreover, the availability of water in dryland growing regions and price of water in irrigation regions may have a larger impact on substitution decisions between sorghum and cotton[387].

The inelastic relationship (at the mean) of corn and cotton prices to sorghum acreage is unsurprising given the adjustment time generally required to switch between crops. For example, a 10% increase in the price of corn from its average price is estimated to decrease the area of land planted to sorghum by 5.39%, which is in line with other studies evaluating elasticities of substitutes[106]. Future research could explore the impact on sorghum acreage of price changes in other summer crops, as well as winter crops such as wheat and barley. This may highlight the importance of the overarching farming system to farm productivity and provide an insight into potential synergistic relationships between different crops.

While previously observed prices have been shown to influence the planting decision, price expectations also contribute to the decision to grow grains. A key assumption behind the analysis of price expectations is that the futures contract maturing in the month of March is an appropriate proxy for price expectations. While this time point aligns with the harvest of sorghum, there may be more value in the application of the contract ending in May (or later periods), particularly if farmers have access to storage facilities and are not forced to sell their grain immediately after harvest. Moreover, there is as yet no gold standard approach to generate price expectations, with Miao *et al.*[200] suggesting that there is no clear evidence that a backwards (using lagged prices) or forward looking (using futures prices)[399] approach is superior at generating price expectations in future periods. Nonetheless, the forward looking approach implemented for this empirical study identified that a higher expected sorghum price would increase the area of land planted to sorghum.

The complexity involved in price expectations is further highlighted through the unexpected positive coefficients that were seen for the expected corn and cotton prices in Model 4. The interpretation of this result is that a higher expected price for these substitutes would encourage more land area to be planted to sorghum. This runs counter to the theory of substitutes in production (outlined previously) and may indicate that Australian farmers use strategies other than the futures market to develop their harvest price perceptions[196]. One such strategy involves the basis price, which was shown to have a negative coefficient. This contrasts with Boussios and Barkley[196] and suggests that farmers decrease their sorghum acreage in instances when there is an improvement in the basis price (that is, the spot price of sorghum increases in value relative to the futures price). Rather than relying on one-off basis price movements, future research could explore changes in the basis price over a number of years. This may reveal the impact of persistent differences in spot and futures prices on acreage decisions.

The positive coefficient on the variable representing the real price of fertiliser price is initially counterintuitive. This suggests that a $1 increase in the real price of fertiliser is anticipated to increase the area of land planted to sorghum by about 40 hectares. To contextualise the relevance of these findings, the 2011 Australian agricultural census estimated that approximately 36% of farms covered between 50 and 500 hectares and 28% covered more than 500 hectares[400]. The puzzling result identified in this research may however be explained by the relative fertiliser usage of sorghum. United States Department of Agriculture (USDA) Economic Research Service data suggests that the fertiliser costs per dollar of acreage for sorghum are lower than crops such as corn and cotton[401]. In addition, the proportion of operating costs attributable to fertiliser is lower for sorghum than it is for corn. Despite this data being derived from the US, these findings suggest that the financial burden of a fertiliser price increase is less significant for sorghum than it is for other competing crops and therefore may encourage farmers to plant more land to sorghum. This finding offers a fruitful avenue for future research, which could also explore the impact of the adoption of precision agriculture (e.g. efficient fertiliser application that can further reduce input costs) on planting decisions. This could be used to assist in the identification of the most appropriate technologies that farmers should adopt, taking into account their time and resource constraints[402].

The incorporation of variables that capture the influence of weather helps to explain an important element of the acreage decision[200]. Rainfall is particularly relevant for the planting of sorghum acreage since a large proportion of the grain is grown outside the irrigation regions[244]. The results from the empirical model provides evidence that rainfall in the months leading up to planting has a significant positive impact on sorghum acreage, which is in line with the results of Boussios and Barkley[196]. In the context of shifting rainfall patterns across Australia[75], there may be potential scope to adopt sorghum into more growing systems that do not traditionally grow sorghum, particularly if the summer rainfall bands continue to shift in ways anticipated by climate modelling[75].

The combination of the empirical findings provide evidence for sorghum acreage being influenced by previous land area decisions, crop prices, fertiliser input prices and rainfall. By exposing these variables as important elements of the acreage decision, it is possible to inform stakeholders of the relevant considerations shaping the supply of sorghum and potentially other novel grains. This will have implications for the supply of grain to market and the potential to capture value through the incorporation of novel grains into the food supply.

5.4.2 Implications for the Business Ecosystem

The results generated through this empirical work support the assumption that farmers are influenced by crop prices in the lead up to planting and by extension, the potential returns that they can earn. This aligns with the broader theme of profitability that is evident across the business ecosystem. For example, if farmers are unable to generate sufficient monetary returns for particular grains, they will be unlikely to devote land area to these grains and as a result, there may be negative consequences for supply. In addition, farmers must also consider the suitability of their land for the growing of particular grains.

While the relevance of agronomic considerations were captured through the qualitative work in Chapter 3, capturing agronomic factors and the underlying heuristics shaping acreage are inherently difficult to model and therefore tend to be missed. Efforts to capture these effects in an empirical sense were reflected through the adoption of a partial adjustment framework. As a more general comment, the supply of novel grains is likely to be influenced by the profitability (captured through monetary returns) and suitability (captured through agronomic considerations) of grains that fit within the farming system.

In order to negate fluctuations in supply that could arise from price variation, it may be feasible to establish contract-growing arrangements with specific farmers. This approach is currently in place for specialty crops such as safflower[403] and crops with specific end uses, such as corn used for the production of popcorn[404]. In the absence of a contract approach, the supply of grain to these markets, which are generally small and very specific in their requirements, could be in jeopardy. The application of this approach for novel grains could ensure that an initial supply of grain can be sourced, while still adequately rewarding the farmer for their efforts.

The identification of fertiliser prices as having a positive impact on sorghum acreage could present a unique source of value within the business ecosystem. As environmental and ecological sustainability gains increasing importance in farm management[405], novel grains such as sorghum may become a more desirable alternative for farmers seeking to decrease their exposure to environmental risks. By adopting crops that generate lower input costs there is a dual benefit of being attractive to a farmers net return, while simultaneously reducing the burden on the environment. The net benefit would accrue to society through a more diverse and sustainable food supply. Importantly, there must be a concerted approach to engage farmers and express the potential value associated with the incorporation of novel grains into the food supply. Stakeholders from across the business ecosystem should be encouraged to apply their collective knowledge to coordinate business strategies in the development of products that can assist in meeting these broader objectives[406].

The research presented through this empirical model highlights the importance of considering the supply of a raw ingredient, from the farm, into a production system. Despite encountering difficulties with the formation of price expectations for farmers, the insights that were generated illustrate the fundamental importance of prices and ultimately monetary returns. In addition, there may be scope to apply the current empirical model to other novel grains as a means of evaluating the influences on planting decisions. This may reveal the interplay of economic and social variables and the magnitude of their influence on planting behaviour. This may contribute to the underlying sources of value that can be captured through the incorporation of novel grains into the food supply by stakeholders across the business ecosystem.

5.4.3 Theoretical Contribution and Policy Implications

The empirical model generated through this research is the first to the researchers knowledge to apply a panel data approach to capture Australian sorghum acreage as a function of variables influencing farmer behaviour. By analysing the acreage of sorghum over time, it was possible to observe sorghum production independent of stochastic variation due to variables outside the farmer's control (e.g. growing period weather). The area of land planted to a particular crop can therefore act as a proxy for the degree to which farmers have a desire to incorporate that particular grain into their production system. This can reveal the extent to which a particular grain is being adopted and what the potential implications for grain procurement would be.

It was noted that sorghum is currently grown across a wide range of agro-ecological areas. This versatility reflects the robustness of the crop, which may have implications for its ability to be adapted to fit into growing systems under future climate scenarios. With further government investment and the implementation of policies that support publically funded seed breeding efforts, the range of environmental conditions and agro-ecological areas that sorghum is suitable for could be expanded further. This could have implications for areas of north Queensland, Western Australia and the Northern Territory that are currently limited in their ability to support cereal crops. Ultimately though, commercial interest would have to be underpinned by a source of demand from within the business ecosystem. This is a critical requirement and will be required before the expansion of sorghum growing areas can be considered.

Additional policies should focus on encouraging the diversification of crop growing systems as a means of creating and capturing value in the grains industry. Rather than supporting this behaviour through subsidies and crop insurance programs, which can distort incentives and alter the behaviour of farmers towards risk[389], it would be desirable to provide downstream stakeholders with market incentives. For example, by rewarding manufacturers investigating the incorporation of novel grains into their product formulations (with a certain minimum threshold of inclusion) with R&D tax offsets. Ideally this would encourage entrepreneurial activity and foster innovation in the business ecosystem. This may result in the formulation of synergistic partnerships between downstream entities and farmers, enabling unique sources of value to be realised and assisting in the development of a pathway to market in the Australian food supply.

5.4.4 Limitations

A potential limitation of the overarching analysis is that it was not possible to compare the impact of the variables (discussed here) on the acreage of crops other than sorghum. While economics is driven by choices between alternatives, the aim of this analysis was to explore variables that were thought to influence the area of land planted to sorghum. Moreover, this was an exploratory insight that can now be extended to consider acreage decisions or perhaps allocation decisions across specific parcels of land.

Secondly, the empirical model did not explicitly take into account the influence of crop rotations. Sorghum has been identified as an important addition to the farming system, with its incorporation offering potential disease breaks for wheat diseases, better weed control, decreased probability of herbicide resistance and addition of biomass (carbon) into the soil[407]. Taken in combination, future research could examine the degree to which the rotational benefits of sorghum influence farming practices. This would have important implications for farm management and the support of ecologically sustainable production.

A further limitation was associated with the assumptions behind the selection of optimal planting periods in growing regions where two growing periods existed. The aggregate nature of the data precluded the ability to independently ascertain acreage in these two periods. This had implications for the selection of spot prices in the lead up to planting and may have resulted in biased results. For example, the application of a default planting approach in Model 1 and Model 2 and a regression approach in Model 3 and Model 4 were subject to limitations. The default approach selected spot prices prior to planting in all regions, therefore assuming that all farmers would have access to this information. This approach does not however capture price movements in later periods that could influence acreage behaviour. The regression approach (Model 3 and Model 4) based planting periods on the fit of regression models. While empirically favourable, this approach ignored the influence of variables other than price, (such as weather) which may influence the farmer. Data that is disaggregated at a finer scale, or detailed agricultural census data that estimates the area of land planted to sorghum in both growing periods is therefore required to develop more robust models that can account for variation in intra-region planting behaviour.

