Inquiry into the impact of climate change on Queensland agricultural production

Submission No:	6
Submitted by:	Nicola Thomas
Publication:	Making the submission and your name public
Attachments:	See attachment
Submitter Comments:	

Queensland Government

State Development and Regional Industries Committee

Inquiry into the impact of climate change on Queensland agricultural production

Submission by Nicola Thomas, Senior Economist.

23rd August 2023

To Whom it may concern:

I would like to make a submission to the inquiry, as an economist working for Natural Capital Economics I undertook economic analysis for the 2022 report by DRDMW on the potential to develop irrigated agriculture in the Mitchell, Flinders and Gilbert catchments. I undertook crop modelling simulations using CSIRO Agricultural Production Systems Simulator (APSIM) whilst utilising regional daily climatic data. I calibrated APSIM using previous studies and assumed unlimited water and urea fertiliser was applied to crops as required, using daily climatic data from 2000 – 2015. One key feature I identified was that predicted crop yields are below what is required to cover the variable cost of production. Through analysis of APSIM results, I identified that a key driver of crop yields was temperature with heat spikes above average maximum temperatures during key growth periods impacting crop growth and subsequent yields. When heat exceeds the maximum temperatures, a crop can tolerate the crop responds by dropping flowers, grains or leaves impacting crop yield potential.

Similarly, when higher temperatures are combined with rain events this can increase the conversion of soil carbon into carbon dioxide. As the attached report demonstrates, soil carbon is crucial for retaining nutrients within the soil. Climate shocks with higher temperatures and elevated levels of soil moisture result in a reduction in soil carbon. This impact reduces nutrients available to crops and therefore crop yields. The climate shock induced reduction in soil carbon can persist for several years following the climate shock event, resulting in lower crop yield and therefore biomass or crop stubble returned to the soil generating a negative feedback loop.

One method discussed in the report that may mitigate the impacts of climate shocks and increase fertiliser input efficiency is hydro-priming seeds in liquid fertiliser prior to planting. Hydro-primed seeds absorb nutrients through the seed, which are retained once the seed is removed from the liquid and dried. Hydro-primed seeds can be stored and sown as normal. A benefit of hydro-primed seeds is that it delivers the nutrients required for early crop growth and may improve fertiliser efficiency. Hydro-priming is a technique commonly used in horticultural production processes and represents a new method that may reduce fertiliser usage and mitigate the impact of soil carbon climate shocks. Hydro-priming has not had field trials and has only been explored in the report attached to this document. Combining hydro-primed seeds with variations in sowing times may reduce the impact of climate shocks.

If the panel would like to discuss any of the information contained in this note or the report please contact Nicola Thomas, [redacted].

Regards

Nicola Thomas.

THE IMPACT OF CLIMATE SHOCKS ON DRYLAND CROP PRODUCTION IN SOUTH-EAST AUSTRALIA

Nicola Thomas
BComm (Econ)(Hons) (1st Class), BEcon, BAcc

Submitted in fulfilment of the requirements for the degree of
Doctor of Philosophy

Monash Business School
Department of Economics
Monash University
2023

Copyright Notice

Keywords

Agricultural Adaptation, Agricultural Land Use, Agricultural Production Risk Mitigation, APSIM, Australia, Carbon Emissions, Climate Change, Climate Shock, Crop Emissions, Crop Farming Systems, Crop Production, Crop Productivity, Crop Profitability, Crop Rotation, Crop Simulation, Dryland Crop Production, Farmer Utility, Fertiliser Efficiency, Fertiliser Emissions, Field Peas, Food Production, Gross Margin, Hydropriming, Land Management, Land Profitability, Land Value, Low Rainfall, Net Present Value (NPV), Nitrogen Use Efficiency, Production Risks, Soil Carbon, Soil Nitrogen, Soil Nutrient Balance, Soil Productivity, South-eastern Australia, Sustainability, Wagga Wagga, Wheat.

Abstract

Australian dryland low-rainfall crop producers experience significant variance in rainfall and are vulnerable to climate shocks and climate change. This study investigated the effect of climate shocks and predicted climate change on dryland wheat production net present value (NPV) returns and soil productive capacity for a representative study site in south-eastern Australia for 1960-2015. This study found that crop heat stress and the effect of increased soil moisture combined with hotter temperatures on the soils productive capacity had the largest effect on wheat yields and NPV returns.

The study found that higher fertiliser input quantities increase interannual yield variance nonetheless improves soil nutrient content and mitigates the effect of climate shocks on wheat yields, maintaining soil productivity and thus maximising profits. An alternative fertiliser application method to reduce climate shocks on wheat crops is hydro-priming, which further increases wheat yields, NPV returns and maintains soil productive capacity. Fertiliser inputs are currently used to increase production intensity and mitigate climate shocks, however, emit a greenhouse gas, nitrous oxide (Popp, Lotze-Campen, & Bodirsky, 2010). An extension is undertaken to evaluate the effect of a policy change to include a price on fertiliser emissions, farmer fertiliser input decisions, and NPV returns from crop production.

Technological development has provided farmers with a wealth of site soil data. This study utilises site soil carbon and nitrogen variance to develop a method for valuing agricultural land. The soil productivity index applied to land value is tested across various fertiliser input quantities using historical data and predicted climate change providing farmers with a method of evaluating land management decisions.

Table of Contents

List of Figures

List of Tables

List of Abbreviations

APSIM	Agricultural Production Systems Simulator
ASRIS	Australian Soil Resource Information System
BOM	Bureau of Meteorology
CEC	Cationic Exchange Capacity
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DCCEEW	Department of Climate Change, Energy, the Environment and Water
DPI	Department of Primary Industries (NSW)
EU	European Union
FAO	Food and Agriculture Organisation
GHG	Greenhouse Gas Emissions
GRDC	Grains Research Development Corporation
Ha	Hectare
IFA	International Fertiliser Agency
IPCC	Intergovernmental Panel for Climate Change
KG	Kilogram
Kg/ha	Kilograms per hectare
NARCliM	NSW and Australian Regional Climate Modelling
N	Nitrogen
NUE	Nitrogen Use Efficiency
NPV	Net present value
NZ ETS	New Zealand Emissions Trading Scheme
TFP	Total Factor Productivity
UN	United Nations

Statement of Original Authorship

The work contained in this thesis has not been previously submitted to meet requirements for an award at this or any other higher education institution. To the best of my knowledge and belief, the thesis contains no material previously published or written by another person except where due reference is made.

5/08/2023

X Nicola Thomas

Signature: Signed by: a8c70bf3-cf33-4d4c-b8ac-8520f9decc54

Date: 5th August, 2023

Acknowledgements

This research was supported by an Australian Government Research Training Program (RTP) Scholarship. An online proofreading service was used to improve grammar and punctuation. A big thank you to my children Joshua and Lillian Simpson, for their support and encouragement over the course of my PhD. Thank you to Edwyna Harris for her patient guidance, practical advice, and support along the way. Thank you to Michael Ward for his ongoing support and guidance throughout. Thanks to Jeffrey LaFrance and Russell Smyth for their time and efforts guiding me at various stages throughout my thesis.

I appreciate the time and feedback given to me by colleagues including discussions on soil structure, hydrology and soil carbon with Petter Nyman and discussions on APSIM programming with Rohan Eccles. I'd like to thank Professors David Pannell and Bill Malcolm for their time and insightful comments when reviewing my work, their feedback has been particularly appreciated.

Chapter 1: Introduction

This study aims to investigate the effect of climate shocks on dryland wheat net present value (NPV) returns and soil productivity for a representative study site in south-eastern Australia. Climate change is predicted increase to climate shocks and therefore wheat yield variance, reducing the land's productive capacity and farmers' NPV returns. This study aims to identify the climate shocks that significantly affect the income from land and the soil's productive capacity, developing a new method of evaluating land utilising soil productivity variation.

The study aims to determine the most efficient quantity of fertiliser required to mitigate climate shocks to maintain soil carbon and nutrients, or soil productivity, and land value and thus maximise profits. In addition, an alternative fertilisation method, hydro-priming, will be presented and evaluated to determine whether it reduces the effect of climate shocks and whether it produces any improvements in fertiliser input efficiency, crop yields or profits. Finally, climate change is exacerbated by fertiliser emissions. The effect on farm management decisions of a policy shift to reduce fertiliser emissions will be explored to provide insight into potential solutions to improve fertiliser input efficiency usage and reduce agricultural greenhouse gas emissions.

This chapter provides the framework for the research undertaken to complete the study. An outline of current dryland crop production in south-eastern Australia is provided in Section 1.1. Previous research investigating the effect of climate shocks on dryland agricultural production and the methods used to value agricultural land will be summarised in Section 1.2. The objectives and proposed outcomes of this study will be discussed in Section 1.3. The significance and scope of this research are evaluated in Section 1.4, and the contents of the remaining chapters are outlined in Section 1.5.

1.1 CROP PRODUCTION AMID CLIMATE SHOCKS

Prevailing climatic conditions influence crop productivity; low-rainfall dryland crop-producing regions in Australia are exposed to significant climatic variation, experiencing extreme heat and recurring droughts (Hertzler, 2007). Dryland wheat production is a critical component of the agricultural industry in Australia, with Australian producers contributing 13% of total global wheat exports in 2022 (ABARES, 2023). The New South Wales (NSW) region is a critical grain-producing region in Australia, producing 22% of Australia’s winter grains in 2022 (ABARES, 2023). The region is exposed to significant climate variability that results in interannual wheat yield variance (Hughes et al., 2015). Predicted climate change will further affect wheat yields and exports through increased water scarcity, heat stress and climatic variability (Hughes et al., 2015). The development of alternative methods to mitigate the effect of current and future climate shocks on wheat crops is a crucial research theme for supporting south-eastern Australia’s dryland crop producers.

Climate shocks affect wheat yields, but there has been less focus on the effect of climate shocks on soil carbon and nutrient content. Some attention has been given to the relationship between climate shocks and soil physical properties. Zhao et al. (2015) found a link between the productivity capacity of the soil, wheat stubble, climatic conditions and soil organic content. In a review of studies in the United States, Mann et al. (2002) found a link between soil organic carbon, crop yields and climatic conditions. Soil carbon is critical for maintaining crop productivity, soil nutrient accessibility and water-holding capacity (Bauer & Black, 1992). There is an established link between soil carbon and crop yields, but what is less understood is how climate shocks effect soil carbon and the future income that can be derived from land.

Climate shocks effect wheat yields and therefore farmers’ income, but can also impact the future productive capacity of the land and therefore it’s value. Brown et al. (2016) identified land soil productivity as a natural capital asset supporting farmers faced with climate shocks. Previous research valuing individual site characteristics has used hedonic methods or empirical regression analyses of market data to elicit land values (King & Sinden, 1988; Phipps, 1984). Agricultural land with higher soil productivity is found to have a higher market value (Xu et al., 1993). Yet market values may not reflect site-specific soil characteristics or the effect of climate shocks and management practices on the land’s productive capacity. Developing a method of valuing land that can be calibrated to site characteristics is a research area requiring more consideration.

Predicted climate change is expected to increase climatic variability in south-eastern Australia, with an increased frequency of drought and flood events (Speer et al., 2021). Research has focused on the effect of climate change on wheat yields and potential adaptation options, including developing drought-resistant cultivars and varying planting times (Hertzler, 2007; Hughes et al., 2015; Hunt et al., 2019). Wheat is a critical agricultural export; thus, there is continued research into ways to mitigate climate risks and improve wheat yields. While agricultural soil carbon sequestration garnered significant interest with the development of the *Carbon Farming Initiative* in 2013 (Chen et al., 2014), less attention has been given to the effect of climate shocks on the interrelationships between crop yields and soil's productive capacity. Further work is required to better understand how the increased frequency of climate shocks will affect soil productivity and to explore mitigation options.

Australian dryland crop producers are restricted by low average annual rainfall and low-nutrient soils (O'Keeffe, 2018). Increasing nitrogen-rich fertiliser input is one method used to increase wheat yields. Smith et al. (2019) found that increasing fertiliser application quantities improved crop yields in south-eastern Australia with little environmental effect. Maintaining soil nutrients allows wheat crops to maximise growth from available soil moisture (Smith et al., 2019). In addition, the efficient application of fertilisers may improve crops' resilience to climate shocks.

1.2 SUMMARY OF PREVIOUS RESEARCH

Dryland crop productivity is more vulnerable to climate shocks and climate change effects than other forms of crop production because it depends on the rainfall and temperatures throughout the growing season (Venkateswarlu & Shanker, 2012). Excessive rainfall, drought and heat stress during critical phases of crop growth can reduce wheat yields (Asseng et al., 2011). In addition, low-rainfall dryland crop producers are particularly vulnerable to climate production risks, with many producers in Australia located on low-productivity soils (Sadras et al., 2003). Climate risk is a significant driver of seasonal profit variation in Australia (Carberry et al., 2011). Studies have investigated ways to mitigate climate risk effects using variations in dryland wheat planting times and cultivars (Zeleke & Nendel, 2016).

Climate shocks can significantly affect wheat yields and thus the returns generated from agricultural land.

Climate shocks affect crop yields and profits but can also change the quantity of carbon and nutrients stored in the soil. Williams et al. (1989) identified a link between economic returns from land use and soil carbon, soil productivity and temperature. Another climate shock, heat stress, also effects wheat yields and soil carbon content (Sadras, 2002). There is a relationship between soil nitrogen, soil carbon, variable crop yields and climate shocks that requires further exploration to better understand the linkages and explore mitigation options (Baldrock & Farrell, 2013; Davidson & Janssens, 2006; Thorburn et al., 2010).

One potential way to increase early wheat growth rates and improve yields and resilience to climate shocks is by hydro-priming seeds. Hydro-priming is a process whereby seeds are soaked in liquid fertiliser and dried before planting; it is commonly used in commercial horticultural production (Samarah et al., 2016). Field trials in India found that the practice increases early crop growth and enhances crops' tolerance to environmental stresses, including drought, salinity and extreme temperatures (Farooq et al., 2013; Patra et al., 2016). In addition, the method may increase fertiliser input efficiency and reduce soil nutrient extraction, improving the wheat crop's resilience to climate shocks. However, the effect of hydro-priming wheat on soil quality, or the economic benefits to farmers has not been considered previously in the relevant literature (Farooq et al., 2013; Patra et al., 2016).

Climate shocks include seasonal rainfall deficits or storm events. Changes in precipitation may affect the availability of nutrients in the topsoil, where crops' roots are located (Lynch, 2007). With predicted climate change, there will be increased rainfall variability in south-eastern Australia, which may alter the quantity of fertiliser nutrients entering the topsoil. Urea and slow-release fertilisers are generally applied to the soil surface or in subsurface trenches. Reduced rainfall will thus reduce the quantity of fertiliser solute released into the topsoil, reducing nutrients available to wheat and wheat yields. In contrast, during higher precipitation events, the quantity of fertiliser solute entering the soil will increase; nonetheless, higher rainfall will also increase the movement of nutrients through the topsoil and into the subsoil (Sadras, 2002). Therefore, changes in rainfall associated with predicted climate change will alter the quantities of nutrients in the soil, effecting wheat growth and yields (Ghaley et al., 2018).

Fertiliser is one of the most critical inputs for increasing the productive capacity of low-nutrient dryland crop-producing regions. However, nitrous oxide has 298 times the emission intensity of carbon dioxide (Reay et al., 2012). Despite being some of the most efficient users of fertiliser inputs, Australian dryland crop producers contribute to global nitrous oxide emissions. Research by Chen et al. (2008) has found that only 41% of fertiliser applied is used by wheat plants. Increasing fertiliser input efficiency is a key research theme, one way to stimulate the necessary technical innovation and change is by developing a regulatory framework to reduce nitrous oxide emissions. The United Nations Paris Agreement, an emissions reduction policy with 197 signatory countries, does not include agricultural emissions (Waisman et al., 2019). Developing a policy or technical improvements to decrease fertiliser usage while recognising its importance in crop production is an essential research focus.

A critical research focus is the effects of climate shock in Australia on farm management decisions, the income derived from land use and the future productive capacity of the land. Farmers more exposed to climate change in the Murray–Darling

Basin were found by Wheeler et al. (2021) to have higher debt levels and to be located in areas with comparatively higher temperatures and lower rainfall. Farmers more exposed to climate change attempted to mitigate climate risks by changing the mix of crops sown, to maintain farm income and the land’s productive capacity (Wheeler et al., 2021). Another response of farmers exposed to climate risks is to tactically apply fertiliser inputs and utilise cultivars suited to the predicted climatic conditions, to overcome climate shocks and maintain wheat yields and farm income (Hunt et al., 2019; McDonald & O’Leary, 2016). Farmers exposed to climate risk who respond tactically are more profitable than farmers who maintain rigid land management practices (Kingwell et al., 1992).

Agricultural land value represents the present value of future income derived from the land (King & Sinden, 1988). Farmers typically have long-term land use plans, such as holding land for ongoing income generation or as part of a bequest or to meet a succession-planning objective; this contributes to the thin property markets in rural Australia (Hemmings & Hill, 2003). In addition, Australian dryland soils are typically low in nutrients and carbon, which is reflected in the market value of the land (King & Sinden, 1988). Therefore, variations in soil productivity resulting from crop management practices effect future returns from land and, consequently, land value.

A common approach to valuing land is empirical analysis using realised yields and land market data (Tsoodle et al., 2006). Another approach to valuing land is the hedonic willingness-to-pay method used by King and Sinden (1988). However, given the thin agricultural land markets in Australia, using empirical data in an economic analysis may not reflect the current site-specific productive capacity of the land. Chen et al. (1986) suggested that land value returns can be characterised as unrealised dividends from land assets; consistent with this, soil productivity improvements can be considered periodic unrealised dividends that need to be accrued to the asset’s value. To date, there are limited methods of evaluating how soil productivity variation effects the value of agricultural land.

1.3 AIM OF THIS STUDY

Investigating how climate shocks effect wheat yields and soil productivity can support farm management decision-making. Farmers currently mitigate climate shocks through targeted fertiliser input application and the use of crop rotations to maintain soil productivity. However, understanding the interrelationship between climate shocks, wheat yields and soil productivity requires more research. This study will simulate wheat yields using the Agricultural Production Systems Simulator (APSIM) crop modelling software and utilise biophysical data to identify and investigate the effect of climate shocks on wheat yields and the land’s productive capacity. Using biophysical data with a fixed production function will allow the effects of climate shocks on subsequent wheat yields and soil productivity to be evaluated in order to support farm management decision-making and mitigate the effect of climate shocks on farmer income.

The effect of climate shocks from 1960 to 2015 on a study site representative of south-eastern Australia dryland crop producers will be used to calculate the NPV of the profit from a one-hectare plot of land. This will be done using simulated yields with fixed input and output prices in a fixed production function with continuous wheat production. Fixing the production function and prices will enable the clear identification of the effects of climate shocks on wheat production profits and enable the evaluation of the effect of different climate shocks that occur in different seasons.