5.5 Conclusion

The main contribution of this research is to apply a panel data approach to explore a range of variables that influence the area of land planted to sorghum over time and across distinct regions of Australia. Specifically, the empirical results illustrate the significant influence of previous acreage, own and substitute prices, input prices and rainfall on sorghum acreage over time. Given that the farmer acts as the initiator of supply, the results of this work have important implications for the supply of sorghum that must be considered when exploring a potential pathway to market. Specifically, value creation opportunities may lie in developing contractual growing arrangements and leveraging the potential low input nature of the grain to establish a diversified food system that is robust to future environmental challenges.

The exploratory nature of this research presents the foundation for future research to further refine the model. In particular, further efforts are required to identify the optimal approach to capture price expectations that are formed by the farmer. This is an important consideration for grains that do not currently have a well-established futures market. As an extension, this empirical model should be applied to other novel grains as a tool to expose the range of variables that are likely to influence the area of land planted to them. This is critical, as the farmer is responsible for the supply of a grain to market and without their actions, it will be very difficult to see a pathway to market and ultimately incorporation in the food supply.

Finally, the policy implications of these findings can be evaluated in the context of the business ecosystem. Encouraging public investment in plant breeding activities can enhance the scope to grow novel grains across a range of agro-ecological areas. In addition, incentives for manufacturers to pursue R&D activities with novel grains can foster innovation and lead to partnerships across the business ecosystem. Ultimately though, there must be farmers that are willing and capable of growing the grain as part of their farming system in order to supply downstream stakeholders with quantities that are sufficient to meet their requirements for product development.

Chapter 6: Conclusions and Strategic Recommendations for Incorporating Novel Grains into the Australian Food Supply

6.1 Summary of Findings

The interdisciplinary research presented in this thesis explored insights across the domains of strategic planning, nutrition science and economics to identify potential sources of value associated with the incorporation of novel grains into the food supply. A case study approach that considered sorghum and quinoa as examples of novel grains was used to conduct the research. The incorporation of these grains into the food supply was conceptualised as an incremental innovation for the agri-food industry. Rather than exploring strategies aimed at improving incumbent grain systems, this thesis focussed on a perceived research gap that centred on the potential for novel grains to be incorporated into the food supply. The resulting findings revealed the potential value to agribusiness of incorporating novel grains, and highlighted the contribution an inter-disciplinary approach can make in exposing the multi-dimensional nature of innovation in the agri-food industry.

The research underpinning this thesis was presented across three studies. Study 1 was divided into two sections (Part A and Part B). It exposed considerations relevant to strategic planning by exploring the insights of stakeholders involved in the pathway to market for novel grains. Part A applied the concept of the business ecosystem to capture the series of activities that were required to deliver grain from farm to fork. This was augmented with an overview of potential sources of stakeholder value associated with the incorporation of novel grains into the food supply and the diffusion pathway shaping the market for novel grains. The key finding was the need for the ecosystem to be orchestrated, which would enable a clear value proposition to materialise, enhancing the prospects of stakeholders adopting novel grains and engaging in value co-creation. Part B investigated the type and position of risks that may be encountered when considering the incorporation of novel grains into the food supply. It was recognised that risk faced by upstream and downstream stakeholders in the form of co-innovation risk and adoption chain risk could influence the scope to create value and secure a pathway to market that would result in the generation of market traction and ultimately sales.

Study 2 focussed on the nutritional attributes of sorghum and quinoa by conducting systematic reviews of the nutrition literature. While the reviews focussed on potential health effects associated with consuming these grains, the motivation behind the work centred on identifying properties that may be of commercial value to stakeholders across the ecosystem. For example, the consumption of sorghum may generate superior glycaemic responses in comparison to staple grains such as wheat and corn, and the consumption of quinoa by animals (in the context of diet induced obesity and overfeeding) may attenuate weight gain. Despite these desirable nutritional attributes, the challenge lies in translating the science into messages that will resonate with consumers and also align with the food standards framework. While nutritional attributes may appeal to consumers with health-centric values, other factors such as taste, price and convenience (partially explored in Study 1) must also be considered in the context of generating repeat purchase behaviour.

Study 3 explored the empirical influence of a range of variables on sorghum acreage by adopting a panel-data regression model. Specifically, the area of land planted to sorghum was evaluated across Australian geographical regions between 1984 and 2015. A fixed-effects specification was adopted to account for time-invariant variables (variables that differ across regions, but remain relatively constant over time, such as soil type). The empirical model revealed that economic returns (captured as crop prices), previous acreage decisions, input prices and rainfall have a significant influence on sorghum acreage over time. These results suggest that farmers appear motivated by profit when determining sorghum acreage decisions. Further research is required to explore agronomic considerations, particularly for novel grains, which may require tailored management strategies. Moreover, the empirical results have potential implications for the maintenance of supply continuity in the market for novel grains and therefore a deeper recognition that farmers are crucial stakeholders in the value creation process. Strategies that seek to encourage farmers to incorporate novel grains into their growing systems may secure upstream supply within the business ecosystem and support a pathway to market for novel grains.

Taken in combination, the results from these three areas of research have exposed the potential value associated with developing a pathway to market for novel grains. By combining the domains of business and science, it was possible to identify unique characteristics associated with these grains and present an overarching model that could be implemented to explore other novel grains. Crucially, this research identified the need to ensure that stakeholders across the business ecosystem are connected to one another to foster value co-creation that would exceed the value created by any one stakeholder in isolation.

6.1.1 Research Hypotheses

The exploration of strategic planning, nutrition science and economics, enabled the identification of unique sources of value associated with the incorporation of novel grains into the food supply. Examples of value included the ability to deliver innovation to the agri-food industry, pursuit of profitable business ventures through alignment of stakeholder objectives, development of products with desirable nutritional attributes and adoption of novel grains into production systems as a tool to diversify output. In combination these attributes reflected the potential innovative capacity that is embedded in the agri-food industry and the need for further entrepreneurial activity to engage in value creation. The central thesis hypothesis was thereby confirmed by addressing the following five elements.

> *H_1: To enhance the diffusion of novel grains across the business ecosystem, collaborative activity is required by key stakeholders (Study 1 Part A).*

Collaboration and cooperation across the business ecosystem were identified as the formative elements of a successful business venture. This was combined with a deeper recognition that aligning the objectives of key stakeholders was necessary to execute the incorporation of a novel grain into the food supply.

> *H_2: The presence of execution risk, co-innovation risk and adoption chain risk will be revealed at multiple positions across the business ecosystem (Study 1 Part B).*

Execution risks, co-innovation risk and adoption chain risk were identified at multiple positions across the business ecosystem. There was tendency for co-innovation risks to manifest in product development, while adoption chain risk was noted at the farm, in product development and in the sales pipeline.

> *H_3: There is evidence that the consumption of sorghum in human populations may lead to superior nutritional outcomes compared to control grains (Study 2 Part A).*

There was emerging evidence that the consumption of sorghum may generate health outcomes that are superior to other grains, specifically the attenuation of blood glucose responses and decreases in the expression of markers of oxidative stress.

H_4: There is evidence that the consumption of quinoa (in the context of experimental animal studies) may lead to superior nutritional outcomes compared to control grains (Study 2 Part B).

There was emerging evidence that the consumption of quinoa may generate health outcomes that are superior to other grains, specifically decreased weight gain (in animals subject to over-feeding), improvements in the lipid profile and enhanced ability to respond to oxidative stress.

H_5: Economic (price) variables will have a significant impact on acreage decisions by farmers (Study 3).

The price of grain and the price of substitute grains had a statistically significant impact on acreage. Expected prices (derived from the futures market) did not appear to have a statistically significant impact on acreage.

6.2 Contribution to the Field

The research that was performed as part of this thesis has contributed to the broader field of agribusiness by developing a series of important theoretical and practical insights. These contributions may therefore have implications for the formulation of research plans across strategic planning, nutrition science and economics.

6.2.1 General Contributions

1. Incumbent stakeholders within the business ecosystem lack motivation to incorporate novel grains into their systems, due to the changes that would be required. This extends the notion of path dependence to stakeholders in the agri-food sector and suggests that this nascent market would be better serviced by new players who are not burdened with legacy systems.
2. The business ecosystem typology has been extended to the agri-food industry. This contribution enables the pathway to market for novel grains to be

conceptualised as a business ecosystem where stakeholder interaction contributes to the transformation of grain from farm to fork.

3. This research identified that value must be perceived by stakeholders across the ecosystem in order to proceed with the incorporation of novel grains into the food supply. In the majority of instances (but not exclusively), this value tended to be monetary in nature.
4. The diffusion of innovation theory (generally applied as a retrospective analytical tool) has been applied to a forward-looking planned innovation as a tool to explore the potential factors influencing the adoption of novel grains across the business ecosystem.
5. The incorporation of novel grains into the food supply would require the orchestration of stakeholders to co-create value. It was proposed that the farmer could have a role to play as the manager of the innovation ecosystem for novel grains.

6.2.2 Novel Contributions

1. Conceptualising the incorporation of novel grains into the food supply as an incremental innovation may be an oversimplification. There was conflicting evidence surrounding the degree of change that incumbent stakeholders would need to absorb in order to incorporate novel grains into their operations. This extends the notion of modular and architectural changes into the agri-food sector.
2. Potential execution, co-innovation and adoption chain risks faced by stakeholders across the business ecosystem for novel grains were identified. This is possibly the first example of this strategic planning tool being implemented to evaluate innovation risks across the grains industry.
3. The position of risks (execution, co-innovation and adoption chain) with respect to the business ecosystem was identified. This research is the one of the first examples that considers how risks at different points of the business ecosystem can influence the incorporation of a novel grain into the food supply.
4. The systematic review of the nutritional attributes associated with the consumption of sorghum was the first to be published in the scientific literature that summarised and critically appraised the evidence base for sorghum consumption in a human cohort.

5. The systematic review of the nutritional attributes associated with the consumption of quinoa was the first to be published in the scientific literature that applied a quality appraisal tool to critically appraise the evidence base for quinoa consumption in the animal model literature.
6. The panel data approach to evaluate the influence of variables on sorghum acreage was one of the first models developed exclusively for Australian grown sorghum.
7. The interdisciplinary research approach was to the knowledge of the investigators, the first to combine strategic planning, nutrition and economics to explore the potential incorporation of novel grains into the food supply. This approach enabled the development of an interdisciplinary research framework that could be adopted in future research to explore potential sources of value associated with other novel grains for the Australian food supply.

These contributions assisted in addressing a series of perceived gaps in the literature and demonstrated the ability to advance the field of agribusiness by showcasing the unique potential associated with novel grains. It is also acknowledged that these findings and associated contributions are subject to a series of limitations.

6.3 Limitations and Considerations

The purpose of the research presented in this thesis was to explore the potential sources of value associated with the incorporation of novel grains into the Australian food supply. The exploratory nature of the research supported the case study approach, and ultimately the application of sorghum and quinoa as examples of novel grains. However, by focussing on sorghum and quinoa, it could be argued that intricacies associated with all known novel grains may not have been captured. Despite the potential validity of this point, the underlying methodological approach that was developed for this thesis could be applied to other novel grains as a tool to evaluate potential sources of value. For example, lupins have a similar paradigm to sorghum while chia is more closely aligned with the experiences of quinoa. This suggests that the approach is robust to grains other than sorghum and quinoa and therefore has broader applicability for novel grains in Australia.

The adoption of the business ecosystem approach to evaluate the range of stakeholders involved in the process of delivering novel grains to market revealed the complex and multi-faceted nature of the overarching product development process. The exploratory nature of the research however, precluded certain aspects of the ecosystem to be assessed in sufficient detail. Examples include the potential governance framework that would be required to ensure that novel grains are delivered to market. While the importance of orchestrating stakeholders was briefly outlined, this was only considered in the early phase of product development and market penetration. If products containing novel grains were to experience sustained market traction, it is conceivable that the governance structure would undergo changes to reflect the demands of the ecosystem. This potential eventuation was not considered in this thesis and could be explored in future research.

Inherent in the design of this thesis was a supply-centric lens that purposefully constrained the scope of the research. For example, factors that influence demand, such as perishability, packaging that can extend shelf-life and sensory attributes, that would be critical in the product development phase[(169)] must be considered in further research. Furthermore, a deeper demand-orientated analysis (for example through discrete choice experiments) that can elucidate the relative importance of variables that shape the choice to purchase novel products could be explored in future research. This would assist in the commercialisation phase of the product development cycle and offers fruitful avenues of research for individuals engaged in the domain of food science, rheology, perceptual psychology, marketing and other related fields.

A further limitation is the absence of a formal environmental assessment of these novel grains. While the agronomic considerations associated with growing these grains are alluded to, in the absence of deeper lifecycle assessments, it is difficult to predict the environmental sustainability of these novel grains. There is however a strong argument for diversification from a profitability and environmental sustainability perspective, particularly with productivity improvements in staple grains beginning to plateau or be eroded by changes in the climate. Nonetheless, environmental sustainability extends beyond the farm and should also consider the overarching impact of each stage of production (e.g. transport and logistics), from farm to fork. These limitations, while not exhaustive, suggest that there is significant scope to conduct future research exploring the incorporation of novel grains into the food supply.

6.4 Future Directions

6.4.1 Extension of Business Ecosystem Research

The current research captures the business ecosystem for novel grains from an aggregate perspective (namely, the combined activities of all stakeholders in the pathway to market are considered). This has enabled the key stakeholders involved in the pathway to market to be revealed, which could provide the basis for further research into stakeholder or firm level ecosystems. Potential research avenues lie in exploring ecosystem buy-in from the stakeholders that are required to deliver novel grains from farm to fork and trade-offs that may have to be introduced to proceed with the innovation. The application of a finer-grained analysis (rather than aggregate overview) may therefore reveal upstream and downstream dependencies that could be used to identify strategies to enhance competitive advantages. Strategising in this entrepreneurial setting could consider the process (action, cognition or some combination of both) that underpins the formation of the strategy[(408)]. Research avenues could focus on specific stakeholders in the ecosystem, such as a grain miller, breakfast cereal manufacturer or wholesale distributor, identify their upstream and downstream linkages and consider their propensity for ecosystem buy-in.

6.4.2 Governance Framework for Novel Grains

A potential research avenue lies in evaluating the governance framework that underpins the ecosystem for novel grains. This would provide insight into the activities that are required to orchestrate the actions of stakeholders across the ecosystem and could assist with the coordination of activities across the ecosystem. In comparison to the value capture context, governance remains understudied in the context of value creation[(409)]. Given the stochastic nature of production in agricultural systems, unique governance structures that acknowledge this inherent risk may be identified. The results from research of this nature would have implications for the structure of strategic partnerships and potential synergies that could be leveraged to participate in value co-creation.

6.4.3 Consumer Acceptability Research

The importance of identifying a source of demand in the product development process is a critical requirement for a potential product to succeed. Once a concept for a product has been developed, it must be tested among a sample of consumers in order to explore its potential acceptability. Sophisticated methods to gauge consumer preferences, such as discrete choice experiments could be implemented to capture different attributes of a product and force consumers to choose between these to identify their true preferences. Other methods such as best worst scaling could also be implemented to identify consumer desires, as well as desirable attributes across the business ecosystem. For example, this method could be applied to evaluate the characteristics of a novel grain that are most relevant for individuals engaged in grain handling and distribution. This approach could reveal additional insights that complement the findings from the qualitative research carried out in this thesis.

6.4.4 Identifying Compounds with Desirable Nutritional Attributes

As an awareness of the link between health and nutrition continues to grow, there may be opportunities to advance the underlying research that explores the health effects associated with the consumption of novel grains. This work should be underpinned by independent tests of the composition of the grain, including any changes that may arise as an artefact of different processing methods, in order to generate a clearer picture of the compounds that may be responsible for delivering health outcomes. Having access to this information would be commercially desirable for manufacturers, since the presence of specific compounds may provide a point of differentiation in the market. In addition, this research should be performed in human cohorts in order to identify the efficacy of specific effects on health outcomes. This may contribute to the underlying body of evidence that could be synthesised for the purposes of pursing health claims within the health claims framework.

6.4.5 Value-Addition Opportunities for Functional Compounds

The research exploring the nutritional attributes of sorghum and quinoa identified the presence of unique bioactive compounds such as polyphenols, slowly digestible starch and saponins. Future research could focus on exposing the functional properties of these compounds, which could have potential implications for value-addition opportunities. For example, saponins tend to be present in the outer coating of the quinoa seed. The majority of these compounds are however removed upon washing of the quinoa, which forms the first stage of processing. Rather than discarding the residue from the washing process, there may be commercial opportunities to capture the saponins and formulate products that leverage their nutritional attributes. This may provide a means of augmenting revenue streams from the production of novel grains with value-addition to material derived from the processing phase. Research must first identify the dietary implications of consuming such compounds in isolation and in concentrations that may exceed levels seen in the original grain.

6.4.6 Extension of Empirical Modelling to other Novel Grains

The development of an empirical model to explore sorghum acreage decisions provides the foundation for similar work to be applied to other novel grains. By exposing the influence of variables on planting decisions, it is possible to gain a quantitative estimate of changes in relevant parameters. This informative approach enables the implications for the supply of novel grains to be identified. For example, the potential acreage reaction of farmers to changes in pertinent variables can be explored. In addition, extending this model to other grains can highlight the influence of profit on planting decisions, and to the extent to which agronomic considerations influence decisions.

6.4.7 Comparing Novel Grains with Incumbent Grains

The primary motivation behind exploring sorghum and quinoa was to explore the potential sources of value associated with their incorporation into the food supply. To enhance the practical application of this research, future work could compare and contrast the attributes of novel grains with incumbent grains used in the food supply. This would add further depth and rigour to the analysis and provide a benchmark that begins to highlight the minimum requirements that novel grains would need to display to displace or at the very minimum, augment incumbent grains in the food supply.

6.4.8 Implementation of Research Framework

The overarching framework developed throughout this thesis suggests that it is prudent to consider multiple dimensions when exploring value within the food supply. By applying an interdisciplinary approach, insights across strategic planning, nutrition science and economics were established. The combination of these elements resulted in a deeper overview of the pathway to market and the potential for novel grains to be incorporated into the food supply. The elements considered in this thesis could therefore be applied to other examples of novel grains in order to evaluate the potential sources of value associated with their incorporation into the food supply. In addition, the framework developed here has scope to be refined and extended in order to capture additional elements, such as environmental concerns and consumer insights. These elements could be evaluated in future iterations of this research.

6.5 Summary of Recommendations

The research conducted in this thesis has presented an exploratory insight into the potential sources of value associated with the incorporation of novel grains into the food supply. While the implications of the results from this research have been discussed throughout the thesis, a series of recommendations that have been drawn from the findings are summarised here.

1. The action of stakeholders across the business ecosystem must be orchestrated to drive synergistic partnerships and encourage value co-creation. In the absence of collaboration, it is difficult to see a clear pathway to market for a novel grain.
2. Product development should commence with the identification of a demand stream from the consumer and then proceed to work backwards along the product development chain to identify the stages of value addition and stakeholders that are willing to participate.
3. A clear value driver must be present for stakeholders within the business ecosystem in order to motivate them to incorporate novel grains into their production process. These may be both monetary (profit driven) and non-monetary (for example, social responsibility).
4. Incorporating novel grains into existing products by adjusting their ingredient formulation, rather than developing completely new products can assist in fostering consumer familiarity. This avoids the need for consumers to make radical changes to eating patterns and can assist in securing market traction for novel ingredients.
5. Prior to engaging in the implementation of an agricultural innovation, risks across the business ecosystem should be explored to identify any potential bottlenecks that could derail the successful execution of the innovation.

6. Due to the variable nutritional composition of plant-based foods (introduced by environmental and genetic factors), studies that aim to investigate the effect of consuming plant-based foods should also report the physiochemical and nutritional composition of the food in question.
7. In the context of systematically reviewing animal studies, quality rating tools should be adopted to evaluate the quality of the experimental design of these studies. This may have implications for the ability to replicate the findings in human cohorts.
8. Government policy should consider supporting additional public breeding programs for novel grains as a tool to develop varieties that may not be feasible or attractive for a commercial breeding company.
9. When investigating a complex, multi-dimensional research topic, the implementation of an interdisciplinary approach can enhance the scope to leverage research strategies that capture a robust insight into the question under analysis. This is particularly relevant for agri-food related research, which is heavily dependent on the interactions of stakeholders from across a range of subject and discipline areas.