In addition, simulations will be run in which fertiliser input quantity is varied to determine how increasing or decreasing fertiliser inputs modifies the effect of climate shocks measured using soil productivity and NPV returns from wheat production.

Using a fixed production function and fixed prices will enable the investigation of how predicted climate change will affect soil productivity and farmers' income from wheat production. Daily climate data for 1960-2015 will be varied using the average predicted temperate increase and applied to two simulations using, respectively, the lower and upper bounds of predicted rainfall variation. These simulations have been developed to represent the extremes of predicted climate change. The modified climate data will be used in simulations of continuous wheat production using the fixed production function. The outcomes of climate change simulations will be used to better understand the climate challenges facing farmers and to develop strategies to mitigate the most extreme effects of predicted climate change.

Farmer exposure to climate shocks from predicted climate change will increase, potentially reducing farmer income and soil productivity. Simulations using predicted climate change will vary fertiliser inputs to investigate how fertiliser input variation effects climate risk exposure, farmer income and the land's productive capacity. An alternative management process that could potentially mitigate farmer climate risk exposure, hydro-priming wheat seeds before planting, will be explored, using the process outlined in Chapter 3. The wheat module in APSIM will be varied to account for the effect of hydro-priming on early wheat growth processes, and simulated using identical management techniques and fertiliser inputs identical to those simulated for seeds that are not hydro-primed. A partial budget for the cost of hydro-priming will be constructed and used to compare the profits and NPV returns from hydro-priming to those from using existing management practices. This will be undertaken using historical and predicted climate change data along with various fertiliser inputs to investigate how hydro-priming effects fertiliser input efficiency, soil productivity, farmer climate risk exposure and NPV income from land use.

Using a fixed production function and fixed prices will enable the evaluation of the effect of hydro-priming across a range of climate shocks during the modelling period. As discussed in Section 1.2, hydro-priming has been found to increase wheat’s resilience to drought. However, the benefits of hydro-priming if the land is exposed to above-average rainfall during the production period are unknown. A fixed production function will enable the evaluation of the profitability of hydro-priming across various climate shocks throughout the modelling period.

The profits and NPV returns from existing management practices and hydro-primed continuous wheat production will be compared to those from a crop rotation using wheat and field peas. Currently, crop rotations with a leguminous crop like field peas are used by farmers in the region to mitigate soil productivity losses and as a management technique to reduce pest and disease occurrence. Using historical and predicted climate change data and a range of fertiliser inputs, the soil productivity and economic effects of crop rotations will be investigated and compared to those of primed and non-primed wheat to determine the most effective technique to maintain soil productivity and maximise agricultural NPV returns.

Climate shocks effect not only income from land use but also the productive capacity of the land. This work will develop a soil productivity index (described in Chapter 4) using the biophysical relationships between soil structure, soil carbon, soil nutrients, climatic conditions and land management processes. This soil productivity index will measure the soil’s productive capacity using site-specific soil characteristics. While soil carbon and soil nutrients have been used individually to measure land’s productive capacity, the interrelationship between the variables and its application in economic analysis have not been explored previously. In developing the soil productivity index, the study will incorporate the interrelationship between soil carbon and nitrogen, adding to the literature.

The soil productivity index will evaluate how management processes effect land value. The end-of-period soil carbon and nitrogen content will be extracted from APSIM and incorporated into the soil productivity index to evaluate how a climate shock in a production period effects the land’s productive capacity in the subsequent period and to investigate whether there is any relationship between soil productive capacity and subsequent wheat yields. The soil productivity index will be used to investigate climate shocks in simulations using both historical and predicted climate data. In addition, it will be used to investigate how effective various quantities of fertiliser inputs are in mitigating the effect of climate shocks on the soil’s productive capacity and thus to support farmers’ strategic decision-making.

The soil productivity index provides a mechanism for evaluating the land’s productive capacity. In Chapter 5, a process will be developed where the soil productivity index will be used to vary land value, providing farmers with a site-specific method for evaluating the effect of management decisions on land value. Applying the soil productivity index to land value will provide farmers with a more concrete method of interpreting how management decisions have affected or will affect the future productive capacity of their land. The soil productivity index applied to land value will not capture variations that occur due to changing market preferences for commodity prices. Instead, it will capture only the effect of variations in soil productivity between production periods.

Farmers try to maximise income and the productive capacity of the land. Wheat production requires soil, water, and soil nutrients. A deficiency in any of these will reduce returns from land use. Farmers overcome the low nutrient content in Australian soils by applying fertiliser. Fertilisers increase wheat biomass, grain production and farmer income when combined with sufficient rainfall. However, as discussed in Section 1.1, fertiliser also contributes to climate change through nitrous oxide emissions. The effect on farmer fertiliser input decisions of a policy change putting a price on fertiliser emissions, subsequent yields and NPV profits will be investigated for both hydro-primed and non-primed seed in both historical and predicted climate change simulations.

1.4 SIGNIFICANCE AND SCOPE

Climate risks are a significant driver of income variance for dryland crop producers in south-eastern Australia. Developing a better understanding of how climate shocks effect wheat yields and income from land use will support farmers in mitigating the effects of climate change. Using wheat simulations over a 56-year period will capture a range of climate shocks and their effect on the land’s subsequent productive capacity. Simulating wheat production with fixed production and prices will enable comparisons between periods to determine which kinds of climate shocks have the greatest effects on farmers’ income. The first goal of the study is to use a range of fertiliser inputs will allow the research to generate a better understanding of to what extent regular applications of various quantities of fertiliser to maintain soil nutrient capacity are an effective strategy to mitigate the effect of climate shocks. This work extends the work of Smith et al. (2019) by exploring the economic effect of maintaining soil nutrient capacity.

Second, the study will investigate how climate change effects soil nutrient capacity and the quantity of fertiliser needed to maximise profits and NPV returns from wheat production. The study simulates climate change by varying daily historical climate data records using the statistical downscaling methods used by Jeffrey et al. (2001). Using NSW and Australian Regional Climate Modelling (NARCliM) predicted climate change for the region and applying statistical downscaling to develop predicted climate change datasets for APSIM simulations provides a mechanism to investigate how climate shocks will affect wheat yields and the soil's productive capacity in the future. This work provides a site-specific investigation of the effect of climate change, supporting the development of a better understanding of the effect of climate risks on the wheat production process and how fertiliser input variation can be used to mitigate climate risks and maintain farmer income and the soil's productive capacity.

Third, the application of hydro-priming to wheat production in Australia represents an entirely new wheat production management method, and its investigation makes an essential contribution to the literature. Climate change is predicted to increase heat stress in dryland agriculture, and investigating methods to improve crop resilience to climate shocks is an essential research focus. Hydro-priming is a novel alternative management practice that may improve crop resilience and reduce fertiliser input usage. Evaluating the effectiveness of hydro-priming with current fertiliser application rates and simulating production with a range of fertiliser input quantities will provide insights into an alternative method to increase fertiliser input efficiency, crop productivity and land use returns. Therefore, this work contributes usefully to the body of research on dryland crop production in Australia.

The present study's investigation of hydro-priming includes the construction of a partial budget and the inclusion of an economic analysis that will determine whether hydro-priming is a profitable technique. Previous studies have not considered the economic cost of hydro-priming seeds. This work represents a first attempt at quantifying the economic cost of hydro-priming. The partial budget will cover three different methods to prime seeds, as well as a sensitivity analysis.

Hydro-priming's effects will be investigated by developing a new soil productivity index. The soil productivity index incorporates biophysical data to enable the evaluation of the effect of management decisions. The development of this index and its application to land value represent a new method of evaluating the effect of climate shocks and management decisions on land's productive capacity. The application of the soil productivity index to land value can be combined with agronomic soil analysis to investigate, using site-specific soil characteristics, how a crop rotation sequence, a fertiliser input management process or another method of land use has affected the land's productive capacity.

Fourth, the soil productivity index contributes to research by identifying the link between soil carbon and soil nutrient retention. It provides value by explaining how reductions in soil carbon have an exponential effect on subsequent soil nutrient retention and crop yield. This finding of an exponential relationship between soil carbon and nutrient retention aligns with the findings of De Neve and Hofman (2000). Applying the soil productivity index to climate shocks provides a mechanism for identifying how climate shocks effect soil's productive capacity. Applying the soil productivity index to the APSIM simulation results enables the evaluation of how different management techniques can mitigate those shocks.

Fertilisers contribute to climate change through nitrous oxide emissions (Pachauri & Meyer, 2014). Therefore, reducing agricultural emissions is essential to reducing the severity of climate change. This work investigates the carbon pricing of fertiliser emissions within a profit maximisation framework to evaluate the effectiveness of a carbon price on fertiliser input choices. Currently, there is no global policy on agricultural fertiliser emissions. The findings from this study can be used to develop such a policy to address agriculture’s contribution to climate change.

Finally, this work bridges scientific and economic crop analysis, incorporating detailed scientific crop modelling into an economic model to provide a sophisticated framework for future analysis of sustainable crop production. The model can readily be calibrated to demonstrate the economic effects of scientific advances in crop production. In addition, the model can be used to evaluate such advances’ indirect soil conservation benefits and long-term effect on land value. Its beneficiaries include researchers, land users and government departments, who can use the model to implement land management processes that will sustainably maximise crop productivity.

1.5 THESIS OUTLINE

Chapter 2 presents a literature review that outlines the existing crop productivity and land productivity research, together with previous economic modelling approaches to evaluating land value. Chapter 3 will describe the alternative management technique, hydro-priming. Chapter 4 will present a comprehensive outline of the biophysical modelling used to determine the crop productivity variable. The economic model, the data sources and an overview of the study region will be provided in Chapter 5. The results will be presented in Chapter 6, and further discussion and analysis of the results will be provided in Chapter 7. Finally, the research will be summarised in Chapter 8, which will provide concluding remarks.

Chapter 2: Literature Review

The current literature on dryland crop production globally and in Australia was reviewed to better understand the existing body of knowledge. The literature review will evaluate the significance of previous studies, identify gaps, and shape the direction of this research. This review aims to contribute to the existing knowledge and guide future investigations by contextualising the current study and highlighting knowledge gaps.

This chapter begins with an overview of global crop production from the start of the twentieth century in Section 2.1. Section 2.2 investigates the current literature on wheat production in south-eastern Australia. Section 2.3 explores the climate risks to which the region is exposed. Section 2.4 investigates the existing literature on methods to mitigate the impact of climate risks and adapt Australian dryland wheat production to these risks. Section 2.5 evaluates crop modelling software. Section 2.6 discusses the economic methods used in the literature to evaluate crop production and agricultural land use. Section 2.7 investigates the link between wheat yields, farm income and fertiliser inputs, including global fertiliser emissions policies. Section 2.8 investigates a novel alternative management technique: hydro-priming. Section 2.9 discusses the relationship between soil nutrients and carbon content and their link to soil productivity. Section 2.10 explores economic methods of valuing agricultural land, with the chapter concluding with a summary and implications in Section 2.11.

2.1 CROP PRODUCTION

Crop production management techniques have changed dramatically since the start of the twentieth century. The introduction of modern machinery and equipment has revolutionised agricultural production processes. In the twentieth century technological advances have made farming operations more efficient, reducing labour requirements and increasing productivity (Kerridge, 1969). Agricultural technology increased crop productivity and production intensity through a variety of innovations. The development of synthetic fertilisers after World War Two was another innovation that resulted in a significant increase in global crop productivity, primarily when combined with newly developed herbicides and higher yielding crop varieties (Whitehead, 1977).

Developing and adopting improved seed varieties have significantly contributed to increased crop yields. Plant breeding programs have focused on developing cultivars with desirable traits such as high yield potential, disease resistance and drought and heat stress tolerance. These improved seed varieties have enhanced the productivity and resilience of crops, leading to higher yields and global agricultural land use productivity. The increased crop productivity corresponded to rising global population growth rates and food demand (Smil, 2011).

In the latter part of the twentieth century and into the twenty-first century, the development of precision agriculture utilising satellite and electrical engineering innovations increased agricultural productivity (Pedersen & Lind, 2017). Precision agriculture techniques have revolutionised crop production by enabling farmers to apply fertiliser more precisely and efficiently, improving soil nutrient availability and increasing crop yields. Global Positioning System technology, remote sensing and Geographic Information System tools allow farmers to gather data on soil moisture, nutrient levels, and crop health (Pedersen & Lind, 2017). Recent technological developments have provided farmers with information to tailor their input applications, such as fertilisers and irrigation, to specific areas of their fields, optimising resource utilisation and improving soil productivity. For example, using satellite and mobile phone technology to map soil nitrogen variation across a field has enabled more precise fertiliser application and the calibration of machinery to deliver varied fertiliser quantities across fields (Grafton et al., 2015).

Advancements in agricultural technology have enabled farmers to make data-driven decisions. In a survey of European farmers, Södergård (2021) found that farm management software and decision support tools helped farmers analyse data collected from various sources, including weather stations, soil sensors and machinery. Climate information assists farmers in making informed decisions regarding planting dates, crop rotation, pest management and irrigation scheduling, optimising resource allocation and wheat production while minimising environmental impact (Södergård, 2021). Australian dryland crop producers are similarly exposed to variable climatic conditions and utilise the predictive forecasting of the Bureau of Meteorology (BOM) and data from farm-level information systems to support land use management (Cai et al., 2019).

Technological advances in soil and crop growth monitoring to actively apply management interventions are increasingly common and increase the sustainability of production management processes (Hunt, 2021; van Rees et al., 2014). Numerous studies have used data to investigate fertiliser application placement, rate, timing and frequency, focusing on crop yields, land use returns and risk mitigation (Asseng et al., 2012; Hunt, 2021; van Rees et al., 2014). Precision agriculture and specialised fertiliser and herbicide application processes are popular data-driven methods to increase crop yields and reduce the risk of negative returns. In addition, significant innovations in crop production management processes have enabled the expansion of crop production areas and the intensification of existing land use. Technology has supported farmers to increase crop yields and production efficiency.

Technological advancements have improved soil management practices, leading to enhanced soil productivity. Soil testing methods, such as grid sampling and electromagnetic induction, provide farmers with detailed information about soil nutrient levels and variability across fields. Brown et al. (2016) surveyed Australian farmers and found that farmers use a range of indicators to adapt their land management processes in response to predicted climate variability. Soil testing data enables precise nutrient management, which ensures crops receive suitable fertilisers based on their needs. Van Rees et al. (2014) evaluated Australian crop farmers’ use of Yield Prophet® crop simulation and management software to support farmers in deciding when to apply in-crop nitrogen fertiliser using site climate and soil data[1]. That study found that crop simulation technology increased fertiliser efficiency and crop yields. Technology supports farmers’ soil management practices, thus increasing land productivity and farmer income.

Other management practices that increase soil productivity include conservation practices like minimum tillage, stubble retention and cover cropping. Conservation agriculture involves farming practices that help maintain soil structure, reduce erosion, and improve water infiltration, leading to healthier and more productive soils (Hobbs et al., 2008). Australian winter crop farmers are exposed to

---

[1] Yield Prophet uses the Agricultural Production System Simulator (APSIM) model, developed and maintained by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) and the APSIM Initiative, to simulate the effects of environmental variables and management decisions on crop yields. More information is available at https://www.yieldprophet.com.au/yp/Home.aspx.

climate risks, which soil productivity losses can exacerbate with Bellotti and Rochecouste (2014, p. 22) finding that 60% of winter crop producers in Australia utilise soil conversation practices, including retention of crop residue *in situ* and no-tillage crop sowing. Therefore, conservation agriculture is an important management technique for sustainable land use.

2.2 WHEAT PRODUCTION IN SOUTH-EASTERN AUSTRALIA

Dryland wheat production in south-eastern Australia has a rich history that developed throughout the twentieth century due to the adoption of the technological innovations outlined in Section 2.1. In 2022, New South Wales (NSW) produced 22% of Australia’s 67 Mt winter crop harvest (Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES), 2023). Australia is one of the largest wheat producers globally, with Australian wheat exports constituting 13.7% of the global wheat supply (ABARES, 2023). The adoption of global technological innovations throughout the twentieth century made wheat producers in Australia some of the most efficient globally.

Australian dryland crop producers are exposed to significant climate variability, impacting crop yields and production efficiency. Previous works have found Australian farmers are typically risk-averse (Kingwell and Pannell, 2005; Monjardino et al., 2013). However, recent research has found that most Australian farmers consider themselves risk-neutral (Aither, 2020). Therefore, the increased risk exposure accompanying a change in management practices may not be accepted if significant capital investment is required or if there is the potential for production losses compared to existing management practices. A literature review by Pannell

(2017) found that climate risks influence farm management decisions, farmer risk profiles and the marginal benefits associated with the altered management process.

Developing high-yielding and disease-resistant wheat cultivars suitable for the New South Wales region's climatic conditions through plant breeding programs has supported the technical efficiency of the region's wheat production. Zeleke and Nendel (2016) found that matching cultivars to predicted climatic conditions increased wheat yields and income for south-eastern Australian farmers. McDonald and O'Leary (2016) undertook field trials and identified a range of high-yielding drought-tolerant wheat cultivars for Australian states to overcome soil moisture and nutrient deficits. Australian farmers' adoption of improved seed varieties increased wheat productivity and promoted crop resilience to climate risks.

Farmers utilise improved wheat cultivars with synthetic fertilisers to increase wheat yields. As discussed in Section 2.1, the development of synthetic fertilisers after World War Two, combined with a more recent improved understanding of soil science, enabled farmers to optimise nutrient levels in their fields (Price, 2009). This practice enhanced soil fertility, which improved yields and crop quality (Angus & Grace, 2017). Advancements in pest and weed control technologies, such as developing herbicides and insecticides, helped farmers manage pests and weeds effectively (Umina et al., 2019). These efficacies reduced crop losses and increased overall productivity, enabling south-eastern Australian farmers to increase the area devoted to a single crop and reduce production costs through increased economies of scale. However, Umina et al. (2019) found that Australian crop producers have recently been witnessing increased resistance to herbicides and insecticides used to control pests and diseases. More holistic conservation agriculture methods, including rotating crops, have been found to prevent pest and disease prevalence naturally while also improving soil productivity (Armstrong et al., 2019).

Despite improved production efficiency and technological advances, south-eastern Australia is susceptible to climate variability, including droughts, heatwaves, and frosts, which can significantly impact yields. Research by Hochman et al. (2017) found that crop productivity increases have slowed in Australia in recent years due to increased climatic variability. With the predicted climate change and an increased frequency of climate shocks, strategies to enhance productivity, mitigate climate risks and conserve natural resources are critical research areas. Continued research, innovation and collaboration among farmers, researchers and policymakers will play a crucial role in ensuring the long-term viability of dryland wheat production in south-eastern Australia.

2.3 SOUTH-EASTERN AUSTRALIAN DRYLAND CROP PRODUCER'S CLIMATE RISKS

As identified in Section 2.2, dryland crop producers in south-eastern Australia are vulnerable to various climate risks that can significantly impact their agricultural operations. Climate risks such as droughts, heatwaves, extreme weather events and changes in rainfall patterns pose challenges to crop yields and the overall health of agricultural systems (Talan, 2014). Climate risks directly impact the crop yields of dryland producers in south-eastern Australia. Feng et al. (2018, p.561) found that rainfall extremes in the NSW wheat belt explained 41–67% of the interannual yield variance. Reduced rainfall and prolonged dry spells decrease soil moisture availability, impairing plant growth and yield potential. Extended periods of below-average rainfall can lead to soil moisture deficits, reduced crop growth and yield losses (Sadras, 2002). Drought conditions reduce crop productivity and may result in decreased plant residue inputs to the soil, leading to lower carbon inputs and potential soil productivity losses.

High temperatures can accelerate crop evapotranspiration rates, further depleting soil moisture and reducing soil carbon and productivity. High temperatures during critical crop growth stages can impact pollination, grain development and wheat yield potential. Flohr et al. (2017) studied 28 locations across the Australian wheat belt between 1963 and 2013 found that heat stress can impact flower development and grain set, with heat damage and rainfall variation significantly affecting wheat yields.

Severe storms, hail and frost can damage crops, cause yield losses, and disrupt farming operations. Barlow et al. (2015) found that extreme weather events, including frost, can damage or kill wheat crops. During early growth stages, frost can kill juvenile wheat plants, while frost during flowering or grain filling reduces wheat yield. Other climatic risks that can impact wheat yields and soil productivity include changes to rainfall patterns that disrupts planting and harvest schedules. Shifts in rainfall timing and intensity can affect planting and harvest schedules and crop growth and development (Potgieter et al., 2013). Additionally, changes in rainfall patterns can affect soil nutrient content, moving nutrients through the topsoils into the subsoils where they are inaccessible to wheat root systems (Sadras et al., 2016). Climate shocks introduce significant variability in crop yields and can impact soil productivity, with the variability increasing farmers’ risk exposure, which may impact land use income.

Crop yield reductions resulting from climate shocks can lead to substantial economic losses for farmers. Li et al. (2022) found that south-eastern Australian wheat yields experienced significant interannual variations. However, they identified no specific trend in yield variations between the 1930s and 1990s. Over time, farmers reduced yield variability by adopting newer climate-resilient cultivars. However, Li et al. (2022) found yield variance remained despite newer climate-resistant cultivars. Lower yields directly impact farm income and profitability; Browne et al. (2013) found that regional wheat farmers’ income is more affected by climate-induced yield variance than global commodity price variance. Consequently, climate-induced income variance can significantly impact farmer income and farmers’ ability to repay debts and invest in farm improvements.

The variance in wheat yields resulting from climate shocks has financial and biophysical impacts. Climate shocks disrupt soil processes and adversely impact soil carbon and nitrogen levels and overall soil health. Reduced soil carbon and nutrient availability can impact future crop productivity and the long-term sustainability of agricultural systems. An NSW Government framework identified a link between soil carbon, climate risks and the sustainability of food production systems (Boylan et al., 2018). Climate shocks lead to the adoption of adaptation strategies and the development of resilient farming practices. Rochecouste et al. (2015) found that Australian dryland crop producers seek to mitigate climate shocks’ economic impact on soil productivity by implementing conservation agriculture practices.

Dryland crop producers in south-eastern Australia are exposed to various climate risks. Climate shocks, including droughts, heatwaves, extreme weather events and changes in rainfall patterns, can lead to yield losses, reduced soil carbon and nitrogen and economic challenges for farmers. Therefore, understanding the significance of climate shocks is essential for developing adaptation strategies, improving resilience, and ensuring the long-term sustainability of dryland crop production in the region.

2.4 MITIGATING CLIMATE SHOCKS AND ADAPTING WHEAT PRODUCTION

Research to support south-eastern-Australian wheat producers adapting to climate shocks has developed a range of strategies to reduce the vulnerability of wheat crops to climate shocks and improve the resilience of agricultural systems. Key research themes include crop breeding and cultivar selection, crop rotation and land use diversification, soil conservation practices, integrated pest and disease management, weather forecasting and technology to improve production management decisions.

As discussed in Section 2.1, the development and use of climate-resilient wheat varieties adapted to local conditions can help mitigate the impact of climate shocks. Climate-resilient wheat cultivars are drought- and heat-tolerant and disease-resistant (Celestina et al., 2023). There has been significant research and development undertaken to breed and select varieties that are better suited to the changing climate, with a wide range of wheat varieties available bred for different growth, flowering and grain traits, which farmers can use to reduce exposure to climate shocks (Celestina et al., 2023).

Utilising more resilient wheat cultivars developed to suit Australian conditions is one method to reduce climate risk exposure. Another is utilising crop rotations to improve soil health. Implementing crop rotation systems and diversifying the range of crops grown can help reduce the risk of crop failure and enhance soil health (Armstrong et al., 2019). Including legume crops in rotations enables soil nitrogen fixation to occur and this improves soil fertility while reducing reliance on synthetic fertilisers. Another benefit of crop rotation is reduced pest and disease exposure. Murray and Brennan (2009, p. 563) found that during the millennial drought between 1998 and 2008, pathogens reduced the annual regional wheat value by 19.5%. Climate shocks can lead to increased pest and disease pressure implementing integrated pest and disease management practices, including crop rotations, can help mitigate the impact of these challenges and maintain healthy wheat crops.

Maintaining healthy wheat crops requires healthy soils, and conservation tillage practices, such as no-till or reduced tillage, can help conserve soil moisture, reduce erosion, and enhance soil productivity (Chan et al., 2003). Increasing soil organic carbon content can improve soil fertility, water-holding capacity, and overall resilience to climate change. Using organic amendments can increase carbon sequestration in agricultural soils. Rabbi et al. (2014, p. 50) found that 9.2% of the soil carbon variation in farming soils in NSW occurred through variation in land management practices, with rainfall positively correlated with soil carbon content. Research by Meier et al. (2017) across the Australian wheatbelt found that soil clay content positively correlates with soil carbon balances. Improved soil productivity is a critical management practice to reduce the exposure of wheat production to climate risk.

Access to accurate and timely weather forecasts and climate information is crucial for making informed decisions about planting, irrigation, and crop protection. By combining climate data with site soil analysis, farmers can calibrate management decisions to predicted climatic conditions (Cai et al., 2019). As discussed in Sections 2.1 and 2.2, the development and implementation of farm management technology has increased land productivity, improved farm management decision-making and reduced climate risk exposure. Incorporating weather monitoring systems and decision support technology into land use management can enable farmers to reduce the impact of climate shocks. However, continued research into reducing climate shocks is required to support farmers with an integrated approach to wheat production that considers a suite of climate risk mitigation and adaptation measures to ensure the long-term sustainability and productivity of wheat crops.

2.5 CROP MODELLING SOFTWARE

Investigating the impact of climate shocks and mitigation options on wheat production has been facilitated using crop modelling software. Crop modelling software is a valuable tool that simulates and predicts crop growth, development, and yield under different environmental and management conditions. These software programs utilise mathematical models and input data such as weather, soil characteristics, crop management practices and genetic information to simulate the behaviour and performance of crops.

To generate crop yields, crop modelling software simulates crop production using soil characteristics, including soil nitrogen and carbon, combined with study site climatic conditions and land management processes. The development of crop production simulation models commenced when computer technology became widespread throughout developed economies. The first crop production simulation was the Decision Support System for Agrotechnology Transfer (DSSAT) model developed in the late 1980s (Koo, 2016). DSSAT enables users to evaluate the effects of climate variability, soil fertility, irrigation and management practices on crop performance and productivity, incorporating the country’s gross domestic product (GDP) and output demand into land use production decisions. DSSAT utilises site climatic conditions, soil structure, soil organic material and macronutrient daily, weekly, or monthly timesteps to calculate crop yield and productivity. DSSAT uses soil pools through which nutrients cycle, which allows organic material build-up to occur; however, the simulation cannot be readily calibrated to individual variables of interest outside the modelling parameters.

A model that evolved in the late twentieth century was the Agricultural Model Intercomparison and Improvement Project (AgMIP). AgMIP is a global community modelling crop, livestock, and socioeconomic practices to assess regional land productivity (Rosenzweig & Hillel, 2013; von Lampe et al., 2014). Like DSSAT, AgMIP integrates economic analysis into production to evaluate the impact of a changing supply on market pricing and crop production, resulting in welfare impacts (Rosenzweig & Hillel, 2013). The DSSAT and AgMIP crop modelling software packages do not vary the decomposition rates of soil organic material, instead using set ratios for organic material decomposition (Jones et al., 2003; Parton et al., 1988; Rosenzweig & Hillel, 2013). AgMIP and DSSAT software requires extensive training and cannot be easily recalibrated to include variables other than those predetermined by the program.

The Agricultural Production Systems Simulator (APSIM; McCown et al., 1996) is a flexible model which can be calibrated to individual research questions. It is a multidiscipline crop modelling research platform with ongoing support and online training. APSIM is freely available and was initiated by the Commonwealth Scientific and Industrial Research Organisation. With continued collaboration and development through a GitHub platform, it is one of the most widely used crop modelling suites globally. APSIM uses plant, animal, soil, climate, and management interactions to evaluate land use. APSIM can simulate crop growth and development aspects, including phenology, water balance, nutrient cycling, and pest dynamics. APSIM centralises decision-making around the soil system, which varies with daily climatic data and management processes. APSIM contains individual modules which can be customised by users to suit their needs (McCown et al., 1996; Rötter, 2018).

Crop modelling software programs help researchers, agronomists and farmers examine crop performance, optimise resource allocation, assess risks, and make informed decisions regarding planting dates, fertilisation, irrigation, and other management practices. As a result, they are valuable tools for improving agricultural productivity, optimising resource use, and mitigating the potential impacts of climate variability on crop production. Crop modelling software has been utilised for various economic land use analyses globally to investigate different aspects of climate risks to which farmers are exposed. For example, Asseng and Pannell (2012) investigated the impact of climate change on agricultural production using APSIM crop modelling software and forecast climatic data within an economic analysis. They found that the precipitation variation forecast by the BOM for the study site in Western Australia had minimal impact on winter wheat crop returns.

Crop modelling software can simulate and account for daily soil carbon and nitrogen content fluctuations. By incorporating daily changes in soil carbon and nitrogen dynamics, crop modelling software can provide insights into the temporal dynamics of these nutrients in agricultural systems. This information can be valuable for assessing nutrients available to crops, understanding nutrient cycling processes and optimising management practices such as fertiliser application timing and rates. Dai et al. (1993) evaluated the impact of stochastic variables such as fertiliser application rates on farmer utility derived from corn production in Indiana, United States (US), comparing the returns generated through different fertiliser application quantities. Smith et al. (2019) used APSIM software in south-eastern Australia to simulate wheat production and yields with varied fertiliser input quantities to evaluate the impact on soil nitrogen and wheat yield. Cann et al. (2020) investigated the economic impact of continuous wheat production compared to crop rotation or a crop-fallowing system with various fertiliser inputs using APSIM. Crop software enables the investigation and evaluation of alternative management practices to improve soil nutrients and productivity, thereby improving farmer income and reducing climate risk exposure, as identified in Section 2.4.

Determining the success of new management methods under predicted climate change scenarios requires evaluation of the impacts of a varied climate on novel management methods. Statistical downscaling is a method developed by Gaffin et al. (2004) to investigate climate change impacts. Statistical downscaling uses the relationship between historically observed climate data and predicted climate change to create a future climate dataset. APSIM software has been used with the statistical-downscaling method to investigate the impacts of climate change on crop production in Australia with varied research questions, including the impact on wheat yields, land management and climate change adaptation strategies for wheat production across the Australian wheatbelt (Asseng & Pannell, 2012; John et al., 2005; Keating et al., 2003; Ludwig et al., 2009). Crop software simulation outputs using predicted climate change are valuable for reducing farmer climate risk exposure.

2.6 ECONOMIC EVALUATION OF CROP PRODUCTION

Improving land use management decisions through crop software is supported by applying an economic framework to research outcomes. Economic modelling plays a crucial role in understanding and predicting changes in agricultural land value. Economists use various techniques to identify factors influencing land value and to develop models that simulate and forecast these changes. Utilising economic analysis to support land management practices can demonstrate economic incentives to farmers, increasing the uptake of new management methods.

Economic regression analyses of factors impacting crop production returns have investigated factors affecting crop productivity, including soil degradation, soil erosion, climate change mitigation strategies, soil carbon sequestration, the financial and yield impacts of variable seeding, and fertiliser application rates (Görlach et al., 2004; Kragt et al., 2012; McNunn et al., 2019; Van Grinsven et al., 2013). The analyses have focused on biophysical effects and returns from land use with researchers paying less attention to how climate shocks impact farmer income, land value and the economic impact of predicted climate change.

Economic evaluations of the methods to maximise crop production returns from land use vary, with the modelling technique used depending on the research question posed. One strand of research has focused on management methods to increase returns from land used for crop production; this includes investigating crop rotations, varied fertiliser inputs and soil preparation within an optimisation framework (Doole & Hertzler, 2011; Grace et al., 2019; Miranowski, 1984; Mjelde et al., 1988). This optimisation allows for periodic adjustment, capturing individual farmer risk management responses to changing land use, input or output market price variation or forecast climatic variation. Optimisation is a flexible modelling system utilising backward induction within discrete modelling and is suited to analysis with empirical data. However, novel management processes have not been captured in empirical data therefore, optimisation processes are unsuitable for evaluating the economic impact of new management techniques.

An alternative method of investigating the effectiveness of novel management processes is simulations. Various studies at sites across Australia have used crop simulation software to examine the economic impact of climate change on crop yields, varied fertiliser input quantities, farmer land use evaluation and the timing of fertiliser application on land use returns (Cann et al., 2020; Kandulu et al., 2012; John et al., 2005). Crop simulation software simulates crop growth and yields for a study site, incorporating the output into economic modelling. Crop simulations utilise forward induction, with future returns from land use influenced by prior period management decisions.

One land use analysis method commonly used with crop production investigations using simulation data is net present value (NPV) economic evaluations. Various studies have used NPV modelling to evaluate climate change's impact, soil carbon variation and alternative crop rotations' impact on land use returns (Asseng & Pannell, 2012; Kandulu et al., 2012; Keating et al., 2003). NPV models calculate a discounted NPV for land use returns generated over the modelling period. In addition, NPV can incorporate price variation, undertake sensitivity analysis to verify the modelling outcomes and provide a more flexible method suited to simulations where empirical data is unavailable.

2.7 FERTILISER USAGE IN CROP PRODUCTION

Fertiliser use in crop production can significantly impact the efficiency and productivity of agricultural systems. Efficient fertiliser use involves applying the right type and volume of fertilisers at the right time to optimise crop growth while minimising negative environmental impacts. Australian crop producers are some of the most efficient fertiliser users globally and use several methods to improve fertiliser efficiency, including soil testing, precision application technology, placement and timing.

Conducting regular soil tests helps farmers understand the nutrient status of their soils, enabling them to make informed decisions about fertiliser application. Soil testing helps identify nutrient deficiencies or excesses, allowing farmers to adjust fertiliser rates accordingly. Recent studies in crop production fertiliser use have promoted the maintenance of a soil nitrogen bank, which applies nitrogen fertilisers more regularly to maintain soil nitrogen content rather than applying nitrogen strategically during the production period to maximise yield (Hunt, 2021; Smith et al., 2019). These studies found that maintaining higher soil nitrogen levels, regardless of the crop production lifecycle stage, increases crop productivity with minimal environmental impact. Developing a nutrient management plan based on soil test results and crop nutrient requirements can optimise fertiliser use efficiency.

Precision agriculture technologies, such as variable rate application (VRA) systems, can enhance fertiliser use efficiency. VRA systems apply fertilisers at varying rates across a field, considering spatial variability in soil nutrient levels. Basso et al. (2011, p.219) found that variable fertiliser application in a Mediterranean environment improved environmental and economic outcomes in spatially variable fields. Similarly, for fields prone to waterlogging in south-eastern-Australia VRA systems, increase wheat yield by 1% while reducing fertiliser inputs by 7% (Nordblom et al., 2021, p.10). Research has shown that VRA systems increase fertiliser input efficiency while maintaining wheat yields. A central Queensland study by Bell et al. (2020) found that placement techniques, such as banding or side dressing, improve wheat nutrient uptake efficiency and reduce nutrient losses. Side dressing or banding targets fertiliser application near the crop’s root zone, minimising nutrient losses.

Applying fertilisers at the right time is crucial for maximising nutrient uptake and minimising losses. Splitting fertiliser applications into multiple smaller doses throughout the growing season can synchronise nutrient availability with wheat demand, reducing wastage and environmental impacts when combined with sufficient precipitation (van Rees et al., 2014). Efficient fertiliser application over the wheat production period increases yields and farm income while supporting soil productivity. Angus and Grace (2017, p. 442) found that only 40% of nitrogen fertiliser applied in Australia is recovered by dryland wheat crops, with the remainder denitrified, retained in the soil, or converted into nitrous oxide. Further, fertiliser efficiency improvements can improve wheat yields and increase farming sustainability.

Efficient fertiliser use in crop production is essential for sustainable agriculture, as it ensures optimal crop growth while minimising the potential for nutrient runoff and environmental degradation. Farmers do not commonly consider fertiliser nitrous oxide emissions or residual effects on land value when making fertiliser input decisions. Rather, they primarily consider yield and utility benefits (Reader et al., 2018). Fertiliser usage can increase nitrous oxide emissions and exacerbate the greenhouse effect, increasing the rate of climate change. Up to 16% of fertiliser applied to the soil surface becomes nitrous oxide. Nitrous oxide has a 298-times stronger warming effect than carbon dioxide, accounting for 55% of Australia’s agricultural soil emissions annually (Mielenz et al., 2016, p. 565). A crucial research area is investigating methods to reduce fertiliser input usage and contribution to climate change.

Several countries have implemented policies and initiatives to reduce fertiliser emissions and promote sustainable agricultural practices. The Netherlands has implemented a nitrogen reduction program that includes measures to reduce nitrogen emissions from fertiliser use in agriculture (Guenther et al., 2022). New Zealand has introduced a policy to reduce nitrogen and phosphorus losses from agriculture[2]. The New Zealand Government has set limits for nutrient runoff from farms and encourages farmers to adopt nutrient management plans and practices that minimise nutrient losses (Guenther et al., 2022). Australia has various initiatives and programs to address fertiliser emissions and promote sustainable agriculture. For example, the Australian fertiliser industry *Code of Practice* (Fertilizer Australia, 2018) promotes best-management practices for fertiliser use to minimise nutrient losses and reduce environmental impacts.