6.6 Concluding Remarks

While innovation is difficult to do well[410], it is recognised as being fundamental to the formation of strategy that can lead to competitive advantages and generate consumer demand for new products. By conceptualising the incorporation of sorghum, quinoa, or any other novel grain into the food supply as examples of incremental innovation, this thesis adds a new dimension to the innovation landscape in the field of agribusiness. Moreover, the adoption and implementation of an interdisciplinary approach, that captures insights from strategic planning, nutrition science and economics, has demonstrated the potential sources of value embedded in the pathway to market for novel grains.

After spending the best part of the last 3 years engaging with stakeholders across the business ecosystem, I am confident that the value proposition that underpins sorghum, quinoa and potentially other novel grains, has the potential to expand the value creation opportunities into more mainstream markets. While significant work remains to be completed, an important lesson from this research is that insights can be applied to the food industry from a diverse range of sectors. A significant component of the adoption process involves connecting stakeholders that have the conviction and belief that there is a truly innovative opportunity to pursue the market for novel grains. If this can be achieved, it is only a matter of time before a greater number of products incorporating novel grains appear on supermarket shelves.

In the words of Facebook CEO, Mark Zuckerberg, "*There are different ways to do innovation. You can plant a lot of seeds, not be committed to any particular one of them, but just see what grows. And this really isn't how we've approached this. We go mission-first, then focus on the pieces we need and go deep on them and be committed to them*". The mission in the context of this thesis is to incorporate novel grains into the food supply. The pieces are represented by the exploration of strategic planning, nutrition science and economics. This thesis has only scratched the surface of an area that has both vast commercial opportunity and significant social utility. The challenge now is for commitment from stakeholders across the ecosystem to pursue the incorporation of novel grains into the food supply.

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Appendix 3-A: Interview Guide

Table 3-A-1 Introduction

Topic	Questions
Participants role in the market for novel grains	What is your current position? What are your major responsibilities? What is your experience with novel grains such as sorghum and quinoa? What is your current involvement with novel grains such as sorghum and quinoa?

Table 3-A-2 Organisation of business ecosystem

Topic	Questions
Membership in the ecosystem	What is the principle market you operate within? Who do you see as the end-user of the market you operate in?
Position in the ecosystem	Who are your suppliers? Who are your customers?
Relationships in the ecosystem	Who drives the market for novel grains? Who do you need to collaborate with to derive value from your position in the market? What are your primary sales channels? What role does health have in the market for novel grains? How do the end-users influence your role?
Value proposition	What value is there for you to operate in the market for novel grains? What is the key value proposition behind novel grains?

Table 3-A-3 Sources of value associated with the incorporation of novel grains into the food supply

Topic	Questions
Sources of value	Why are novel grains of interest to you? What attributes would make novel grains attractive to you?
Market Value	Have you identified markets that would be attracted to novel grains?
Information Exchange	How can the potential value associated with novel grains be translated to stakeholders?
Coordination	Who else do you need to interact with to derive value from novel grains?
Action Steps	What changes would you need to make to derive value from novel grains?

Table 3-A-4 Diffusion of novel grains into the food supply

Topic	Questions
Relative advantage	Do novel grains possess any unique attributes that would make them attractive to stakeholders across the food system? Why would you choose to include novel grains into your system?
Compatability	What impact would the uptake of novel grains have on incumbent (production, distribution, consumption) systems?
Complexity	Do novel grains require specialist knowledge to include in the food system?
Trialability	How could novel grains be consumed by the end-user? Are novel grains more difficult to use than incumbent alternatives?
Observability	What benefits are there from adopting novel grains?

Table 3-A-5 Risks in the business ecosystem

Topic	Questions
Challenges	What technical challenges do you face when working with novel grains? What strategic challenges do you face when working with novel grains? Are there other bottlenecks in the pathway to market that may have an impact?
Innovation	Are there any barriers to food innovation in Australia? How do costs influence the innovation agenda for novel grains?
Sustainability	Is the sustainability and regularity of supply an issue for novel grains?
Management	How do you manage risks?

Appendix 3-B: Job Industry of Interview Participants

Table 3-B-1 Industry involvement of interview participants

Participant Number	***Industry***
1	Commercial R&D
2	Artisan Producer
3	Nutrition & Dietetics
4	Primary Industry
5	Primary Industry
6	Primary Industry
7	Information & Consulting
8	University Research/Education
9	Management
10	Management
11	University Research/Education
12	University Research/Education
13	Commercial R&D
14	Business & Innovation Science
15	Primary Industry
16	Primary Industry
17	Management
18	Commercial R&D
19	University Research/Education
20	Commercial R&D
21	Primary Industry, Marketing
22	Commercial R&D, Primary Industry
23	Food Industry Company
24	Commercial R&D
25	Commercial R&D
26	Food Manufacturing
27	Commercial R&D, Marketing
28	Primary Industry
29	Commercial R&D, University Research/Education
30	Primary Industry
31	Food Manufacturing & Retail
32	Management
33	Marketing
34	Primary Industry
35	Primary Industry
36	Commercial R&D
37	Primary Industry

38	Primary Industry
39	Management
40	Nutrition & Dietetics
41	Primary Industry
42	Primary Industry
43	Marketing
44	Management, Marketing, Manufacturing
45	Primary Industry

Appendix 4-A: Summary of Studies Investigating the Impact of Sorghum Consumption on Outcomes Related to Chronic Disease

Table 4-A-1 Characteristics of intervention studies exploring the effect of sorghum consumption on outcomes related to chronic disease

Reference	*Study Design*	*Participants*[a]		*Country*	*Control Diet*	*Intervention Diet*	*Health Outcome*	*Main Findings*	*Quality*[b]
		Intervention	*Control*						
Khan *et al.*[(323)]	RCT[c]	N=20 Age=23.5 M=30%	N=20 Age=23.5 M=30%	Australia	100% semolina pasta	Semolina pasta with 30% whole grain red sorghum (tannin free) or 30% whole grain white sorghum (tannin free)	Oxidative Stress	Baseline plasma total polyphenols (216.90mg GAE[d]/L), total antioxidants (297.08µmol/l), SOD[e] activity (10.16U/ml) and protein carbonyl (38.01nmol/l) in the red sorghum pasta group. Levels at 120 minutes were 269.4mg GAE/L), total antioxidants (375.44µmol/l), SOD activity (13.66U/ml) and protein carbonyl (28.23nmol/l) (all $p<0.05$). The net change (levels at 120 mins minus levels at 0 mins) in plasma polyphenol concentration, antioxidant capacity, SOD activity and protein carbonyl content was greater than the net change in these levels for the control pasta (all $p<0.05$).	High
Abdelgadir *et al.*[(327)]	Compa-rative study	N = 10 Age=50.2 M=40%	N = 10 Age=50.2 M=40%	Sudan	Maize acida (porridge)	Sorghum kisra (flat bread) and	Blood Glucose Response	AUC[f] (glucose) for sorghum flat bread, sorghum porridge and maize porridge were 389.3, 296.1 and 392 respectively (no stats).	High

[a] Unless specified, age refers to the mean age of participants in years and M represents the proportion of male participants. Where age is absent, the mean age or age range was not expressed in the study. Where M is absent, gender was not specified in the study
[b] The quality of the studies (high or low) was based on the Health Canada Quality Appraisal Tool: High (≥7) and Low (≤6)
[c] RCT = Randomised Control Trial
[d] GAE = Gallic Acid Equivalent
[e] SOD = Superoxide Dismutase
[f] AUC = Area Under the Curve

						sorghum acida (porridge)		AUC (insulin) for sorghum flat bread, sorghum porridge and maize porridge were 2950.6, 2418 and 4367 respectively (no stats).	
Poquette *et al.*[(328)]	Compa-rative Study	N=10 Age=25.1 M=100%	N=10 Age=25.1 M=100%	US	Whole grain wheat muffin	Whole grain sorghum muffin	Blood Glucose Response	Plasma glucose (insulin) responses to sorghum muffins were reduced at 45, 60, 75, 90 and 120 (15, 30, 45, 60, 75 and 90) minutes (all $p<0.05$) compared to the wheat muffins. Compared to the wheat muffin, the sorghum muffin reduced mean glucose and insulin responses by 25.7% (3863 to 2871mg/dL) and 55.2% (3029 to 1357mg/dL) respectively (both $p<0.05$).	High
Prasad *et al.*[(329)]	Compa-rative Study	N=10 Age=25.6	N=10 Age=25.6	India	Wheat roti (unleavened flat bread), wheat coarse rawa upma (thick porridge), wheat fine rawa upma, rice flakes poha (flattened flakes), wheat pasta and wheat biscuits	Sorghum multigrain roti, sorghum coarse rawa upma, sorghum fine rawa upma, sorghum flakes poha, sorghum pasta and sorghum biscuits	Blood Glucose Response	Compared to the respective control, a lower GI[g] was obtained for sorghum coarse upma ($p<0.05$), poha and pasta (both $p<0.01$). The GL[h] of sorghum upma, poha, pasta and biscuits were lower than the control ($p<0.01$). Sorghum roti had a higher GL than wheat roti ($p<0.05$).	High
Mani *et al.*[(332)]	Compa-rative Study	N=5 Age>40	N=5 Age>40	India	50g glucose	Sorghum containing 50g available carbohydrate	Blood Glucose Response	There were no significant differences in blood glucose response between sorghum and glucose at 1 or 2 hours ($p>0.05$).	Low

[g] GI = Glycaemic Index
[h] GL = Glycaemic Load

Lakshmi and Vimala(335)	Compa-rative Study	N=6 Age range: 45 – 60 M=50%	N=6 Age range 45 – 60 M=50%	India	Wheat missiroti, rice semolina upma, rice dhokla (fermented and fried grain)	Whole and dehulled sorghum missiroti, semolina upma, dhokla	Blood Glucose Response	Mean plasma glucose rose by 21.9mg/dL, 20.3mg/dL and 26.6mg/dL after one hour among those consuming whole sorghum (missiroti, semolina upma and dhokla respectively). In comparison mean plasma glucose rose by 30.8mg/dL, 30.8mg/dL and 35.8mg/dL after one hour among those consuming wheat missiroti, rice semolina upma and rice dhokla respectively.	Low

Table 4-A-2 Characteristics of observational studies exploring the effect of sorghum consumption on outcomes related to chronic disease

Reference	***Study Design***	***Participants***[i]		***Country***	***Inclusion criteria***	***Dietary Assessment Method***	***Health Outcome***	***Main Findings***	***Quality***[j]
		Cases	***Controls***						
Zheng *et al.*(336)	Case Control	N=404 Age range 18 – 80	N=404 Age range 18 – 80	China	All oral cancer patients admitted in one of seven hospitals in Beijing	FFQ[k]	Cancer	Compared to consuming sorghum less than once a month, consuming sorghum 1-2/month and three or more times/month was associated with an 89% and 65% higher chance respectively of suffering oesophageal cancer (both p>0.05).	High
Gao *et al.*(338)	Case Control	ESCC[l] N=600 Age=58 M=63% GCA[m] N=599	N=1514 Age=59 M=73%	China	Aged at least 20 from Taiyuan, Linfen, Jinzhong, Changzi and Xinzhou, recently diagnosed with cancer of the oesophagus or stomach without previous treatment.	Interviews	Cancer	Consuming sorghum as the primary staple prior to 1984 had a 5% risk reduction for ESCC, 12% risk reduction for GNCA and 1% risk increase for GCA (all p>0.05). Consuming sorghum as the dietary staple after 1984 had a 1% reduction in	High

[i] Unless specified, age refers to the mean age of participants in years and M represents the proportion of male participants. Where age is absent, the mean age or age range was not expressed in the study. Where M is absent, gender was not specified in the study
[j] The quality of the studies (high or low) was based on the Health Canada Quality Appraisal Tool: High (≥7) and Low (≤6)
[k] FFQ = Food Frequency Questionnaire
[l] ESCC = Oesophageal squamous cell carcinoma
[m] GCA = Gastric cardia adenocarcinoma

		Age=61 M=82% GNCA[n] N=316 Age=57.5 M=76%			Treatment for the tumour had to be performed at the Shanxi cancer hospital and diagnoses were histologically confirmed by pathologists at			risk for ESCC and 101% increased risk for GCA (both p>0.05). No GNCA cases consumed sorghum after 1984.	
Sewram *et al.*[(337)]	Case Contro l	N=670 M=50%	N=1188 M=52%	South Africa	Incident cases of squamous cell carcinoma of the oesophagus diagnosed at one of the three major public referral hospitals in the Eastern Cape Province of South Africa	Interviews	Cancer	Compared to those never consuming sorghum, consuming sorghum less than twice a week was associated with a 64% and 98% increased risk of developing oesophageal cancer among males and females respectively (both p<0.05). There was no significant association with higher intakes of sorghum and oesophageal cancer.	High

[n] GNCA = Gastric noncardia adenocarcinoma

Appendix 4-B: Summary of Studies Investigating the Impact of Sorghum Consumption on Other Health Outcomes

Table 4-B-1 Characteristics of intervention studies exploring other health outcomes associated with the consumption of sorghum

Reference	***Study Design***	***Participants[o]***		***Country***	***Control Diet***	***Intervention Diet***	***Health Outcome***	***Main Findings***	***Quality[p]***
		Intervention	***Control***						
Molla *et al.*[324]	RCT[q]	N=35 Age=29.4 months	N=42 Age=28.7 months	Bangladesh	WHO[r] glucose oral rehydration solution	Sorghum-based oral rehydration solution	Oral Rehydration	After the first 24 hours, 140ml/kg of sorghum ORS[s] was consumed compared to 240ml/kg or glucose ORS (p<0.001). Stool output for the sorghum group was 215ml/kg compared to 343ml/kg for the glucose group (p<0.001)	High
Kenya *et al.*[325]	RCT	N=48 Age=13 months M=100%	N=50 Age=11 months M=100%	Kenya	WHO glucose oral rehydration solution	Sorghum-based oral rehydration solution	Oral Rehydration	After the first 24 hours, 177ml/kg body weight of Sorghum ORS was consumed, compared to 214ml/kg body weight of glucose ORS (p<0.05). No significant difference in stool output or diarrhoea duration	High
Mustafa *et al.*[326]	RCT	N=34 Age=18.1 months M=100%	N = 30 Age=14 months M=100%	Sudan	WHO glucose oral rehydration solution	Sorghum-based oral rehydration solution	Oral Rehydration	Duration of diarrhoea (46.7 hours) and ORS intake (2419.8ml) in the sorghum group were lower than respective values (735.5 hours) and (3487.5ml) for the glucose ORS group (both p<0.05).	High
Lepage *et al.*[330]	RCT	N = 50 Age=10.7 months M=100%	N=50 Age=9.6 months M=100%	Rwanda	WHO glucose oral	Sorghum-based oral rehydration solution	Oral Rehydration	Mean duration of diarrhoea after starting rehydration for sorghum ORS (26 hours) compared to WHO ORS (38.8 hours) (p<0.01). Total stool output for the sorghum	Low

[o] Unless specified, age refers to the mean age of participants in years and M represents the proportion of male participants. Where M is absent, gender was not specified in the study
[p] The quality of the studies (high or low) was based on the Health Canada Quality Appraisal Tool: High (≥8) and Low (≤7)
[q] RCT = Randomised Control Trial
[r] WHO = World Health Organisation
[s] ORS = Oral Rehydration Solution

					rehydration solution			group (134.5g/kg) and ORS intake (185.5ml/kg) were lower than WHO ORS 225.4g/kg and 284.2ml/kg respectively (both p<0.05).	
Pelleboer *et al.*[331]	Comparative Study	N=34 Age=13 months M=65%	N = 30 Age=12.5 months M=57%	Nigeria	WHO glucose oral rehydration solution	Whole grain sorghum-based oral rehydration solution	Oral Rehydration	Duration of diarrhoea for sorghum ORS was 92 hours and WHO ORS was 81 hours (p=0.79).	Low
Ayuba *et al.*[333]	RCT	ART[t] & Jobelyn N=27 Age range 18 – 67 Jobelyn N=8 Age range 18 – 67	ART N=16 Age range 18 – 67	Nigeria	Not specified	Jobelyn	Immune function	CD4+ T-cell counts did not differ between the ART and ART & jobelyn group at baseline. At 6 and 12 weeks, the group consuming jobelyn in conjunction with ART showed an increase in CD4+ T-cell counts (p<0.001) compared to the group utilising ART alone. CD4+ T-cell counts among the group consuming jobelyn alone increased at 12 weeks (p<0.01) compared to baseline levels	Low
Prasad *et al.*[334]	RCT	N=133 Age=11.2 (males) Age=10.0 (females) M=41%	N=129 Age=11.07 (males) Age=9.9 (females) M=54%	India	Regular rice diet	Sorghum upma or khichide (breakfast) and roti (lunch)	Growth	Relative to the control group, height and weight increased by a greater proportion among females consuming sorghum. Relative to the control group height and weight increased by a smaller proportion among males consuming sorghum. No statistical comparison was made.	Low

[t] ART = Anti-retroviral therapy

Table 4-B-2 Characteristics of observational studies exploring other health outcomes associated with the consumption of sorghum

Reference	***Study Design***	***Participants***[u]		***Country***	***Inclusion criteria***	***Dietary Assessment Method***	***Health Outcome***	***Main Findings***	***Quality***[v]
		Cases	***Controls***						
Foltz *et al.*(339)	Case Control	N=51 Age=11.6 M=55%	Village Controls N=49 Age=8.5 M=44% Household Controls N=44 Age=8.1 M=45%	Uganda	Previously developmental normal 5-15 year olds with nodding episodes as well as another neurological abnormality	Interviews	Nodding Syndrome	The consumption of red sorghum (tannin content not stated) was associated with a 40% increased likelihood of displaying nodding syndrome (p>0.05).	High
Ciacci *et al.*(340)	Pre-test post-test	N=2 M=0%	N=2 M=0%	Italy	None stated	None stated	Coeliac Disease	Anti-transglutaminase levels at baseline were 2.3UL and 3.4UL for the two patients. Levels 7 days after the last sorghum intake were 2.7UL and 3.5UL respectively (no stats).	Low
Tumwine *et al.*(341)	Case Control	N=82[w]	N=84	South Sudan	Cases with head nodding, head nodding and seisures & seisures only	Interviews by key informants	Nodding Syndrome	The consumption of tannin containing sorghum (Serena) was associated with a 522% increased risk of experiencing nodding syndrome	Low

[u] Unless specified, age refers to the mean age of participants in years and M represents the proportion of male participants. Where age is absent, the mean age or age range was not expressed in the study. Where M is absent, gender was not specified in the study

[v] The quality of the studies (high or low) was based on the Health Canada Quality Appraisal Tool: High (≥7) and Low (≤6)

[w] Three separate case-control studies were performed in neighbouring villages. The results from all three are pooled together here

Appendix 4-C: Summary of Studies Investigating the Impact of Quinoa Consumption on Health Outcomes

Table 4-C-1 Summary of all reviewed studies that explored the health effects associated with the consumption of quinoa in animals

Reference	*Animal Species*	*Animal Age at Start*	*Sample Size (n)*	*Trial Length*	*Control Diet*	*Intervention Diet*	*Quinoa in Diet (g/kg)*	*Main Outcome Measure*	*Main Findings*	*Quality*[x]
[356]	Male broilers (ASA Chick A/S)	6 days	525	31 days	Regular broiler feed	Regular broiler feed with raw or processed quinoa	100, 200, 400	Weight gain	Control group gain – 1323g. Weight gain (with increasing raw quinoa content) 1247g ($p>0.05$), 1065g ($p<0.05$) and 765g ($p<0.05$). Weight gain (with increasing processed quinoa content) 1232g ($p>0.05$), 1079g ($p>0.05$) and 875g ($p<0.05$).	Good
		0 days	960	39 days	Regular broiler feed	Regular broiler feed with raw or processed quinoa	50, 150		Control group gain after 20 days – 627g. Weight gain (group eating 150g/kg processed quinoa) 593g ($p<0.05$) after 20 days. Weight gain did not differ between groups at 39 days ($p>0.05$).	
[357]	Landrace Yorkshire Duroc cross-bred piglets	28 days	400	28 days	Basal diet without quinoa	Basal diet with South American or Denmark quinoa hull meal	0.1, 0.3, 0.5	Weight gain	Control group gain – 294g/day. Quinoa groups gained 280-307g/day ($p=0.41$). Jejunum epithelial conductance of control group – 22mS/cm^2. In quinoa groups, conductance was 24-25mS/cm^2 ($p=0.04$).	Good
[358]	Wistar rats	60 days	64	30 days	Rodent chow	Nuvilab® with	2	Weight gain	Sedentary control group gain – 60.2g, exercised control group gain – 94.2g. Weight gain, (among quinoa fed	Fair