Despite global policy initiatives to increase fertiliser efficiency and reduce emissions, emission reductions in agricultural emissions policies are restricted to carbon dioxide (Ignaciuk & Mason-D’Croz, 2014). The New Zealand and European emissions trading schemes (ETSs) are the world’s most developed ETSs. The European ETS is the largest globally, has been operating since 2005 and covers a wide range of activities however, it does not include agricultural sector emissions (Grosjean et al., 2018). A study on a change in the US carbon tax policy and the subsequent effects on crop production choices, market prices and land allocation to crops was completed by Dumortier and Elobeid (2021), who identified a linear relationship between land allocated to crops, and a carbon price on fertiliser

---

[2] The *National Policy Statement for Freshwater Management (2020)*, (Ministry for the Environment, 2023).

emissions. Further work is needed to improve fertiliser input efficiency and evaluate the impact of a price on fertiliser emissions on crop management decisions.

2.8 HYDRO-PRIMING

Hydro-priming is a common seed priming technique used in horticulture to enhance seed performance and may improve fertiliser input efficiency. Hydro-priming involves soaking seeds in water for a specific duration before sowing. The process allows seeds to imbibe liquid which can contain nutrient supplements, and initiate germination, promoting rapid root and shoot growth and leads to early emergence and establishment of seedlings. Patra et al. (2016) found that hydro-priming wheat increased grain yields in India. The enhanced germination and early growth contribute to a better crop stand and reduced susceptibility to biotic and abiotic stresses.

Hydro-priming can be performed mechanically or by hand, using a bucket or machinery and water and dissolving granular fertiliser according to individual crop requirements. Seeds are soaked in the fertiliser solution for up to 24 hours, then dried on a flat surface or in an air dryer and stored until required for sowing (Pedrini et al., 2020). Hydro-priming seeds with liquid fertiliser increases crop germination rates by up to 11% (Di Girolamo & Barbanti, 2012, p. 185) and early growth rates by 6–23% (Di Girolamo & Barbanti, 2012; Farooq et al., 2019; Jisha et al., 2013).

Once primed and dried, seed storage rates decline compared to non-primed seeds, with the seed shelf life longevity influenced by seed type. Di Girolamo and Barbanti (2012) found that priming pepper, onion, and brussel sprout seeds increased shelf storage life while leek, carrot, lettuce, and tomato shelf life declined. Seeds typically have a shelf life of up to 12 years so any shelf life reductions hydro-primed seeds may exhibit are offset by improved nutrient uptake and utilisation, leading to increased grain production. Hydro-priming does not directly impact the soil itself. However, the improved plant growth from hydro-priming may indirectly benefit the soil by enhancing root development and nutrient cycling. Further research is required to understand better the relationship between hydro-primed plants and soil productive capacity.

2.9 SOIL PRODUCTIVITY

Research has identified soil productivity as central to maintaining wheat yields and the sustainability of land (Debonne, 2019). Dryland crop producers in Australia are exposed to flood events, recurring droughts, and high temperatures, which reduce crop yield and can increase soil carbon and nutrient losses (Mallawaarachchi et al., 2017). Soil carbon is essential for sustainable land users: it increases the soil's ability to store moisture and nutrients (Turmel et al., 2015). Climate shocks can increase the rate of soil carbon loss, leading to a reduction in soil nutrients (Arora, 2019).

Management practices to retain organic material increase soil carbon and nutrient retention and crop yields (Grafton et al., 2015; McConnell, 1983; Oldfield et al., 2019). Crop yields are limited by soil nutrient content and texture, and prevailing climatic conditions. Research has identified a link between the soil cationic exchange capacity (CEC), soil nitrogen and carbon content. CEC measures the soil's structure and ability to hold nutrients. Agegnehu et al. (2016) found that increasing soil CEC increases fertiliser retention and crop yield, while Nelson and Mele (2006) found a relationship between soil organic material, CEC rates in the soil and the ability of wheat to absorb nitrogen. Management practices to maintain soil organic material improve soil CEC and, therefore, crop yields and farmer income (Agegnehu et al., 2016; Godde et al., 2016).

Mathematical theorisations of the relationship between soil carbon, organic material additions and the decomposition rate can be utilised to estimate changes in soil carbon content. Olof and Thomas (1997) developed the Introductory Carbon Balance Model (ICBM; see Equation 1), a non-linear soil carbon content model that describes the organic material decomposition rate within soil. The ICBM uses soil carbon measurements taken annually for 30 years from a field in Sweden to derive a mathematical relationship between organic material and soil carbon content. Freshly added organic material decomposes according to the carbon release rate, $-k_t$, a variable that captures the climate impact on surface organic material decomposition, which includes crop residue, r. The decomposition rate for pre-existing organic material within the soil at the start of the period is h. Therefore, the soil carbon decomposition model is as follows:

$$\xi_t = \exp^{-k_t r} + h(1 - \exp^{-k_t r}) \tag{1}$$

The ICBM has a broad application to research questions and has been applied to evaluate the impact of human activity on carbon sequestration in forests (Magnani et al., 2007), how plant diversity affects soil carbon sequestration rates (Lange et al., 2015) and the importance of soil organic material in sustainable agricultural land use (Magdoff & Weil, 2004). Biophysical research has found a positive link between soil clay, carbon, and nitrogen contents however, the ICBM only considers soil carbon variation and does not consider soil nutrient content. Therefore, it has limited application in crop production analysis.

Working concurrently with the ICBM, De Neve and Hofman (2000) used soil data from a Belgian agricultural region to derive a rate at which soil organic material nitrogen mineralises. Soil nitrogen mineralisation is the process that releases nitrogen from soil organic material and converts it into a state accessible by crops. Mineralised soil nitrogen can become a solute (liquid) or be further converted into a gas (nitrous oxide), which is then emitted from the soil into the atmosphere (Probert et al., 1998). The quantity of nitrogen mineralised (released) depends on the percentage of nitrogen held within soil organic material, τ_A, and the mineralisation rate, $^{-k_t}$. De Neve and Hofman (2000) used their data analysis to develop an exponential function, $\tau_t = \tau_A(1-\exp^{-k_t})$ which describes the relationship between soil organic material and the quantity of nitrogen released from organic material and available for crops to use.

The soil nitrogen mineralisation model has been applied to a range of research endeavours. For instance, Tejada et al. (2008) used the model to investigate the impact of green manures on soil restoration and crop yields in semi-arid environments. Hamza and Anderson (2005) used the model to evaluate soil compaction from farm machinery with short crop rotations and increased production intensity. In addition, Sadras et al. (2016) used the model to assess the impact of alternative land management processes on available soil nitrogen and the subsequent effects on crop yields. The soil nitrogen mineralisation model provides a flexible method for calculating nitrogen release rates from soil organic material; however, no studies consider this model within an economic framework.

Individually, the soil nitrogen mineralisation model describes the quantity of soil nitrogen accessible to crops for crop growth and yields, while the ICBM describes the amount of carbon in the soil. Droge and Goss (2013) developed a method for calculating the quantity of nutrients held within the soil structure, π_t, using the amount of organic material in the soil. The quantity of soil nutrients stored in the soil depends on the percentage of clay, cc, and the fraction of organic material, om_t, in the soil. Clay and soil organic material have a positive electrical charge, while nutrients entering the soil, such as nitrogen, have a negative electrical charge (Agegnehu et al., 2016). Increasing the nutrients within the soil requires an equivalent increase in clay or organic material to create the positive electrical charge or cationic capacity necessary for nutrients to be held within the soil. The cationic capacity parameter for clay, CEC_{cc}, or the rate at which clay holds nutrients in the soil, and the rate at which soil organic material retains nutrients, f_{OC}, are both fixed exogenous variables. If the nutrients applied exceed the clay and soil carbon content, water mobilises the nutrients through the soil into subsoils (Godde et al., 2016). Therefore, the quantity of nutrients it is possible to store in the soil is,

$$\pi_t = cc \cdot CEC_{cc} + f_{OC} om_t .$$

Fertiliser is rich in nitrogen nutrients; once fertiliser enters the soil, it adheres to soil carbon, according to the model presented by Droge and Goss (2013). Similarly, crop residue left *in situ* decomposes and enters the soil, providing material to which fertiliser and organic nitrogen can adhere. The soil nutrient model provides a mathematical relationship between soil organic material, which includes soil carbon and soil nutrients, including nitrogen. Van Groenigen et al. (2006) found that soil nitrogen availability limits soil carbon sequestration and increasing soil nitrogen is necessary to increase soil carbon sequestration. There are no studies that employ the combined application of the work of De Neve and Hofman (2000), Olof and

Thomas (1997), and Droge and Goss (2013) to create a soil productivity variable. Nevertheless, these variables could be combined and utilised in periodic crop production analysis where soil carbon and nitrogen data are available.

Research has focused on climate shocks effects on crop yields, less attention has been paid to soil carbon and nutrient content variation. As discussed in Section 2.3, climate shocks increase soil carbon and nitrogen losses. The combined effect of reductions in soil carbon and nitrogen has yet to be considered, with previous research limited to individual analysis of either soil component. Combining soil carbon and nitrogen losses may provide insight into the overall change in soil productive capacity following exposure to climate risks.

2.10 AGRICULTURAL LAND VALUE

Agricultural land is one of the most significant assets a farmer controls. The value of the land reflects its future productive capacity. Valuing agricultural land using market prices in Australia is complex, with spatially diverse land characteristics impacting market values. Various factors, including physical attributes, economic variables, and regulatory and environmental factors, can influence land value. Palmquist and Danielson (1989) developed a hedonic pricing model using North Carolina market price data to value the impact of erosion and drainage control on agricultural land value. The effect of soil conservation on the market value for wheat farms in NSW was investigated by King and Sinden (1988) using a hedonic pricing model. Hedonic pricing models estimate the implicit values of agricultural land based on observed market prices of properties with similar characteristics.

Regression analysis is another method of using market price data to identify relationships between land value and various explanatory variables. King and Sinden (1994) used price data from the NSW wheat farm market and regression analysis to identify factors influencing market prices, including proximity to a town, site slope and the number of market participants. A national study of farmland values across the US was undertaken by Plantinga et al. (2002) to identify relationships between future land development, proximity to cities, and current farm value. Regression analysis utilises historical data to identify statistically significant associations between land value and the explanatory variables.

The development of technology enabling spatial mapping of land characteristics has enabled the incorporation of historical market data with potential drivers of land value. Utilising spatial population, soil, rainfall, and temperature data can provide deeper insight into land valuations. Marcos-Martinez et al. (2017) utilised spatial population density, farm debt, soil characteristics, access to market and climatic data to evaluate Australian agricultural land. Historical data and vascular plant and bird species indices were utilised by Mannaf et al. (2022) to identify a link between organic farming, biodiversity, and conservation in South Australia. Spatial data enables the incorporation of data that provide more explanatory value than regression analysis however, spatial data can be regional and not sufficiently granular to enable site-specific analysis.

Site-specific analysis can utilise market land value with land use optimisation modelling. Dynamic simulation models simulate the long-term effects of changes in land value by integrating economic, physical, and regulatory factors over time. For example, Burt (1981) investigated the optimal sequence of fertiliser and wheat management practices over the modelling period to reduce soil erosion in the Palouse region in the US. Similarly, utilising dynamic modelling of maize with landholder household use of crops and market income from crop sales, Berazneva et al. (2019) identified the carbon price required to maintain soil carbon for small landholders in the west-Kenyan highlands. Dynamic simulation models utilise empirical data to provide insights into the potential impacts of different scenarios on land value and help policymakers and investors make informed decisions.

Existing methods of valuing agricultural land include hedonic pricing models, regression analysis, spatial-econometric models, and dynamic simulation models to simulate and forecast land value changes. However, all rely on empirical data, whereas land value is influenced by its site-specific productive capacity. Therefore, further research is required to incorporate the wealth of site-specific soil data generated with recent technological advances into land valuation to generate site-specific land valuation techniques and support informed land management decision-making.

Climate shocks, such as droughts, heatwaves, extreme weather events and changes in rainfall patterns, can significantly impact dryland agricultural systems. These shocks affect crop yields and have implications for the value of farmland and the underlying soil health, including carbon and nitrogen levels. Yet, a method of evaluating climate shocks and predicted climate change exclusive of survey or empirical land value data has yet to be developed.

2.11 SUMMARY AND IMPLICATIONS

Agricultural crop production has a rich history of economic analysis. Previous works have focused on simulating crop production with varied intensity, land management practices and soil nitrogen fluctuations. Research has identified soil productivity and climate shocks as key variables impacting crop yields and farm income. Climate shocks drive changes in soil carbon, such as increased decomposition or conversion into carbon dioxide. The linkage between soil carbon, soil nutrients and the land’s productive capacity remains unclear in land use and economic analysis. Biophysical studies have found a connection between soil organic material and nutrient content however, to date, economic work has not developed a soil productivity variable incorporating biophysical modelling, independent of survey data, that can be utilised across various land uses. Creating a new method for evaluating soil and land productivity and value that can be utilised across many agricultural and environmental economic analyses is required.

Australian dryland crop producers are exposed to significant production risks, with climate shocks being the most serious. Existing management processes try to manage climate risks yet need to consider the impact on soil productivity and the land’s productive capacity, as well as climate shocks. Understanding how climate shocks impact future crop yields and returns from crop production land use can improve farmland management decision-making and long-run farmer profits. One method to mitigate the impact of climate shocks is maintaining soil productivity. South-eastern Australian dryland crop producers are vulnerable to the effects of forecast climate change. Mitigating the impact of climate shocks is a critical research area that requires further investigation.

The impact of climate shocks and predicted climate change on long-run land quality and crop yields is an essential research theme. Agricultural land has thin markets in Australia and valuing crop-producing land to determine how land degradation impacts land value is an area that has relied on empirical data. Further research to develop methods to evaluate the impact of climate shocks and new management processes is required to continue to support farmers’ land management decision-making. One method traditionally used to increase crop production returns is fertiliser. Agricultural fertiliser emissions are currently excluded from various emissions policies globally. A research gap exists in evaluating farmers’ crop production management decisions with a carbon price on emissions. Studies on the impact of a change in emissions policy on crop producers have yet to be completed at the field scale to determine the long-run impact and effectiveness of a carbon price on emissions.

Chapter 3: Hydro-Priming Biophysical Process

This chapter describes the technical process for an alternative management practice, hydro-priming, that may increase crop productivity, including the method to calibrate crop simulation software. Hydro-priming is a process widely utilised in commercial horticultural production to improve seed germination rates and reduce the time to seed establishment (Pill et al., 2009).

This chapter commences with an overview of how hydro-priming delivers nutrients and compares it to current fertiliser application methods in Section 3.1. The scientific process and potential impact on crop growth are described in Section 3.2, including results from field trials. The data from field trials will be used to calibrate crop modelling software, which will be used to simulate wheat yield with the method presented in Section 3.3. The production process with a partial budget is outlined in Section 3.4, and a summary in Section 3.5 concludes the chapter.

3.1 FERTILISER APPLICATION AND HYDRO-PRIMING MANAGEMENT PRACTICES

Hydro-priming seeds is an alternative method to increase crop productivity and fertiliser efficiency and potentially reduce the impact of climatic variation (Farooq et al., 2006). Hydro-priming is the commercial horticultural production process where seeds are immersed in water before planting. This method does not significantly impact seed viability or storage times (Schwember & Bradford, 2010). Hydro-priming seeds before sowing ensures that all the nutrients required for early crop growth phases, including germination and establishment, are contained within the seed. In addition, the method stores nutrients within the seed, which may reduce the soil nutrient extraction rates or overcome soil nutrient deficits during wheat germination, thus potentially improving the soil nutrient content. Hydro-priming offers a limited quantity of nutrients utilised in germination to establish phenological phases of wheat growth, shown in Table 3.1 (Zheng et al., 2014, p. 4).

Table 3.1

Crop Phenological Stages

Stage	Stage description
1	Sowing
2	Germination
3	Seedling emergence
4	End of the juvenile phase
5	Floral initiation
6	The appearance of the flag leaf
7	Start of linear phase of grain filling
8	End of linear phase of grain filling
9	Physiological maturity
10	Ready for harvest, harvest
11	Crop finished and absent from the simulation

Note. From Zheng et al. (2014, p. 4).

The direct delivery of nutrients through hydro-priming before sowing the seed overcomes the problem of inaccessible fertiliser in early growth phases. Aerially broadcast fertiliser pellets may be inaccessible to seeds during germination and early growth (Hunt et al., 2019). An alternative method for delivering nutrients to crops is to apply granular fertiliser in subsurface trenches adjacent to seeds during ground preparation before sowing wheat (Rochette et al., 2013). Granular fertiliser spread across the soil surface or placed in subsurface trenches may not be readily accessible to seeds during germination and early growth; however, they provide nutrients to wheat crops over an extended period.[3] One method of delivering fertiliser directly to crops is the application of liquid fertiliser, which is sprayed aerially across fields or injected into the soil at sowing (Incitec, 2021). A drawback of liquid fertiliser injected into soils is that it may not penetrate the topsoil surface and reach seeds during the early growth phases.

Although hydro-priming increases nutrients available to wheat during early growth phases, it is complementary to existing fertiliser application processes. Hydro-priming does not provide adequate nutrients to support wheat growth and development across the entire production period. Abid et al. (2018) utilised hydro-primed wheat seeds and found that they increased drought tolerance compared to non-primed wheat seeds for up to 130 days after germination. This suggests that while the nutrients are limited to early growth processes, the benefits continue throughout the wheat lifecycle.

3.2 THE HYDRO-PRIMING PROCESS

Seed priming immerses seeds in water for five to 48 hours, depending on the species, and initiates the pre-germination process. Hydro-priming adds water-soluble nutrients that the species require to support germination and early growth processes

---

[3] Slow-release diammonium phosphate (DAP) fertiliser applied at sowing provides nutrients over the production period. A urea top dressing is commonly applied at the end of the juvenile phenological phase (see Table 1).

(Pedrini et al., 2020). Germination can be arrested by drying seeds after being immersed in the liquid fertiliser solution. Seeds retain nutrients imbibed through the priming process and can be stored for several months before planting using identical methods as non-primed seeds. Dried seeds can be stored for up to 24 months before being sown and still germinate successfully (Farooq et al., 2019). The hydro-priming method has been used in commercial horticultural production to increase seed germination rates and reduce establishment time (Sisodia et al., 2018).