[x] The quality of the studies (excellent, good, fair or poor) was based on the Methodological Quality Assessment score: excellent (17-19), good (14-16), fair (10-13) and poor (less than 10)

					(Nuvilab ®)	hydrolysed quinoa		Lipids	groups) sedentary – 16.5g (p<0.05) and exercised – 60.0g (p<0.05) Sedentary control group triglycerides – 92.9mg/dL, exercised control group – 63.1mg/dL. Triglycerides (among quinoa fed groups) sedentary – 73.9mg/dL (p<0.05) and exercised – 60.9mg/dL (p>0.05). Non-significant difference in cholesterol between control and quinoa group (p>0.05).	
(359)	C57BL/6J mice	6 weeks	36	3 weeks	1. Low fat (LF) diet 2. High fat (HF) diet	High fat diet with added quinoa extract (HFQ)	Not stated	Weight gain	LF group gain – 3.0g. HF group and HFQ group gain 5.1g (p<0.001) and 5.6g (p<0.001) respectively. HF group epididymal adipose tissue (EAT) – 28.8mg/g body weight. HFQ EAT – 21.7mg/g body weight (p<0.01). HF group plasma leptin – 6.0ng/ml. HFQ group plasma leptin – 3.9ng/ml (p<0.05). Plasma adiponectin and expression of mRNA for SREBP-1c[y] and PAI-1 were lower in HFQ compared to LF group (p<0.05). Expression of mRNA for LPL[z], PPAR-γ, PEPCK, Leptin, TLR4, MCP1, CD68, GILZ, OST and PAI-1 were lower in the HFQ group and mRNA expression for UCP2[aa] and	Fair

[y] SREBP-1c = Sterol Regulatory Element-Binding Proteins, PAI-1 = Plasminogen Activator Inhibitor-1
[z] LPL = Lipoprotein Lipase, PPAR-γ = Peroxisome Proliferator-Activated Receptor-γ, PEPCK = Phosphoenolpyruvate Carboxykinase, TLR4 = Toll-Like Receptor 4, MCP-1 = Monocyte Chemoattractant Protein-1, CD68 = Cluster of Differentiation 68, GILZ = Glucocorticoid-induced Leucine Zipper, OST = Osteopontin
[aa] UCP2 = Uncoupling Protein 2, UCP3 = Uncoupling Protein 3

								Lipids	UCP3 were higher in HFQ group compared to the HF group (all p<0.05). LF and HF group triglycerides – 0.50g/l and 0.53g/l. HFQ group triglycerides – 0.51g/l (p>0.05). LF and HF group plasma cholesterol – 1.25g/l and 1.33g/l. HFQ group plasma cholesterol – 1.35g/l (p>0.05).	
(360)	Male Wistar rats	Not stated	24	5 weeks	Corn or corn with 31% fructose	Quinoa or quinoa with 31% fructose	310	Antioxidant activity	The quinoa group had lower liver GPX[bb] and CAT, lower CAT in the testis and higher GPX in the spleen (all p<0.05) compared to the corn control. The quinoa with fructose group showed lower MDA[cc] levels compared to the corn with fructose group (p<0.01).	Fair
(361)	Male Wistar rats	Not stated	24	5 weeks	Corn or corn with 31% fructose	Quinoa or quinoa with 31% fructose	310	Lipids	Cholesterol, triglycerides and LDL of the quinoa group were significantly lower (p<0.05, p<0.05, p<0.008 respectively) than levels in the corn control group.	Fair
(312)	Male Sprague-Dawley rats	Not stated	15	4 weeks	Casein	1. Quinoa flour 2. Cooked quinoa	680	Weight gain	Control group gain – 57g. Weight gain for the quinoa flour group – 43g (p>0.05) and for cooked quinoa group – 89g (p<0.01). Control group protein efficiency ratio (PER) – 2.67. PER for quinoa flour group – 2.09 (p<0.01) and 2.71 (p>0.05) for cooked quinoa group.	Fair

[bb] GPX = Glutathione peroxidase, CAT = Catalase
[cc] MDA = Malondialdehyde

[362]	Male Broiler chicks	3 days	90	28 days	Maize diet (13.2% protein)	Raw or polished quinoa (13.2% protein)	953.5	Weight gain	After 14 days, control group gain – 76g. Weight gain in raw and polished quinoa group 64.2g and 67.6g respectively (both p<0.05).	Fair
			90	28 days	Maize diet (18% protein)	Raw or polished quinoa (18% protein)	835		After 21 days, control group gain – 486.9g. Weight gain in raw and polished quinoa group 118.6g and 210.1g respectively (both p<0.05).	
			120	14 days	Maize diet (13.3% protein)	Raw, polished or washed quinoa (13.3% protein)	962.5		After 7 days, control group gain – 87.5g. Weight gain in raw, polished and washed quinoa group 53.0g (p<0.05), 54.9g (p<0.05) and 92.9g (p>0.05) respectively.	
			120	31 days	Maize diet (23% protein)	Raw, polished or washed quinoa (23% protein)	800		After 31 days, control group gain – 891.4g. Weight gain in raw, polished and washed quinoa group 160.4g, 383.3g and 737.6g (all p<0.05) respectively.	
[363]	Male Wistar-ST rats	4 weeks	10	13 days	Diet free of quinoa	Control diet with methanolic quinoa extract	11	Weight gain Antioxidant activity	Control group gain – 15.1g. Quinoa group gain – 15.1g (p>0.05). Control and quinoa group serum α-Tocopherol – 8.5µg/ml and 5.6µg/ml (p<0.05) respectively. Control group serum and liver MDA 2.0nmol/mL and 33.3nmol/g respectively. Quinoa group serum and liver MDA 3.0nmol/mL and 40.3nmol/g (both p<0.05) respectively. No differences in serum or liver GPX (p>0.05).	Fair
[364]	Male Crj: CD-1 (ICR) mice	7 weeks	18	4 weeks	0.5% cholesterol, 20% casein	Control diet with casein substituted for a quinoa protein extract	25, 50	Weight gain Lipids	Control group gain – 11.28g. Weight gain (with increasing quinoa extract) 12.02g and 10.78g (p>0.05). Plasma cholesterol (0 to 5% quinoa) 268.2mg/dl, 199.9mg/dl (p<0.05),	Fair

									204.5mg/dl (p<0.05). Liver cholesterol (0 to 5%) quinoa 10.31mg/dl, 8.16mg/dl (p>0.05), 6.30mg/dl (p<0.05). Plasma triglycerides (0 to 5% quinoa) 84.5mg/dl, 55.4mg/dl, 45.2mg/dl (p>0.05). Liver triglycerides (0 to 5% quinoa) 14.06mg/g, 10.36mg/g, 9.24mg/g (p>0.05). Daily faecal bile acid (0 to 5% quinoa) 125.8, 212.3 (p<0.05), 202.5µg/50g body weight (p<0.05). Expression of HMG-CoA[dd] reductase was significantly lower (p<0.05) in the quinoa groups than the control group.	
(365)	Male Wistar Rats (albino strain)	Not stated	16	15 days	Casein	Quinoa in place of casein	200	Weight gain Lipids	No difference in weight gain between control and quinoa group (p>0.05). Control group and quinoa group postprandial CCK[ee] levels 8.63ng/ml and 12.56ng/ml (p<0.01) respectively. No differences in fasting CCK, ghrelin and leptin and postprandial ghrelin and leptin between groups (p>0.05). Cholesterol in the quinoa group was significantly lower (p<0.01) than the control group.	Fair
(366)	Wistar rats	Not stated	40	14 days	Milled and cooked wheat cereal	Bitter, washed bitter or sweet quinoa	862, 866, 873	Weight gain	The control group gained more weight than the bitter, washed bitter and sweet quinoa groups (no statistics provided).	Fair

[dd] HMG-CoA reductase = 3-hydroxy-3-methylglutaryl coenzyme A
[ee] CCK = Cholecystokinin

(367)	Y DY commercia l cross piglets	8 weeks	144	5 weeks	Maize and wheat meal	Maize and wheat meal with quinoa	50, 100	Weight gain	Control group gain – 294g/day. Weight gain (with increasing quinoa content), 285g/day and 248g/day (both p>0.05).	Fair
(368)	Male C57BL/6J mice	6 weeks	Not stated	3 weeks	High fat (HF) diet	High fat quinoa (HFQ) diet	2.8	Weight gain Lipids	Over a 24-hour period, the respiratory quotient and glucose oxidation of the HFQ group was higher than the control group (both p<0.05). Control and HFQ plasma leptin – 4.2ng/ml and 3.6ng/ml (p>0.05) respectively. Control and HFQ plasma triglycerides – 0.62g/L and 0.68g/L (p>0.05) respectively. Over a 24-hour period, HFQ faecal lipid content was higher than control group (p<0.05).	Fair
(311)	Rats	Not stated	20	4 weeks	Corn starch with casein	Dehulled quinoa	641	Weight gain	Control and quinoa group gain – 130g and 126g (p>0.05) respectively. Control and quinoa group protein efficiency ratio – 3.5 and 3.8 (p<0.05) respectively.	Poor
(369)	Male Hooded-Lister rats	32 days	8	10 days	Basal diet with casein	Basal diet with quinoa	758	Weight gain	Control and quinoa group gain – 11.0g/day and 1.2g/day respectively (no statistics provided).	Poor
(370)	Male Sprague-Dawley rats	Not stated	10	9 days	Maize starch with casein	Maize starch with quinoa	Not stated	Weight gain	The quality of protein from quinoa was poorer than the protein from the control diet (no statistics provided).	Poor
(310)	Male Sprague-Dawley rats	Not stated	Not stated	9 days	Maize starch with casein	Maize starch with quinoa	Not stated	Weight gain	Gain (in increasing order) was control group, washed quinoa group and raw quinoa group (no statistics provided).	Poor

Appendix 5-A: Historical Summer and Winter Crop Production in Sorghum-Growing Regions