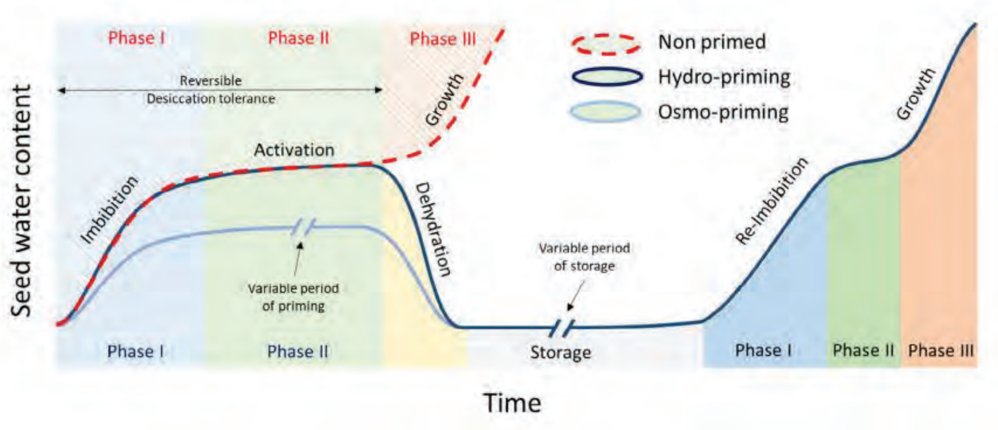
A similar technique is osmo-priming, which involves the temperature-controlled rehydration of seeds (Pedrini et al., 2020). Both methods involve the partial germination of the seed through liquid immersion, as illustrated in Figure 3.1. Hydro-priming and osmo-priming start the germination process, which is halted when the seed is dried at the end of Phase II. (Pedrini et al., 2020). Seed germination involves three phases: (1) the absorption of water, (2) the transformation of energy and (3) the active growth of the root and shoot, referred to as a radicle (Taylor et al., 1992). [4]

---

[4] 'Seed water uptake can be divided into three phases: imbibition, the initiation of germination (activation) and embryo and radicle/epicotyl growth (growth). In seed priming, imbibition is interrupted at the beginning of the growth phase and seed are dried back to be stored' (Pedrini et al., 2020, p. S268).

Figure 3.1

Hydro-Priming and Osmo-Priming Seed Germination Process



Source: Pedrini et al. (2020, p. S268).

Hydro-priming can be undertaken months before sowing and can be performed manually or automatically, depending on the farmer's capital endowments and production area. Farmers with smaller landholdings or capital endowments can manually hydro-prime seeds by placing the seeds in a receptacle filled two-thirds with a liquid fertiliser solution. The process is similar to rehydrating dried peas or lentils before cooking. For automated priming, osmo-priming equipment is required to prime seeds (Pedrini et al., 2020).

Both methods utilise liquid fertiliser created by dissolving 5 kg of granular diammonium phosphate (DAP) fertiliser in 200 L of water, or a 1:40 ratio of fertiliser to water.[5] The seeds remain in the liquid for five to 48 hours before being removed and dried. The seeds can be manually air-dried by placing them on a flat surface until moisture has evaporated from the seeds. The air drying time and efficacy depend on

---

[5] DAP fertiliser consists of 18% nitrogen and 20% phosphorus, with an average price of AUD 664 per metric ton for the period 1/2003–1/2023 (IndexMundi, 2023).

ambient temperatures and humidity. A more reliable method is an automated drying process, with commercially available systems. Automated drying of 100 kg of seeds can be completed within three hours.[6] Once dried, seeds can be stored until they are required for sowing.

Hydro-priming has been used in several crops to increase the available nutrients. Mavi et al. (2006) found that hydro-priming seeds with liquid fertiliser increased tomato root and radicle growth rates through increased nutrient and energy availability at germination. Similarly, Taylor et al. (1992) found that broccoli seeds primed with potassium nitrate increased root and shoot growth rates while decreasing germination and establishment time. Farooq et al. (2020) found that hydro-priming wheat seeds reduced the time for seed radicles (shoots) to emerge from the soil surface.

Field studies measuring wheat root and radicle growth rates following hydro-priming found that growth rates increased compared to non-primed seeds (Basra et al., 2006). In field studies by Farooq et al. (2019), wheat germination rates increased with seed hydro-priming. Hydro-priming is a successful technique to increase crop germination and establishment; however, further research on fertiliser uses and crop returns with hydro-priming is required.

3.3 AGRICULTURAL PRODUCTION SYSTEMS SIMULATOR (APSIM) CALIBRATION

Previous research by Patra et al. (2016) for a study site in Uttar Pradesh, India, generated wheat yields of 4.3 t/ha. Field trials with hydro-primed wheat seeds

---

[6] Based on personal communications with Agratetechniek on 25 February 2023 and 6 March 2023.

have yet to be undertaken in Australia therefore, there is no empirical data available for analysis. To overcome this crop simulation software will be used to simulate wheat yields for the study site. Simulating hydro-priming wheat production and yields will enable comparison with current management processes and determine how effective the method is in mitigating climate shocks on wheat yields. Modelling will be simulated for the period 1960 to 2015, with the study site experiencing variable climatic conditions, including recurring droughts and flood events. Previous research has identified hydro-priming as a technique to reduce wheat stress and improve yields during drought (Farooq et al., 2019). Using simulations will enable investigation of the hydro-primed wheat response to climatic shocks over various climatic conditions.

The APSIM software was developed by the Commonwealth Scientific and Industrial Research Organisation and will be used to simulate wheat yields with hydro-priming. The software includes various crop files, including wheat. A GitHub repository has been created where knowledge is freely shared between APSIM users. However, it does not include any information or crop files on hydro-priming, there is no publicly available information on the GitHub site discussing hydro-priming.[7] Therefore, the APSIM wheat crop file needs to be calibrated to account for the impact of hydro-priming on crop growth processes.

To simulate hydro-primed wheat growth and yield, a copy of the APSIM wheat module (Wheat.json, version 155) will be made. The following discussion focuses on the specific growth processes that hydro-priming will impact based on the work of Zheng et al. (2014). Appendix E contains a detailed description of Zheng et

---

[7] The APSIM GitHub is located at https://github.com/APSIMInitiative. Public users can freely access information and share data. A post was made requesting verification of the wheat file code modifications described later in this section on 10 May 2023.

al. (2014) wheat growth processes used in APSIM from germination to harvest. Seeds are placed in the ground during sowing, the wheat germination rate depends on the seed depth, the climatic conditions and soil moisture (Probert et al., 1998).[8]

Once germination has occurred, following Zheng et al. (2014), a root and radicle emerges from the seed. The seed contains a finite amount of energy that is used by the juvenile wheat seedling to grow the radicle towards the soil surface at a rate of 5 mm per day, where the radicle breaks the soil surface. Once the radicle emerges from the soil it will use photosynthesis to generate energy for plant growth.

Therefore, hydropriming with fertiliser increases the quantity of nutrients stored in the seed, increasing growth rates between germination and emergence. After germination the initial radicle elongation rate is slow, T_{lag}, before a linear growth period, using a relationship between the crop-specific radicle elongation rate and sowing depth, D_{seed}. The root that emerges from the wheat seed, r_ϵ, after germination is used to source water and nutrients, which are also utilised to create biomass. The root grows at a rate of 5 mm per day. Hydro-priming increases root growth rates, r_ϵ, during the germination to emergence phenological stages using field trial results presented in Table 3.2. The increased root growth rates decrease the period for germination to emergence, T_{emer}, (1) compared to non-primed seeds. This is calculated in APSIM using:

$$T_{emer} = T_{lag} + r_\epsilon D_{seed} \tag{1}$$

---

[8] Temperatures influence crop growth processes. The use of thermal temperatures is a method of measuring crop development. Thermal targets are an accumulation of daily maximum air temperatures required for plants to progress to the next stage.

Table 3.2

Hydro-Priming Root and Radicle Growth Rates

Source	Root	Radicle
APSIM	5 (mm/d^{-1})	1.5 (mm/d^{-1})
Hydro-priming		
Farooq et al. (2020)	12.7%	12.7%
Basra et al. (2006)	23.7%	27.7%
Farooq et al. (2013)	13.0%	13.0%

Source: APSIM (2019), Basra et al. (2006, p. 509), Farooq et al. (2020, p. 729), Farooq et al. (2013, p. 15), Holzworth et al. (2014) and Zheng et al. (2014, p. 6).

After germination, hydro-priming increases the daily root and radicle elongation rates, with this study using results from field trials in simulations which are presented in Table 3.2. The daily change in the root system growth rates and total root volume is calculated daily in APSIM using the daily root growth, ΔD_r (2). The wheat daily root growth rate in equation (2) is comprised of the root growth rate, R_r, the soil temperature, f_{rt}, and the impact of soil compaction on root growth, B, (Zheng et al., 2014). The root growth rate is tempered by soil moisture using the minimum amount of moisture in the soil, f_{rw}, and root accessible soil moisture, f_{rwa}:

$$\Delta D_r = R_r \times f_{rt} \times \min(f_{rw}, f_{rwa}) \times B \tag{2}$$

The impact of the hydro-priming seeds wears off once the seed has germinated and emerged from the soil (Farooq et al., 2019). The APSIM wheat crop file will be varied, and simulations will be undertaken to explore the impact of hydro-priming on wheat yields and NPV profits, varying the early root and radicle growth rates in the germination and emergence phases. The wheat crop file

(Wheat.json, version 155), the root growth rates (R_r) from equation (2) and radicle growth rates, r_ϵ, in equation (1) will be increased by 13% in the germination phase using the data from field trials presented in Table 3.2. In the APSIM wheat file, the radicle growth rate for germination to emergence phenological stages, as shown in Figure 3.2 (line 1,071), will increase by 13% from 1.5 to 1.695 (mm/d^{-1}). In the APSIM wheat crop file, the root growth rate for germination to emergence phenological stages, as shown in Figure 3.3 (line 3,176), will be increased from 5 to 5.65 (mm/d^{-1}).

Simulations will be undertaken with the varied root and radicle growth rates using identical wheat sowing times, sowing depth and fertiliser inputs as used with non-primed seeds. The hydro-priming version of APSIM software will be calibrated to ensure all variables, including the climate, soil, and planting time, are identical to those used in simulations to investigate crop yield with existing management practices. Using current and predicted climate change, the hydro-primed wheat cultivar will simulate wheat growth and yield.

To test the robustness of the root and radicle growth hydro-priming variation, the APSIM wheat file root and radicle growth rates shown in Figure 3.2 and Figure 3.3 will be varied using the field trial results presented in Table 3.2.[9] Simulations will be undertaken with various fertiliser inputs and climatic conditions using the alternative root and radicle growth rates. The results will be exported from APSIM and used in an economic analysis to determine if the root and radicle growth rates used in the initial hydro-priming simulation are robust.

---

[9] Hydro-primed roots will be varied by 5.28, 5.95 mm/d^{-1}, and shoot rates will be varied by 1.585, 1.785 mm/d^{-1}.

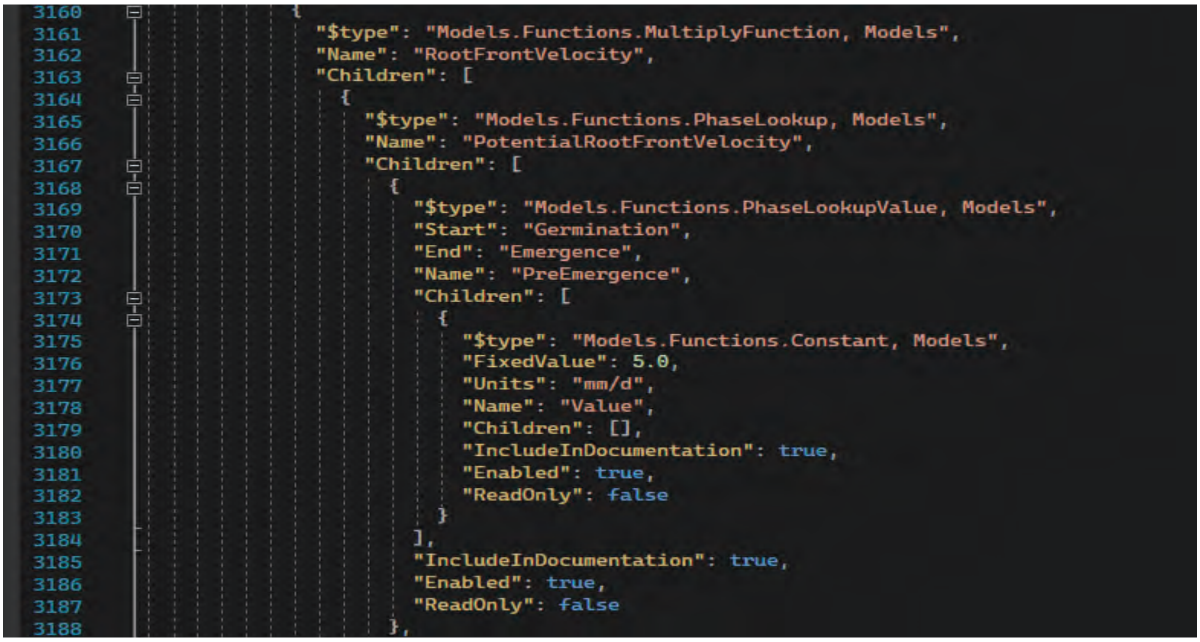
Figure 3.2

APSIM Wheat Module. Radicle growth rate: germination to emergence

```
{
  "$type": "Models.Functions.MultiplyFunction, Models",
  "Name": "DepthxRate",
  "Children": [
    {
      "$type": "Models.Functions.VariableReference, Models",
      "VariableName": "[Plant].SowingData.Depth",
      "Name": "SowingDepth",
      "Children": [],
      "Enabled": true,
      "ReadOnly": false
    },
    {
      "$type": "Models.Functions.Constant, Models",
      "FixedValue": 1.5,
      "Units": null,
      "Name": "ShootRate",
      "Children": [],
      "Enabled": true,
      "ReadOnly": false
    }
  ],
  "Enabled": true,
  "ReadOnly": false
}
```

Figure 3.3

APSIM Wheat Module. Root Radicle growth rate: germination to emergence



```
{
  "$type": "Models.Functions.MultiplyFunction, Models",
  "Name": "RootFrontVelocity",
  "Children": [
    {
      "$type": "Models.Functions.PhaseLookup, Models",
      "Name": "PotentialRootFrontVelocity",
      "Children": [
        {
          "$type": "Models.Functions.PhaseLookupValue, Models",
          "Start": "Germination",
          "End": "Emergence",
          "Name": "PreEmergence",
          "Children": [
            {
              "$type": "Models.Functions.Constant, Models",
              "FixedValue": 5.0,
              "Units": "mm/d",
              "Name": "Value",
              "Children": [],
              "IncludeInDocumentation": true,
              "Enabled": true,
              "ReadOnly": false
            }
          ],
          "IncludeInDocumentation": true,
          "Enabled": true,
          "ReadOnly": false
        },
```

3.4 HYDRO-PRIMING PRODUCTION COST

Several studies have investigated the benefits of seed priming to increase crop resilience to limited water supply. The use of seed priming to increase drought tolerance has been studied for various crops, finding a positive relationship between seed priming and crop yields with drought conditions compared to non-primed seeds (Kaur et al., 2002; Mahawar et al., 2016). Farooq et al. (2013) investigated wheat seed priming with ascorbic acid and found that it improved wheat crop drought tolerance. Patra et al. (2016) investigated the impact on wheat yields with hydro-primed seeds and various sowing times. Nevertheless, the economic impact of improved crop resilience with seed priming remains unexplored.

The production function in Section 5.3 outlines the seeding rate per hectare based on Grains Research Development Corporation recommendations for the Wagga Wagga region. Three methods of hydro-priming will be investigated: a low-technology solution where seeds are manually hydro-primed; an automated process where the priming and drying processes are undertaken by machinery; and a semi-automated process where the priming is done manually, and the seeds dried using machinery. To allocate costs, it is assumed that farmers operate a 500 ha area devoted to crop production, and the entire 500 ha is allocated to wheat production using hydro-priming technology, as stated in Section 5.1. A simplifying assumption is made that farmers do not consider the opportunity cost of their time spent priming seeds and farmers undertake priming over the summer fallowing and have spare capacity.

The low-technology manual hydro-priming method is suitable for small landholders. Hydro-priming is undertaken by dissolving 5 kg of granular DAP fertiliser in 200 L of water.[10] Seeds are manually placed in a large receptacle with the liquid fertiliser for five to 24 hours before they are removed and air-dried on a hard surface and stored until required. The costs of manual hydro-priming of 100 kg of wheat seeds includes the price of the 300 L receptacle, the cost of the fertiliser used, the water needed for the process and the labour to complete the process.[11] The costs are presented in Table 3.3 in 2020 AUD.

Automated hydro-primed seeds are processed through drums with 40–1,800 kg of seed capacity for commercial hydro-priming, depending on the configuration. The liquid and seeds remain in the drums for the programmed time before being transferred into a commercial drying machine that utilises heat pumps to extract water from the seeds.

A priming unit used in automated priming costs $51,207 and is capable of priming up to 40 kg of seeds at a time[12]. A conditioned seed dryer costs $77,168 and can dry up to 100 kg of seeds in three hours. The cost in 2020 AUD of purchasing the unit including an taxes, transfer and shipping costs to Australia has been included. However, installation costs are site-specific and have been excluded from production cost data. The installed priming drum capacity is 40 kg, constraining the volume able to be processed through automatic priming. Therefore, automatic priming will be calculated using 40 kg of seed with costs presented in Table 3.3. The

---

[10] DAP fertiliser consists of 18% nitrogen and 20% phosphorus. The average price of AUD 664 per metric ton was for the period 1/2003–1/2023 (IndexMundi, 2023).

[11] Using a 300 L water tank at a cost of $170.60 (DickSmith, 2023), Riverina Water supply cost of $1.51 per kL (RiverinaWater, 2023) and DAP fertiliser at a cost of $664.48 per ton (IndexMundi, 2023).

[12] Personal communications with Agratetechniek on 2 February 2023 and 6 March 2023 for small-scale agriculture found that an osmotic priming unit (5 x 8 L), VLM-4150, costs $51,207. In personal communication, prices were supplied in Euros. Conversion of the prices from Euros to AUD used the average €/AUD exchange rate for 2020, €1 = $1.6561 (ExchangeRates, 2023). The total cost, including the $5,211 shipping cost, is $133,577 for both units. MoverDB. (2023). *2023 Sea Freight Container Shipping Rates To & From Australia*. MoverDB. Retrieved 6/03/2023 from https://moverdb.com/container-shipping/australia/.

fertiliser, electricity, water and labour cost for 40 kg of seed hydro-primed utilises the same cost assumptions as discussed in the low-technology hydro-priming, with the addition of $2.54 of electricity to operate the osmo-priming and seed drying machinery using 3 kw/h for three hours.[13]

Table 3.3

Seed Hydro-Priming Cost ($/ha)

Input	Manual ($/ha)	Automatic ($/ha)	Semi-automated ($/ha)
Receptacle/machinery ($/unit)	170.60	128,375.00	11,482.00
Fertiliser used ($)	0.90	0.83	0.83
Water ($)	0.15	0.06	0.09
Electricity ($)		2.54	0.90
Labour ($)	58.00	29.00	43.50
Total ($)	229.65	128,407.43	11,527.32
Cost per ha (year 1)	59.39	289.18	68.28
Marginal cost p/ha (subsequent years)	59.05	32.43	45.32

Note. Values are in 2020 AUD.

A lower cost option involving more manual labour is the semi-automated hydro-priming process. It uses a 1,000 L tank (Equip2go, 2023) filled with the fertiliser solution to immerse 500 kg of wheat seeds in 500 L of water, with costs

---

[13] Wrigley (2023) is used to estimate energy costs. The average cost of electricity in NSW in 2023 is $0.2866 per kw/h.

presented in Table 3.3. The solution is manually drained by removing a plug at the base of the receptacle before a tractor transports the seeds to the drying unit, where seeds are manually loaded for drying.[14] DingXin (2023) has a drying unit[15] that can dry up to 3 tonnes per hour using 3.15 kw/h of electricity. Therefore, the drying cost includes electricity to operate the seed drying machinery per 500 kg of seed dried.

As outlined in the Australian Taxation Office Tax Ruling TR 2022/1 *Income tax: effective life of depreciating assets* (ATO, 2022), agricultural seed drying equipment has a useful life of 20 years. Using the ATO Tax Ruling, in the automated and semi-automated scenario, hydro-priming machinery is assumed to be replaced every 20 years. Depreciation and machinery repairs are not considered in this analysis. Therefore as illustrated in Table 3.3, the marginal cost of automatic hydro-priming is $289 per/ha, and semi-automated is $68 per/ha in the first year. In years 2–19, the marginal cost is $32 per/ha and $45 per/ha respectively, before the equipment is replaced in the 20th year, 1980. The cycle was repeated, and the machinery was replaced in 2000, with all costs inflated using the applicable discount rate.

The marginal cost of semi-automated hydro-priming is higher than the automated cost due to significantly higher labour input costs, as shown in Table 3.3. Consistent with this, the highest cost in manual hydro-priming is the labour cost, with the cost in the first year $59 per/ha and $59 per/ha in subsequent years. Plastic receptacles used with manual and semi-automated systems are assumed to have a useful life of five years, in line with the ATO's (2022) expected useful life for

---

[14] It is assumed the tractor is a pre-existing asset held by the farmer and is excluded from cost estimates. It has a drying unit cost of $7,484, and shipping from China to Sydney costs $2,511.

[15] In personal communications with DingXin (2023), prices were supplied in USD. Conversion to AUD used the average USD/AUD exchange rate for 2020, USD 1 = AUD 1.4533 (ExchangeRates, 2023).

agricultural bins. The highest cost for manual hydro-priming is the plastic receptacle used to hydro-prime seeds, which is replaced every five years.

Hydro-priming seeds may reduce the profit-maximising quantity of fertiliser required while improving crop nitrogen use efficiency. To investigate the amount of fertiliser required to maximise returns from land use, various fertiliser input qualities will be simulated using the New South Wales Department of Primary Industries (NSW DPI) (2013) recommended fertilisers (urea and DAP) and crop application times. An economic analysis of the process is presented in Chapter 5.

A further benefit of hydro-priming may be improved crop nitrogen use efficiency (NUE). The NUE of hydro-priming with wheat will be evaluated by dividing the grain weight by plant available soil nitrogen in the soil (g/plant), following the process by Moll et al. (1982). The economic impact of hydro-priming seeds on crop NUE with different quantities of fertiliser will be evaluated following the process outlined in Section 5.8 to determine the NPV profitability of hydro-priming and any soil productivity benefits.

3.5 SUMMARY

Hydro-priming is a technique that has not been previously applied to crop production in Australia. Therefore, the yield and soil productivity benefits still need to be discovered. Hydro-priming is an alternative fertiliser delivery method applied in commercial horticulture production and effectively boosted other agricultural crop germination rates. Utilising results from wheat field studies, a simple change will be made to the APSIM wheat module to investigate the productivity benefits using the method described in Chapter 5. Field studies reviewed in Chapter 2 suggest that hydro-priming may be an effective management treatment to reduce the impact of drought on wheat growth processes and increase wheat yield with rainfall deficits compared to non-primed wheat.

The partial budget constructed in this chapter represents a first attempt at quantifying the cost of hydro-priming and suggests that marginal costs are similar when hydro-priming is undertaken across a large property with economies of scale. The development of the hydro-priming process in APSIM and the economic analysis represents a first attempt at simulating hydro-primed crops. This chapter introduces a method to overcome this knowledge gap. Further, it contributes to the research literature by offering a first attempt at quantifying the economic costs of hydro-priming on wheat crops.

Chapter 4: Biophysical Soil Productivity Processes

Climate shocks impact wheat yields but may also impact soil nutrient and carbon content, which are considered valuable attributes in agricultural land (Xu et al., 1993). Therefore, a method of evaluating the impacts is required to investigate the effects of climate shocks on the land's productive capacity. This chapter examines the biophysical relationships between land management methods, soil structure, soil carbon content and soil nutrient availability. The biophysical relationships are used to create a soil productivity index used in the economic model to evaluate the impact of management decisions and climate shocks on the future productive capacity of the land.

This chapter introduces the soil physiological processes that impact crop productivity. Section 4.1 discusses how crop production and management methods affect soil carbon and nutrient content. The soil biophysical characteristics of the study site are outlined in Section 4.2. Simplified models describing how soil carbon and nitrogen vary and the interrelationship between soil carbon and nitrogen are presented in Section 4.3. Building on the identified relationship between soil carbon and nitrogen a method is proposed to create a soil productivity index, described in Section 4.4. The chapter concludes with a summary in Section 4.5.

4.1 CROP PRODUCTION

Crop production combines rainfall, sunlight and nutrients extracted from the soil to create grains. Globally, crop production in Australia is among the most efficient. However, management practices can extract soil nutrients over what is replenished through organic and inorganic supplementary inputs (Kik et al., 2021). Extracting nutrients above what is replenished reduces the soil's future productivity and potential crop yields. Therefore, evaluating the impact of crop production management processes on the land is critical to ensure the maintenance of current and future soil productivity.

Soil productivity is a function of the land management practices and the previous period's soil productivity. Soil productivity is an essential determinant of agricultural productivity, farm resilience and environmental quality (Kik et al., 2021). Small periodic changes in soil carbon and nutrient content have a cumulative effect that may lead to long-term changes in soil productivity. The quantity of nutrients a crop extracts depends on the crop type, the amount of fertiliser input applied, the climatic conditions experienced in the production period and crop production intensity. Soil productivity losses occur when the crop extracts nitrogen in quantities over and above what can be replenished by organic material and fertiliser application. The soil's productive capacity is determined by the soil structure, including the clay content, the amount of carbon in the soil and the nutrient content (Wolman, 1985).

Climatic conditions can influence crop extraction of soil nutrients and the quantity of nutrients available in the soil. Soil nutrient content is affected by rainfall in the production period. Rainfall deficits reduce fertiliser infiltration, and excess rain increases fertiliser transport through the soil into the subsoil, which is inaccessible to crops (Probert et al., 1998). Lower rainfall reduces crop growth and nutrient extraction but also reduces the decomposition and movement of organic material and fertiliser inputs applied to the soil surface into the soil. Above-average rainfall may reduce crop growth through waterlogged soils reducing soil oxygen content, and reducing soil nutrient content by moving nutrients through the topsoil into the subsoils, which is inaccessible to crop roots (Chen et al., 2013). Sadras (2002) investigated the impact of variable rainfall on winter crops in the Mallee region of south-eastern Australia and found that calibrating fertiliser usage to predicted rainfall is a common management strategy to reduce economic risks associated with rainfall deficits in wheat production.

The impact of variable climatic conditions on wheat yields has been studied. However, more attention needs to be given to how variable climatic conditions impacts soil productivity. Soil productivity is a critical determinant of future crop yields and farmer income. Maximising land value is critical for Australian farmers who understand that soil is an essential component of their business operations (McKenzie, 2013). Determining the impact of management processes on future land productivity and value can support farmer decision-making regarding current climate risks and predicted future climate change.

4.2 SOIL CHARACTERISTICS

Soil productivity depends on the quantity of carbon and nitrogen that can be held in the soil and overall soil structure. Soil structure is defined by how individual particles of sand, silt and clay are assembled (United Nations Food and Agriculture Organiation, n.d.). Wagga Wagga soils are dominated by red kandosols, which are characterised by low organic and nutrient content reducing soil water and, therefore, nutrient and organic matter infiltration and retention (McKenzie, 2004; Li et al., 2016). The average soil carbon content in Australian topsoil is estimated to be 1.65% of the topsoil total volume (Viscarra Rossel et al., 2014, p.5238 Table 1). The biophysical relationship between soil nutrients and carbon content can be negatively impacted by climate shocks or management processes, resulting in soil nutrient losses exceeding what is replenished and reducing the soil's productive capacity.

The ability of the soil to retain nutrients is measured by the cationic exchange capacity (CEC) of the soil. Soil CEC is an inherent quality and an indicator of the overall fertility of the soil (DPI, n.d.(a)). Cations are positively charged elements within the soil, and the most commonly measured soil cations are nitrogen (N), calcium (Ca), magnesium (Mg), potassium (K), sodium (Na), and aluminium (Al) (McKenzie et al., 2012). The soil CEC combines soil cations with soil clay and carbon particles, known as colloids, which have negative electrical conductivity or cationic exchange. The negatively charged soil clay and carbon particle combine to hold the positively charged nutrient cations crops use in the soil (McKenzie, 2004). Soil CEC is critical to crop and soil productivity. Clay is insufficient to retain soil cations, it also requires soil carbon.

4.3 SOIL CARBON AND NUTRIENT CONTENT

The CEC of the soil is critical to crops, which requires various soil nutrients to maximise crop growth and yields. The three primary nutrients are nitrogen (N), phosphorus (P), and potassium (K), with calcium, magnesium, sulphur, iron, manganese, zinc, copper, boron and molybdenum being other critical nutrients required for crop growth (DPI, n.d.(b); Van Keulen, 1986). Nitrogen is one of the most significant nutrients utilised by crops for the production of biomass. APSIM software has focused on modelling the relationship between crops and nitrogen. Therefore, the following discussion will focus on the relationship between soil carbon and nitrogen. However, in subsequent modelling developing the soil productivity index, nitrogen is a proxy for the broader suite of nutrients that Van

Keulen (1986) identified as necessary for crop growth. Deficits in any of these nutrients will reduce crop growth, yields and income. Hence, while other soil nutrients are needed to maximise crop productivity, this study is restricted to the relationship between soil nitrogen and soil carbon.

Increasing soil organic material is a standard method to improve soil nutrient holding capacity and crop productivity. Soil organic material contains a range of soil cations, with soil organic material often characterised by soil carbon content. Soil carbon consists of organic carbon, elemental carbon, and inorganic carbon. Organic carbon is generated from decomposed organic material and is the most significant contributor to soil carbon (Pluske et al., 2023). In APSIM, fresh organic matter (FOM), such as crop stubble or decomposing roots, is added to the soil profile and decomposes over time depending on daily temperature and soil moisture. APSIM simulates the movement of FOM through the soil layers as it decays into humus (HUM), microbial biomass and a biomass (BIOM) pool, all containing various nutrients (Luo et al., 2014). Although both the HUM and BIOM pools contain organic soil carbon, the HUM carbon pool is a smaller, inert pool. While the BIOM is an active, larger pool of FOM organic carbon, it is more likely to be used in crop production processes or converted into HUM or carbon dioxide (Yang et al., 2014). BIOM soil carbon characterises this wider pool of active organic soil material that can increase soil nutrient holding capacity and productivity.

The soil nutrient holding capacity fluctuates and depends on soil carbon, crop production intensity, soil temperature, moisture and nutrient content (Keating et al., 2003). In APSIM, FOM decomposition into BIOM depends on soil nitrogen content (Luo et al., 2014). Changes in soil BIOM carbon accumulate over time, with the APSIM capable of reporting soil carbon changes daily or at key phenological stages such as crop harvest. Calculating wheat production's soil carbon and nitrogen usage through APSIM simulations facilitates the evaluation of the long-run impact of management processes on soil and crop productivity. Soil BIOM carbon (kg/ha) after harvest in the APSIM each year will be used to measure the impact of climatic conditions, management practices and soil carbon variation on soil nutrient holding capacity.

The NSW DPI (2013) recommended management practices include the retention of post-harvest crop stubble on the soil surface to reduce soil erosion and soil water loss during the hot summer fallowing period. Crop stubble contains carbon and nitrogen in varying quantities depending on the crop type. Once decomposed, the stubble's carbon and organic nitrogen enters the soil, increasing the soil carbon and nitrogen content and mitigating the crop production's soil carbon and nitrogen extraction (Probert et al., 1998). However, the quantity of nitrogen and carbon in the crop stubble may not be sufficient to replenish what the wheat crop extracts over the growth period.

Olof and Thomas (1997) developed a mathematical relationship for estimating the quantity of BIOM carbon retained in the soil after one year based on 35 years of data from cropped soils in Sweden. They used site soil data to calculate annual soil carbon losses. The soil dataset was used to create an exponential function to predict the yearly effect of climate, the initial soil carbon balance, and surface organic material inputs on carbon content (BIOM) retained in the soil. These findings have been independently validated in subsequent research, including in soil carbon losses in permafrost thaw (Reichstein et al., 2000), agroforestry (Magnani et al., 2007), as well as crop and livestock production land use (Borrelli et al., 2016). The model developed by Olof and Thomas (1997) predicts the effects of climate, FOM input variation, initial BIOM content and quality of FOM inputs on soil carbon pools. It was found that the fraction of soil BIOM carbon remaining after one year can be expressed as follows:

$$\frac{dC_{t+1}}{dC_t} = e^{-k} \tag{3}$$

Where k is the first-order kinetics or rate of decomposition of soil carbon into carbon dioxide and HUM, the decomposition rate, k, depends on the soil carbon type. BIOM carbon decomposes at a different rate (k_1) to HUM soil carbon (k_2). The BIOM soil carbon decomposition rate is influenced by soil temperature and moisture. It is characterised by a dimensionless climate factor (r), as discussed by Olof and Thomas (1997). As previously identified in Section 4.2, the soil carbon retention rate depends on the soil profile's clay volume (% expressed as a decimal; h). The FOM BIOM decomposition rate is estimated as follows:

$$k_1 = -\frac{1}{r}\ln\frac{e^{-k} - h}{1 - h} \tag{4}$$

Climatic variation significantly impacts soil carbon decomposition in equation (4). Fortin et al. (2011) conducted sensitivity testing on the climate factor and found that temperature significantly affects the climate factor (r), with rainfall variation insignificant. Andrén et al. (2007) used climatic data records to construct climate factors for various African sites including Ahero in Kenya and Pointe Noire in The Republic of Congo. Of the study sites evaluated by Andrén et al. (2007, p. 380, Table 2), Pointe Noire has a similar mean temperature to the study site which is located in Wagga Wagga, with average annual rainfall less than 20% higher than Wagga Wagga, NSW, Australia, with an *(r)* factor of 4.2. Ahero has a similar mean temperature to the Wagga Wagga study site. However, it receives an average rainfall of 1,265 mm/year, which is more than double the average annual rainfall of Wagga Wagga. Despite this, Andrén et al. (2007) estimated Ahero's climate factor to be 4.1, confirming Fortin et al.'s (2011) findings. Therefore, climate factor 4.2 will be used for the study site in Wagga Wagga. The average soil FOM decomposition rate (*k*) is:

$$k = -\ln[(1-h)e^{-k_1 r} + h] \tag{5}$$

Combining the FOM decomposition rate (equation 5) into the annual change in soil carbon decomposition equation (4) and incorporating HUM decomposition, the yearly change in soil carbon using Olof and Thomas (1997) becomes:

$$\frac{dC_{t+1}}{dC_t} = e^{-k_1 r} + h(1-e^{k_1 r}) \tag{6}$$

Soils with lower quantities of soil carbon have higher soil density, which restricts plant root growth and reduces water infiltration and microorganism activity in soils. These factors are critical for soil health (DPI, n.d.(b)). Droge and Goss (2013) used standardised European Union soils in their laboratory analysis to fit a model that estimates the nutrient holding capacity of soil (τ_t) using soil carbon and clay, (*cy*), content. The soil nutrient holding capacity uses the cationic exchange capacity of the soil (CEC), a fixed conversion rate of 3.4 for CEC nutrients in the BIOM taken from Droge and Goss (2013, p. 14,234), the ratio of carbon in the organic material in the soil $\left(cc_t = \frac{BIOM_{c_t}}{BIOM} \right)$ and the fresh organic material added to the soil[16]:

$$\tau_t = cy(CEC - 3.4 \cdot cc_t) + (cc_t \cdot FOM) \tag{7}$$

The soil nutrient holding capacity for the study site will use the average topsoil CEC taken from the Australian Soil Resource Information System database (McKenzie et al., 2004), together with the aggregated soil carbon ($BIOM_{c_t}$) and topsoil organic material (BIOM) measurements taken from APSIM modelling after harvest has occurred in each production period. Soil nutrient holding capacity depends on its ability to hold organic material and nutrients in the soil. Therefore, the level of soil carbon will vary in each production period depending on climate conditions and wheat production management decisions.

If FOM inputs decline, the associated BIOM and organic nitrogen inputs decrease, with a subsequent fall in soil carbon and soil nutrient holding capacity in the following period. The quantity of soil nitrogen varies with climatic conditions, consistent with soil carbon variation. Rainfall can result in soil nitrogen being moved downwards through the topsoil into the subsoils below, rendering it inaccessible to plants (Probert et al., 1998). The rate at which soil nitrogen within the BIOM pool is converted into plant-accessible nitrogen is a process called mineralisation. Warmer temperatures increase the conversion rate of mineralised nitrogen to nitrous oxide, or

---

[16] In Droge and Goss (2013) they use a parameter for a single natural or fresh organic material that has not yet decomposed into soil carbon, such as peat, to calculate individual nutrients retention in the soil. For simplicity in this study it is assumed that all fresh organic material is identical and adsorbs nutrients in the same manner.

denitrification.[17] It is generally driven by microbial activity within the soils (Probert et al., 1998). Within the APSIM software, the quantity of nitrogen mineralised is calculated daily and is dependent on soil moisture and temperature.

Crops utilise soil nitrogen daily, reducing the volume of soil nitrogen. Soil nitrogen can be increased by mineralisation, adding organic or inorganic nitrogenous fertilisers to the soils. Consistent with soil carbon, soil layer nitrogen balances at harvest will be extracted from APSIM, aggregated, and used to evaluate the impact of production intensity, management practices and climatic conditions during the production period on soil nitrogen content.