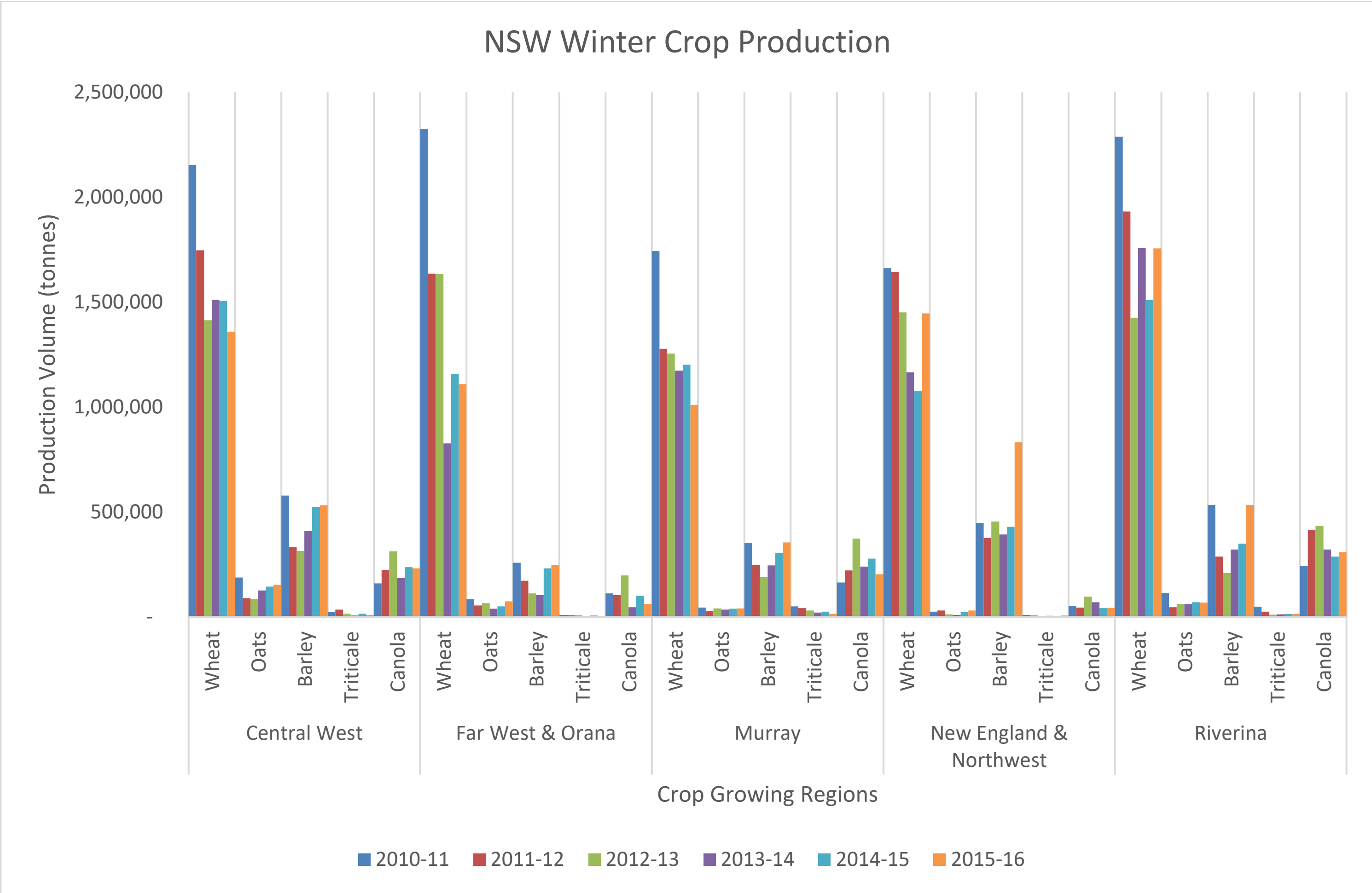

Figure 5-A-1 Historical NSW winter crop production across major sorghum growing regions

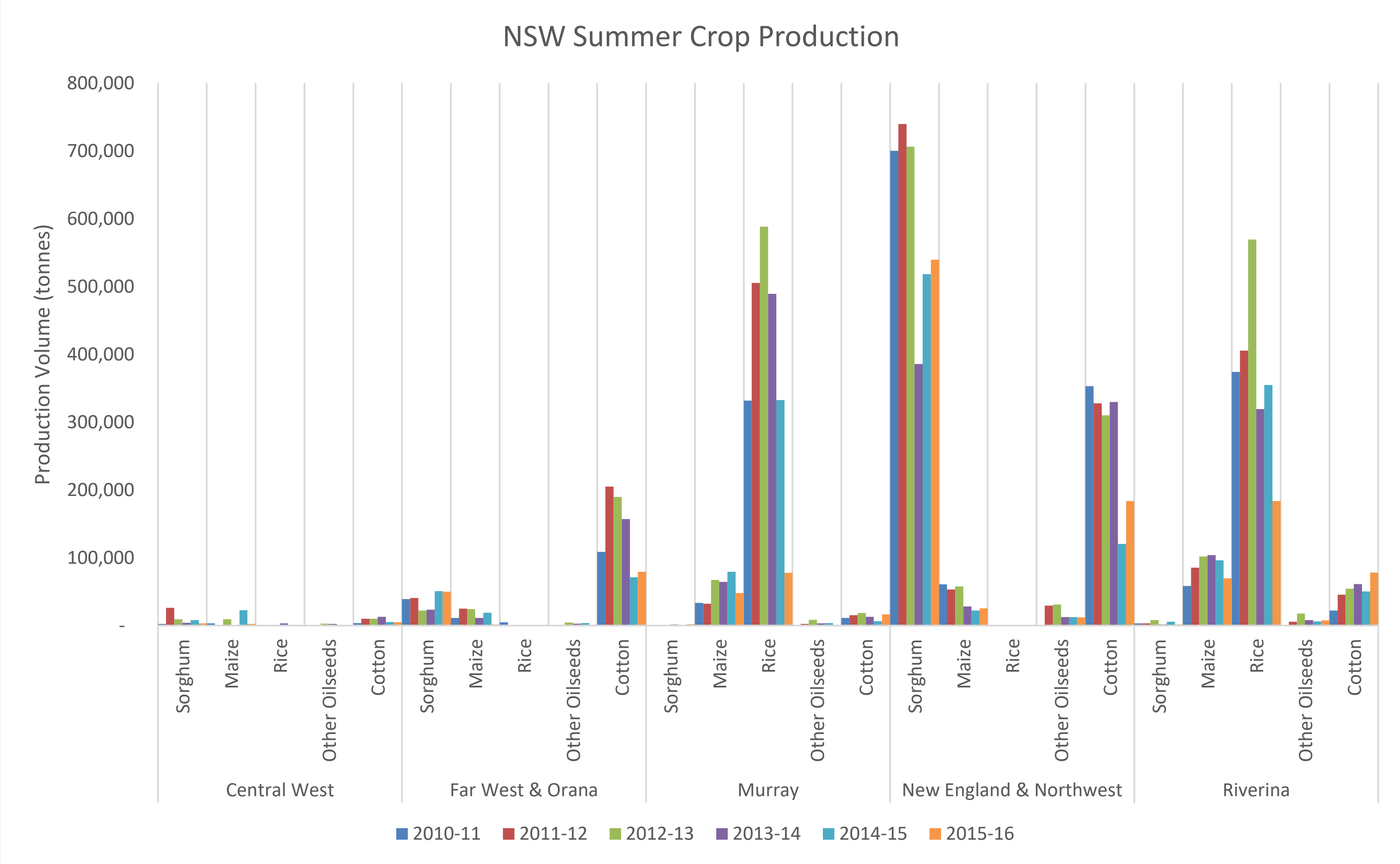

Figure 5-A-2 Historical NSW summer crop production across major sorghum growing regions

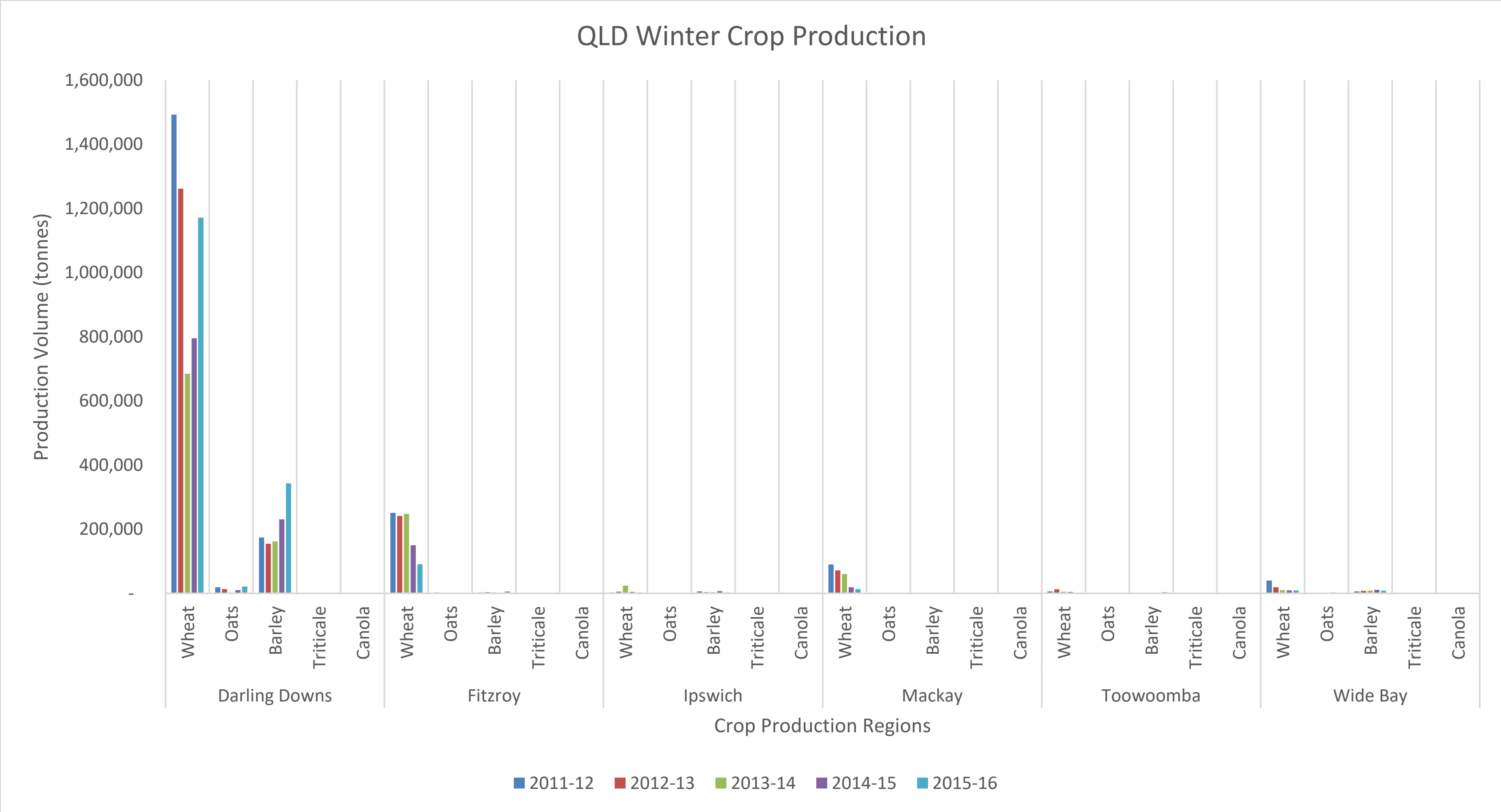

Figure 5-A-3 Historical QLD winter crop production across major sorghum growing regions