4.4 SOIL PRODUCTIVITY

The soil nutrient holding capacity (equation 7) determines soil productivity. This section presents a simple mathematical equation that, given a site's soil characteristics, estimates the maximum quantity of nitrogen the soil can hold. Soil nitrogen represents the broader body of soil nutrients necessary for crop growth, as described in Section 4.2. In this model, the quantity of nitrogen in the soil at the end of each production period will be taken from APSIM modelling results and used to describe the change in topsoil nitrogen content following the method of Thorburn et al. (2010). The net change can be positive or negative; soil nitrogen fluctuates, decreasing with denitrification, immobilisation and leaching, while increasing with mineralisation and the addition of nitrogenous fertilisers.

---

[17] For further information on the movement of soil nitrogen and how it is modelled in the APSIM software, visit https://www.apsim.info/documentation/model-documentation/soil-modules-documentation/soiln/.

The actual amount of nitrogen in the soil accessible to plants must be determined before soil productivity can be calculated. To do this, the soil nitrogen balance (kg/ha) will be taken from the APSIM at the end of each annual production period and converted into a ratio of nitrogen in the topsoil, consistent with the approach taken for soil carbon content. Soil nitrogen comprises organic and inorganic materials converted into plant-accessible nitrogen through mineralisation. Inorganic soil nitrogen in this study is contained in urea and DAP fertilisers that will be applied as part of the management processes. In the National Inventory Report on Greenhouse Gas emissions by The Department of Climate Change, Energy, the Environment and Water (2022), a constant rate is used to estimate fertiliser emissions. Consistent with this, a constant inorganic nitrogen release rate is used to estimate the amount of inorganic nitrogen mineralised. Zheng et al. (2009) presented a mathematical method for estimating the change in soil inorganic nitrogen content, where *w* is a constant release rate:

$$\phi_{I,t+1} = \phi_{I,t} - \phi_{I,t} e^{-\left(\frac{w}{\phi_{I,t}}\right)t} \tag{8}$$

The soil organic nitrogen mineralisation rate, developed by Stanford and Smith (1972), estimates the change in the soil that can be mineralised. This aligns with Zheng et al. (2009). The method has been widely applied to various topics, including evaluating synthetic nitrogen fertiliser impacts on soil nitrogen (Mulvaney et al., 2009), the impacts of mineralisation on plant nutrient cycling (Mary et al., 1996) and nitrogen availability in forest soils (Binkley & Hart, 1989). Assuming no organic or inorganic nitrogen inputs are applied, Stanford and Smith (1972) estimated soil mineralisation potential using a fixed soil mineralisation rate (z_t) based on the change in soil nitrogen balance (ϕ_t) between periods. De Neve and Hoffman

(2000) built on Stanford and Smith's (1972) model by incorporating climate variation, soil bulk density, BIOM and HUM content to estimate the soil nitrogen balance:

$$\phi_{t+1} = \phi_t (1 - e^{z_t}) \tag{9}$$

Using the study site soil average bulk density, taken from the site soil characteristics readily available in ASRIS, the soil mineralisation rate (z_t) was set at 0.110 using the soil organic matter mineralisation rates calculated by De Neve and Hoffman (2000, p. 546, Table 1). Using a fixed mineralisation rate aligns with Zheng et al. (2009), who used a fixed inorganic nitrogen release rate. For simplicity, the inorganic nitrogen release and mineralisation rates are assumed to be identical and a simplifying assumption following Zheng et al. (2009) is made using a fixed mineralisation rate. Combining the soil nitrogen content (equation 9) with the soil carbon calculations in equations (3-8), the soil productivity index for a period η_t, equation (10) can be calculated as:

$$\eta_t = G(\tau_t, \phi_t) = 1 - e^{-\tau_t \phi_t} \tag{10}$$

In APSIM, the soil mineralisation rate depends on climatic characteristics, soil water content and pH level. The soil productivity index provides a simplified method of estimating agricultural soil productivity and the impact of climatic shocks and management processes on the soil's productive capacity. Farmers can utilise agronomic soil testing data from yesterday, last week or even 10 years ago and compare it using current soil data. The results provide information on how the soils productive capacity has changed in the intervening period.

4.5 SUMMARY

The periodic variation in soil productivity depends on the farmer's production management processes. For example, management practices increasing soil organic material inputs will increase soil carbon, thereby increasing the soil's ability to retain nitrogen. However, if farmers choose to increase crop production intensity, it may extract more nitrogen and utilise more soil carbon than replenished.

The productive capacity of agricultural soils is limited by the soil clay and carbon content. Soil clay is not readily changed; however, soil carbon can vary with production management decisions and climatic conditions. As soil carbon changes, the quantity of nutrients able to be stored within the soil also changes. The soil productivity function provides a mechanism to evaluate the impact of soil carbon and, therefore, nutrient variation with crop production management practices on land quality. As soil productivity declines (increases), periodic land quality increases (decreases).

To evaluate the impact of wheat production in a variable climate in south-eastern Australia on soil productivity, continuous wheat production simulations in APSIM will be used to generate crop yields using current management practices and NSW DPI recommended fertiliser application rates (DPI, 2013) in a fixed production system. The APSIM outputs will be used to estimate the impact of periodic changes in soil carbon and nitrogen on soil productivity and identify how climate shocks, such as droughts and above-average temperatures or rainfall during a wheat production period impact soil productivity. The soil productivity index will fill a knowledge gap. Using soil nitrogen or carbon does not sufficiently explain the variation in the productive capacity of the soil. An increase in either carbon or nutrients on their own will not improve the productive capacity of the soil. Both are required to maintain or increase the productive capacity of the soil.

Empirical data is not available for the hydro-priming treatment described in Chapter 3. The APSIM soil data generated with the hydro-priming simulation will be used to investigate the impact of hydro-priming on soil productivity and the Net Present Value of wheat production. Undertaking APSIM simulations and applying the soil productivity index to both current management practices and hydro-priming with a fixed production process provides a mechanism to evaluate if hydro-priming improves the productive capacity of the soil across various climate shocks that the study site is exposed to during the modelling period.

The soil productivity index enhances existing farm management practices. Farmers regularly get their soil tested, and the index quantifies how changes in soil carbon impact their future productive capacity and income derived from land use. The soil productivity index can be applied to evaluate the change in land value using the method described in Chapter 5. The results are presented in Chapter 6 and a discussion on the soil productivity index effectiveness is undertaken in Chapter 7.

Chapter 5: Research Design

This chapter introduces an approximation of the economic model well-informed, rational, and financially literate farmers use to calculate the expected net present value (NPV) profits generated from wheat produced annually on a one hectare plot of land for a study site in Wagga Wagga, New South Wales that is representative of dryland wheat production in South-eastern Australia. The economic model will provide the framework to evaluate the impact of climate shocks on NPV returns with current management practices and NSW DPI (2013) recommended fertiliser inputs.

A biophysical crop model developed by the Commonwealth Scientific and Industrial Research Organisation, the Agricultural Production Systems Simulator (APSIM) crop modelling software will simulate annual winter wheat yields at the study site for 1960-2015. The outputs of the APSIM model and climate data from the Bureau of Meteorology (2020), will be used to identify how climate shocks impact wheat yields, land use income and soil productivity. In addition, APSIM will be calibrated with different fertiliser input quantities to investigate how variations in fertiliser inputs impact wheat and soil climate shock responses.

An alternative management method, hydro-priming seeds before planting, discussed in Chapter 3, will be investigated to ascertain if hydro-priming reduces wheat exposure to climate shock and the impact on soil carbon and nutrients. A simulation will be outlined where wheat is rotated with field peas using current management practices and an alternative using hydro-primed seeds to evaluate the impact of crop rotations on climate shock, soil productivity, and farmer NPV returns. Finally, APSIM outputs will be used to investigate if a policy shift placing a carbon price on fertiliser emissions impacts NPV returns from land use and the impact on fertiliser input management decisions.

The site soil characteristics, climatic conditions and previous land use are outlined in Section 5.1. In Section 5.2, the climate data used in the modelling will be presented. Section 5.3 presents an overview of the APSIM modelling process used to simulate wheat yields and will be calibrated using the NSW DPI (2013) recommended fertiliser production inputs and processes together with Matthews et al. (2020) recommended sowing times, depths and spacing. The crop production function is described in Section 5.4. To evaluate the impact of climate shocks on soil productivity the method used to apply the soil productivity index developed in Chapter 4 to land value is presented in Section 5.5. The periodic impact of climate shocks incorporating the crop production function and the periodic change in land value is incorporated into a NPV modelling process for both current and hydro-priming management practices in Section 5.6.

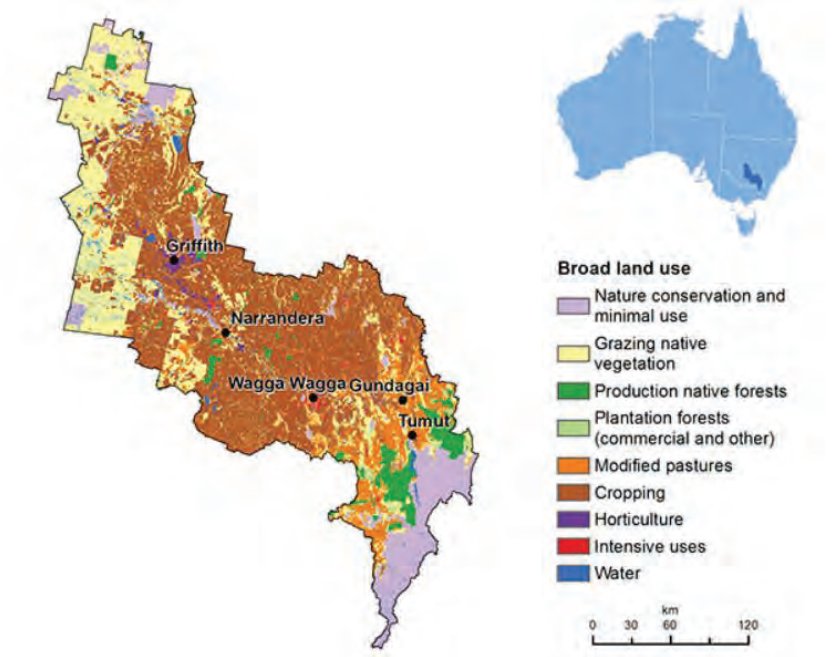
Section 5.7 describes how the NSW DPI recommended fertiliser input quantities will be increased (reduced) in APSIM by 20, 40 and 60% with simulations undertaken to investigate the impact on wheat yields, farmer income and soil productivity. The partial budget used in hydro-priming simulations is described in Section 5.8. The economic model that will be used to examine the impact on farmer fertiliser input decisions and NPV returns from wheat production with a policy change placing a carbon price on fertiliser emissions is outlined in Section 5.9. In Section 5.10, a fixed crop rotation will be discussed and present the data used to calibrate APSIM crop rotation simulations. Limitations to the modelling process will be discussed in Section 5.11 with a summary in Section 5.12 that concludes the chapter. The economic modelling process is summarised in Appendix A, and the APSIM modelling procedure is detailed in Appendix E.

5.1 WAGGA WAGGA STUDY SITE SOIL CHARACTERISTICS AND LAND USE

The study area used in the modelling is a farm in Wagga Wagga, NSW, Australia (Figure 5.1) that is typical of dryland low-rainfall crop production regions in Australia (O'Leary et al., 2018). The average farm size is between 1,000 – 2,000 hectares (DPI, 2018), with dryland grain production of wheat, barley, and other grains dominating the region (ABARES, 2020a). Land use for crop production in the area generally uses a crop rotation system, with field pea, wheat, and canola. This standard crop rotation increases soil nitrogen and economic returns. Moreover, agricultural land in the area has been cultivated for several decades, with agricultural research undertaken by the NSW DPI at a site in Wagga Wagga since 1892 (DPI, 2022). Therefore, in this study, the plot of land used for modelling is assumed to be agricultural land previously managed using a crop rotation system including wheat, field pea, and canola.

Figure 5.1

Wagga Wagga Location and Land Use

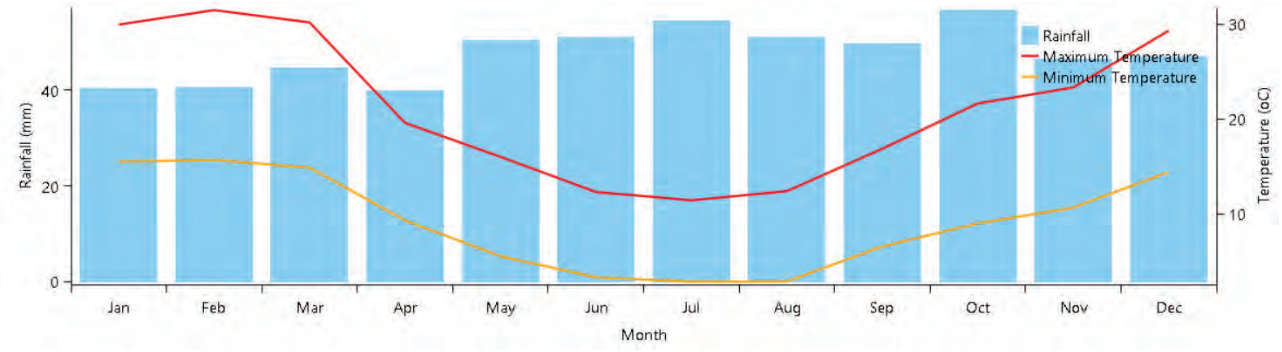


Source: ABARES (2020a)

Wagga Wagga receives an average of 575 mm rainfall annually, evenly spaced throughout the year, with hot, dry summers and cool winters featuring overnight fog and frosts (Figure 5.2) (BOM, 2020). The hot, dry climatic conditions over the summer are not conducive to productive plant growth and therefore, crop fields are commonly fallowed during the summer months with crop production occurring between April and November.

Figure 5.2

Wagga Wagga average climate data 1960 – 2015

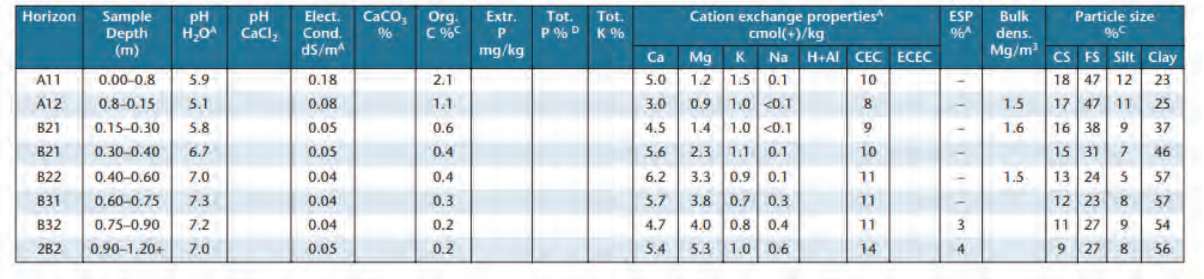


Source: BOM (2020)

Climatic conditions impact crop production but also the soil structure and nutrient content. Red sodosols with low organic content dominate Wagga Wagga soils. As discussed in Chapter 2 and Chapter 4 low soil organic content reduces soil water, nitrogen, and organic matter infiltration and retention, which are essential for maximising wheat growth and yield (Feng et al., 2020; Li et al., 2016; McKenzie, 2004). Table 5.1 presents the study site soil characteristics, which will be used to calibrate APSIM software. The soil cation exchange and capacity (CEC) and organic and clay content characteristics in Table 5.1 are essential for soil nutrient retention. The CEC, clay, soil nitrogen and carbon content are used in the soil productivity index developed in Chapter 4 and applied to vary periodic land value in Section 5.3.

Table 5.1

Australian Soil Resource Information System (ASRIS) Red Kandosol Soil Profile for Wagga Wagga, NSW



Horizon	Sample Depth (m)	pH H_2O^A	pH $CaCl_2$	Elect. Cond. dS/m^A	$CaCO_3$ %	Org. C $\%^C$	Extr. P mg/kg	Tot. P $\%^D$	Tot. K %	Cation exchange properties^A cmol(+)/kg							ESP $\%^A$	Bulk dens. Mg/m^3	Particle size $\%^C$			
										Ca	Mg	K	Na	H+Al	CEC	ECEC			CS	FS	Silt	Clay
A11	0.00–0.8	5.9		0.18		2.1				5.0	1.2	1.5	0.1		10		–		18	47	12	23
A12	0.8–0.15	5.1		0.08		1.1				3.0	0.9	1.0	<0.1		8		–	1.5	17	47	11	25
B21	0.15–0.30	5.8		0.05		0.6				4.5	1.4	1.0	<0.1		9		–	1.6	16	38	9	37
B21	0.30–0.40	6.7		0.05		0.4				5.6	2.3	1.1	0.1		10		–		15	31	7	46
B22	0.40–0.60	7.0		0.04		0.4				6.2	3.3	0.9	0.1		11		–	1.5	13	24	5	57
B31	0.60–0.75	7.3		0.04		0.3				5.7	3.8	0.7	0.3		11		–		12	23	8	57
B32	0.75–0.90	7.2		0.04		0.2				4.7	4.0	0.8	0.4		11		3		11	27	9	54
2B2	0.90–1.20+	7.0		0.05		0.2				5.4	5.3	1.0	0.6		14		4		9	27	8	56

Source: McKenzie (2004, p. 256)

5.2 CLIMATE DATA AND PREDICTED CLIMATE CHANGE

Climate variability impacts wheat yields in South-eastern Australia, and the impact of large-scale climate shocks such as drought and flood on wheat yield are well understood. As such, using APSIM simulations with historical data to generate wheat yields will identify periods where climate shocks have reduced crop yields and therefore, income. The impact on soil productivity and subsequent yields will be investigated to identify any ongoing impacts from climate shocks. Crop simulations will compare current management processes to the new hydro-priming management process to investigate if that process leads to reduced climate shocks and increased wheat yields, soil productivity and NPV returns from land use.

Climate change impacts soil productivity, crop yield, and returns from crop production simulations with current and hydro-priming management practices can provide valuable insights into methods to mitigate climate change impacts. For example, climate-induced adverse production shocks may be generated through rainfall deficits or hotter temperatures at critical stages of crop phenological development. APSIM simulations can provide insight into possible causes of the yield reductions and evaluate how effective hydro-priming or varied fertiliser inputs are in mitigating climate-induced production shocks.

Climate production risks are predicted to continue, with climate change expected to increase temperatures and rainfall variation in the study region. When technology and innovation are fixed, empirical studies have shown that dryland low-rainfall crop-producing areas in Australia have experienced crop yield reductions of 27% between 2005 and 2015 due to climate change compared to crop yields in 1990 (Hochman et al., 2017, p. 2,077). Climate change is predicted to increase climate-related production risks due to increasing variance in returns from wheat production. With an increased frequency of climate shocks, soil productivity may be impacted, resulting in a decline in the land's productive capacity. The impact of climate shocks on soil productivity will be explored by applying the soil productivity index to land value using the method in Section 4.4.