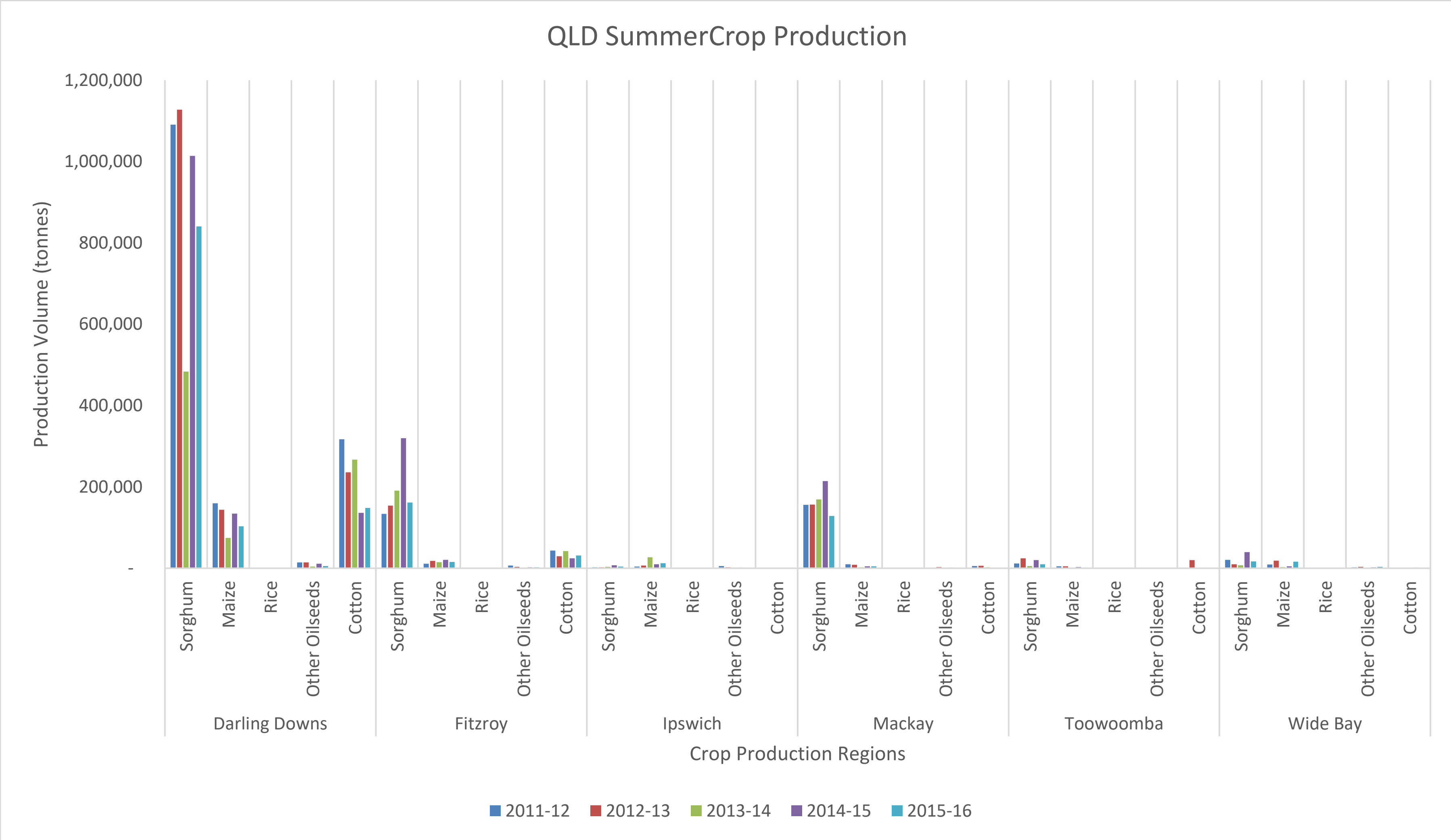

Figure 5-A-4 Historical QLD summer crop production across major sorghum growing regions

Appendix 5-B: Regression Output to Guide the Selection of a Single Planting Period across Regions

For geographic regions where more than one planting period was identified, Ordinary Least Square (OLS) regression models were developed to guide the selection of a single planting period. The summary of the data from these models is supplied in **Table 5-B-1**.

Table 5-B-1 Summary of results from OLS regression models. Rows in italics indicate the planting month that was selected as the planting period for that particular geographic region.

SD Region	*Planting Month*	*Coefficient (SP)*	*Standard Error*	*t-statistic*	*p Value*	*Model R^2*
Northern NSW	*October[a]*	*712.56*	*391.95*	*1.82*	*0.079*	*0.0992*
	December	588.04	323.54	1.82	0.079	0.0992
Hunter	October	14.06	49.97	0.28	0.780	0.0026
	December[a]	*37.76*	*40.72*	*0.93*	*0.361*	*0.0279*
North Western	*September[a]*	*91.50*	*80.30*	*1.14*	*0.264*	*0.0415*
	December	13.386	66.68	0.20	0.842	0.0013
Darling Downs	October	987.47	413.79	2.39	0.024	0.1595
	December[a]	*876.86*	*336.42*	*2.61*	*0.014*	*0.1846*
West Moreton	September	-14.44	12.14	-1.19	0.244	0.045
	December[a]	*-24.46*	*9.07*	*-2.70*	*0.011*	*0.1953*
Wide Bay	September	-107.3	60.66	-1.77	0.087	0.0945
	December[a]	*-112.45*	*47.61*	*-2.36*	*0.025*	*0.1568*
Fitzroy	September	-232.6	433.30	-0.54	0.595	0.0095
	December[a]	*-451.43*	*344.45*	*-1.31*	*0.200*	*0.0542*
Northern QLD	September	2.851	6.49	0.44	0.664	0.0064
	December[a]	*-3.832*	*5.25*	*-0.73*	*0.471*	*0.0175*
Mackay	*September[a]*	*253.01*	*161.47*	*1.57*	*0.128*	*0.0756*
	December	137.61	134.29	1.02	0.314	0.0338

[a] The month selected as the planting period for given regions, based on the regression results

Appendix 5-C: Empirical Model with Additional Explanatory Variables

An additional regression model (building on Model 4) incorporating extra explanatory variables (price risk and non-linear quadratic impact of rainfall) was developed. The price risk variable was defined as the weighted sum of the squared deviations of the spot price at harvest from the futures price that was expected at the time of planting 5-C-1[106]. The selection of weighting factors (0.5, 0.33 and 0.17) was based on previous research[103, 104, 389, 399, 411].

$$Price\ Risk_t = 0.5(SP_{t-1} - FP_{t-1})^2 + 0.33(SP_{t-2} - FP_{t-2})^2 + 0.17(SP_{t-1} - FP_{t-3})^2 \quad \text{(5-C-1)}$$

SP represents the real harvest time spot price of sorghum in a given year and *FP* represents the real futures price of sorghum at planting (for a given year) that is due for maturity at the time of harvest in the same year as the observed spot price. Where the sorghum futures price was unavailable, the same method used to derive the expected price of sorghum, outlined in section 5.2.5 was applied.

The same approach as previously outlined was implemented to generate the empirical model. The summary and statistical significance of the results are presented in **Table 5-C-2**. Sorghum basis was preferred to the sorghum price risk variable due to the ease of interpretation of the coefficient and its superior statistical fit. There did not appear to be a non-linear impact of rainfall and as such the non-linear specification was not included in the primary model.

Table 5-C-2 Summary of model including additional explanatory variables

Parameter	*Coefficient*	*Standard Error*	*t-statistic*	*p Value*
Lagged Area	0.40***	0.08	5.30	0.000
Lagged Yield	327.24	513.73	0.64	0.529
Sorghum Spot Price Regression Planting	126.83	67.12	1.89	0.068
Corn Spot Price Regression Planting	-190.88**	51.26	-3.72	0.001
Cotton Spot Price Regression Planting	-13.95	12.00	-1.16	0.254
Sorghum Price Risk Regression Planting	0.23	0.30	0.77	0.449
Sorghum Basis Price Regression Planting	-37.31	22.84	-1.63	0.113
Fertiliser Price	39.87**	11.47	3.48	0.002
Rainfall Regression Planting	45.01	52.10	0.86	0.394
Rainfall_Sq Regression Planting	-0.01	0.13	-0.10	0.918
Expected Sorghum Price Regression Planting	29.47	43.80	0.67	0.506
Expected Corn Price Regression Planting	53.11	97.67	0.54	0.591
Expected Cotton Price Regression Planting	6.98	10.49	0.67	0.510
R-Square		0.2539		
F Statistic		27.35		
Observations		448		

* p<0.05, ** p<0.01, *** p<0.001

Appendix 5-D: Summary of Elasticity Calculations

The calculation of point elasticities for the observed price (sorghum, corn and cotton) and expected price (sorghum) are outlined in **Table 5-D-1**.

Table 5-D-1 Calculations underpinning point elasticity estimates for price variables

Variable	***Calculation***
Sorghum Spot Price Regression Planting	$\left(\frac{189.92}{46162.52}\right) \times 148.87 = 0.612$
Corn Spot Price Regression Planting	$\left(\frac{156.91}{46162.52}\right) \times -158.55 = -0.539$
Cotton Spot Price Regression Planting	$\left(\frac{494.44}{46162.52}\right) \times -6.78 = -0.073$
Expected Sorghum Price Regression Planting	$\left(\frac{145.25}{46162.52}\right) \times 45.58 = 0.143$