Within the APSIM crop modelling software, climate shocks are captured through daily rainfall, minimum and maximum temperatures, and daily solar radiation variation. Daily climate data in APSIM is used to simulate daily crop growth, flowering, grain development and harvest, soil water, and nutrient content, including the decomposition of soil organic material. Daily meteorological data from the Royal Australian Air Force (RAAF) base in Wagga Wagga for 1960 – 2015 recorded by BOM (2020) will be used in APSIM simulations. The RAAF data has reliable records throughout the modelling period, which includes droughts in 1965-1968, 1982-83, the millennial drought 1997 – 2009 (BOM, 2023) and floods events that occurred in 1974, 1991 and 2012 (Anon., 2023). The comprehensive climate dataset facilitates robust simulations of wheat production and analysis of climate shocks throughout the period.

The RAAF Base BOM (2020) climate dataset will be used with statistical downscaling and incorporated into APSIM simulations to investigate climate shocks with predicted climate change. Predicted climate change will use two scenarios based on climate projections undertaken by the NSW Office of Environment and Heritage through its NARCliM project.[18] The NARCliM modelling uses the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios A2 to model possible climate impacts for the Wagga Wagga region (Evans et al., 2014; Fita et al., 2017; Gaffin et al., 2004; Talan, 2014). The scenarios will utilise the average temperature change and the lower and upper bounds of projected rainfall variation for the Murray to the Murrumbidgee region (Talan, 2014). In addition, the RAAF Base BOM(2020) 1960 -2015 dataset will be varied following the methods of Deihimfard et al. (2018) and Xiao et al. (2018), who use statistical downscaling of predicted climate change applied to observed climate data to generate modified stochastic weather data.

The RAAF database will be calibrated using the NARCliM climate modelling step change process with dataset periods allocated to future periods as defined in Table 5.2. For example, the period 1960 – 1979 will be statistically downscaled with predicted climate change for 2020 - 2039 and 1980 – 1999 will be statistically downscaled to predicted climatic conditions in 2040 – 2059 and 2000 –2015 climate data will be downscaled to represent climatic conditions in 2060 – 2075. The NARCliM lower and upper bound climate datasets will be utilised in APSIM modelling to simulate predicted climate change and investigate the impact of climate shocks on wheat yields, NPV returns, and soil productivity.

---

[18] NSW and Australian Regional Climate Modelling (NARCliM) is an NSW Government-led initiative that generates detailed climate projections and data for NSW (Talan, 2014).

Table 5.2

Wagga Wagga, NSW, Australia, Regional Predicted Climate Variation

Period	Temperature increases (°C)	Rainfall variation summer (%)	Rainfall variation autumn (%)	Rainfall variation winter (%)	Rainfall variation spring (%)
1960–1979 (2020–2039)	**0.6–0.7**	**-16 to +27**	**-13 to +57**	**-9 to +4**	**-26 to -1**
1980–1999 (2040–2059)	**1.3–1.4**	**-12 to +27.5**	**-9 to +63**	**-13 to +10**	**-23 to -4**
2000–2015 (2060–2075)	**1.9–2.0**	**-7 to +28**	**-5 to +69**	**-18 to +16**	**-19 to -8**

Source: Evans et al. (2014); Fita et al. (2017); Talan (2014)

5.3 AGRICULTURAL PRODUCTION SYSTEMS: THE APSIM SOFTWARE

Detailed biophysical data is required to investigate and evaluate the impact of climate shocks and the effectiveness of current and hydro-priming management practices to mitigate climate shock impacts on wheat production. Empirical regression analysis using historical data relies on wheat yields that have utilised historical wheat cultivars, which does not capture the improved drought resilience of modern cultivars (Wang et al., 2019). A further omission of empirical analysis is the lack of soil data to evaluate the soil response to climate shocks. Feng et al. (2018) utilised historical rainfall data to investigate how climatic variation impacts wheat yields, finding a relationship between June – August rainfall and wheat yield but has no data to explain the impacts on soil productivity.

Using APSIM to simulate wheat yields provides detailed biophysical data to explore how climate shocks impact wheat yields and soil productivity. As discussed in Chapter 2, APSIM can be calibrated to individual research questions and will be used to explore how hydro-priming wheat seeds impacts wheat yields. Hydro-primed wheat yields will be simulated in APSIM and compared to wheat yields without hydro-priming simulated in APSIM with both simulations using identical production processes and climatic conditions. Using APSIM will facilitate analysis of how climate shocks impact hydro-primed compared to current management practices.

The APSIM crop modelling software simulates periodic crop yields using site-specific soil, climate data, customised crop rotations, crop-specific sowing times, cultivars, and fertiliser input quantities and types. Holzworth et al. (2014) compared wheat yields generated with APSIM with actual results for a range of sites across Australia and found APSIM simulated yields comparable with real yields. Feng et al. (2020) used regression analysis with empirical wheat yield data and a soil degradation parameter to forecast wheat yield. The results were then compared with the APSIM software simulated wheat yield and actual yield data. They found the empirical regressions less accurate than APSIM software yield predictions. APSIM software is suited to site-specific investigations and has been used in numerous economic and scientific studies (e.g. Asseng et al., 2000; Chen et al., 2010).

As discussed in Chapter 3 there are 11 phenological phases commencing with sowing and finishing with the harvest (see Table 3.1). Progression through the phenological phases depends on climatic temperatures known as thermal times. Thermal time is the minimum temperature accumulation over several days required for a crop to complete a stage, which varies depending on the crop and cultivar. Thermal times are cumulative over the crop life, with a minimum and maximum thermal temperature required for crop survival (FAO, 2006). Celestina et al. (2023) investigated Australian wheat thermal times for a range of wheat cultivars and found that the thermal times for wheat cultivars from sowing to flowering ranged from

800°to 3000°Cd cumulative temperatures.[19] The LongReach Plant Breeders (LRPB) *Trojan* cultivar used in this study was classified by Celestina et al. (2023) as mid-range for time from sowing to flowering and grain production. Hydro-priming seeds will increase germination to emergence wheat root and shoot growth rates with hydro-primed crops achieving the required emergence thermal time quicker than non-primed seeds. This may increase wheat resilience to climate shocks and increase NPV returns.

APSIM software will be calibrated using the BOM RAAF Base climate data discussed in Section 5.2 (BOM, 2020). Daily climate data simulates crop growth, water movement, soil carbon, and nitrogen fluxes. When calibrating APSIM it is assumed that the previous land use was a crop rotation system, as described in Section 5.1 with the site soil conditions calibrated using the ASRIS database NSW DPI Wagga Wagga research site ASRIS record, presented in Section 5.1, Table 5.1. After each production period the post-harvest crop stubble will be left on the soil surface over the summer fallowing period to retain soil moisture and reduce weed growth.

APSIM wheat management processes will be calibrated using the information in Table 5.3. The LRPB Trojan was selected for its resistance to various diseases and its resistance to frost damage during wheat flowering. A further benefit of the LRPB Trojan cultivar is the high protein content with AgGrow (2018, pp. 6, 9) field trials nearby in 2018 returning an average protein content of 11 – 13%, enabling farmers to sell their wheat as Australian Hard wheat in the global export market. The LRPB Trojan cultivar is grown in the Wagga Wagga region, with Grains Research

---

[19] Where Cd denotes the sum of the daily atmospheric temperatures the plant is exposed to, with a threshold required for a plant to move from one phenological stage to the next.

Development Corporation (GRDC) recommending sowing between March to April with harvest from November (Matthews et al., 2020). At the end of each production period, after harvest has occurred crop yields, soil carbon, and nitrogen data will be extracted from APSIM and used in the economic analysis described in Sections 5.5 and 5.6 to calculate the impact of farmer crop production management practices on profits from land use and land value.

Table 5.3

Wheat management characteristics for APSIM calibration

Wheat	
Cultivar	Trojan
Sowing time	March - April
Sowing depth	70mm
Row Spacing	180mm
Plant population	100 m2
Fertiliser	100kg/ha DAP[20] at sowing, 85 kg/ha urea in July
Nitrogen applied	18 kg/ha at sowing, 39 kg/ha in July

5.4 CROP PRODUCTION FUNCTION

In Wagga Wagga wheat is a winter crop, sown in May, with the wheat cultivar *Trojan* selected for APSIM production simulations based on the GRDC, recommended wheat cultivars and planting times (Meppem, 2020; Monjardino et al., 2015). A fixed production function for APSIM was used over the modelling period, repeating the configured crop planting times, management actions, and production inputs in each production period. The crop production function used in the economic model below reflects these fixed characteristics, with climatic conditions and soil productivity state variables. The approach is consistent with Benhin (2008) and

---

[20] Di-Ammonium Phosphate (DAP) fertiliser is a slow-release fertiliser containing 18% nitrogen and 46% phosphorous.

Mendelsohn and Dinar (2003), who use an improved production function to evaluate the impact of climate on agricultural production.

The production function has fixed input prices and wheat output prices. By removing price variation, the impacts of climate shocks on soil productivity and crop production returns can be focussed on. The production function incorporates variable inputs, capital used in the production process, soil productivity, and variable inputs prices which are fixed across the modelling period. Let $\boldsymbol{x}$ be a vector variable inputs used in wheat production, including but not limited to fertiliser, wheat seeds, fuel used in land preparation, fertiliser application, harvesting costs, herbicides, fungicides, and harvest and transport costs. Inputs and variable input prices, $\boldsymbol{w}$, used in the production process are taken from the NSW DPI Southern Winter East Crop Dryland Budgets 2012 (DPI, 2013), ABARES (2019) and GrainTrade (2020, 2021) cost data and are presented in Table 5.4.

It is assumed that all grain produced is sold internationally. Farmers incur transport and loading costs to Port Kembla per tonne of grain produced as part of the variable input costs. The remaining variable production costs are per hectare, with all input prices calibrated to 2020 values using the Reserve Bank of Australia’s annual inflation rates (DPI, 2013; RBA, 2023).

Let, $\boldsymbol{k}$ be a vector of capital inputs used in the production process, including but not limited to tractors, fencing, and shedding**.** To simplify the modelling process, capital and the technology embodied in the capital stock remain fixed across the planning horizon. Moreover, the modelling does not consider the effects of fixed asset depreciation, machinery repairs, and maintenance. Sensitivity testing will be undertaken using the same approach as Howitt et al. (2012) that is, by varying production costs by 20% to assess the impact of production costs variation on gross margins.

Table 5.4

Crop Production Cost Data

Production Cost	**Cost ($ /per ha)**
Weed control	97.53
Sowing	41.87
Pest & disease control	32.84
Cultivation	0.00
Fertiliser[21]	52.77
Contract harvest	42.63
Crop levies & Insurance	12.79
Labour	9.17
Total variable production cost ($)	289.61
Transport, port terminal fees ($/t)[22]	60.39
Revenue ($/t)	269.01

Note: All prices are in 2020 AUD unless otherwise specified

Source: ABARES (2019, 2020b); DPI (2013); R B.A (2020); GrainTrade (2020, 2021)

The soil quality that crops are grown in limits the production function's output. At the beginning of each crop production period, soil productivity, η_t, is measured. Crop yield, y_t, (11), in each production period is constrained by the soil productivity η_t at the beginning of the crop production period and the crop management techniques used by the farmer, m , which is fixed across the modelling period. Each production period is one year long and incorporates the summer fallowing period. The modelling production function process is presented in a

---

[21] Fertiliser prices taken from the average price for 2020 from the World Bank (2020) and calculated using the quantity used. 80kg/ha of urea at $332.95 per ton and 100 kg/ha of DAP at $454.01 per ton.

[22] Transport from Cootamundra to Port Kembla by road or rail, port terminal fees include intake fee, 1 month storage fee, booking, loading and out loading fees (GrainTrade, 2021).

simplified format in Appendix A. Crop yield increases with soil productivity, which is constrained to be non-negative:

$$y_t \equiv f(\boldsymbol{x}_t, \boldsymbol{k}, \eta_t, m) \tag{11}$$

APSIM will be calibrated according to the NSW DPI 2020 (Matthews et al., 2020) winter crop planting guide recommended crop sowing time, depth, and number of plants per square metres and fertiliser input quantities discussed in Section 5.3. Crop yields are a function of soil productivity, climate conditions, management techniques, and variable and capital inputs used in production.[23] Annual crop yield and soil carbon and nitrogen content are calculated after the harvest has occurred for each production period. These values will be exported from APSIM into the economic modelling to evaluate the impact of the production process on farmer profits and soil productivity.

5.5 LAND VALUE

Farmers generate income from land, and the present value of agricultural land is influenced by the productivity of the land and expected future income that can be derived from land use (Featherstone et al., 2017). Therefore, farmers seek to maximise the returns generated from land use and the land value. Climate shocks and management actions can vary soil productivity and therefore land value. As outlined in Chapter 2 empirical data incorporates the prevailing management techniques of the production period into the analysis. However, empirical land value analysis is unsuitable for estimating hydro-priming's impact on land value. Further, as discussed

---

[23] In Section 5.7 a simulation for continuous wheat production will be compared to a simulation with the crop rotation sequence to evaluate the impact on soil productivity.

in Chapter 2, site-specific soil characteristics are not captured in empirical land value analysis. Therefore, this section provides an alternative method of estimating land value that incorporates the soil productivity variable outlined in Chapter 4.

As discussed in Chapter 4 soil productivity is linked to the quantity of soil carbon and clay in the soil. An empirical analysis by Mendelsohn and Dinar (2003) used the quantity of clay in the soil as an explanatory variable in their study of land use and value in developing economies. Following this approach, the soil productivity index developed in Chapter 4 can be used to evaluate the impact of management actions on land value. Changes in soil carbon and the soil nutrient holding capacity are reflected in the soil productivity index and enables site specific evaluation of the impact of climate shocks and farm management decisions on future land productive capacity.

Increasing soil productivity increases the potential yield that can be realised in the subsequent crop production, thereby increasing future returns from land use. In economic modelling, it is assumed that land values grow at the nominal rate of return (LaFrance et al., 2011). Nevertheless, this approach does not capture the impact of management decisions and climate shocks on the land's productive capacity. A standard method for quantifying the rate of return on financial assets is by determining the change in value in one period from the previous period (Chen et al., 1986). Applying this concept to soil productivity, a shift in soil productivity can enable farmers to quantify the impact of land management practices. A soil productivity index will use the net change in soil productivity from one period to the subsequent period where:

$$\delta_{\eta,t+1} = \left(\frac{\eta_{t+1} - \eta_t}{\eta_t} \right) \tag{12}$$

The soil productivity index can be utilised with nominal interest rates to evaluate the crop production intensity, management practices, and prevailing climatic conditions that impact soil quality, future returns from land use and land value. However, the soil productivity index applied to land value does not capture market price variations, which include changing tastes and preferences, farmer expansion with favourable international commodity prices or climatic conditions and other exogenous factors (RuralBank, 2020).

The value of a 1-hectare plot of land, a_t, is \$2,742 (RuralBank, 2020, p. 17).[24] Farmers utilising cropped land area seek to maximise the expected net present value of profits derived from a 1-hectare plot of land over a finite time horizon, $0 \leq t \leq T$, using a discount rate, r_t. The actual price of land, is calculated following the works of LaFrance et al. (2011); Tack et al. (2015), that assumes the current market price of land increases at the nominal rate of growth, $(1+r_t)$ in each production period. Periodic variation in land value comprises the soil productivity index, and the nominal growth rate. Hence, the value of the cropped land at the beginning of the period is:

$$L_t(\delta_{\eta,t}) = (1+r_t+\delta_{\eta,t})p_{L,t}\alpha_t, \forall t = 0,1,...,T. \tag{13}$$

Where T is the last period on the farmer's planning horizon. An increase in soil productivity increases soil quality, which is valuable in a competitive market for farmland. However, soil productivity can also decline depending on the production management practices or climate shocks experienced during the production period. This will decrease land productivity and subsequent returns from land use and is reflected in the end-of-period market value for the land. Similarly, management

---

[24] The 2019 average price per hectare of land taken from RuralBank (2020) p.17 data is harmonized to 2020 prices using the Reserve Bank of Australia average inflation rate of 0.8% for the 2019 to 2020 Calendar year (RBA, 2022).

practices that maintain or improve the quality of the land increase wheat yields in subsequent production periods, increasing the value of the land. In this study, simplifying restrictions are employed to confine attention to evaluating the effectiveness of the soil productivity function. As such, it is assumed that land is held for the entire modelling period, and alternative crops, land uses, management methods, market changes, and production input quantities are not considered.

5.6 CROP PRODUCTION PROFITS AND NET PRESENT VALUE (NPV)

Crop production management practices can increase or decrease periodic returns from land use. The periodic returns from crop production are determined using realised crop prices, crop yield, and production costs to derive the net returns from a 1-hectare plot of land. The crop production realised yield (11), presented in Section 5.4, uses APSIM crop modelling software's output, calibrated to site soil, climate conditions, and fertiliser inputs.

Crop output prices are held fixed and realised at the end of the production period and received by a farmer in the subsequent period. The wheat price used is the World Bank's global average annual Wheat (U.S.), no. 2 hard red winter Gulf export price for 2018, converted to Australian dollars using the average AUD/USD exchange rate in 2018 (WorldBank, 2020) and adjusted to the 2020 price using the RBA inflation rate (RBA, 2023).[25] Following Mendelsohn and Dinar (2003), input costs and quantities are fixed over the modelling period. Input costs are

---

[25] Due to the Ukraine war impacting global wheat prices in 2020 the 2018 World Bank wheat price was used instead of the 2020 average annual wheat price. The US no.2 hard red wheat price was selected because it has a grain protein content requirement of 10 – 13%, consistent with wheat grain protein content achieved in the region (Zeleke & Nendel, 2016).

then adjusted forward to determine the returns from crop production using the discount rate $(1+r)$. The profit function (14) uses a modified version of the periodic profit function described by Cai et al. (2013). Profits are estimated for a 1-hectare plot of land, with revenue being received in *t+1* while production costs are incurred in period *t*.

$$\pi_{a,t+1} = \left\{ \left(p_{Y,t+1} y_t \right) - \left(1 + r \right) \boldsymbol{xw} \right\} \tag{14}$$

At the beginning of the modelling period (1960), the farmer seeks to maximise the discounted NPV of returns generated from wheat production and land value by selecting the management practice that maximises the NPV stream of expected future profits from 1960 -2015, including any changes to land value. The process taken to determine NPV profits is presented in a simplified manner in Appendix A. Land value varies in each production period according to the nominal interest rate and soil productivity index. Therefore, the discounted NPV of expected profits derived from a one hectare plot of land devoted to a single production management treatment over the modelling period is:

$$\max \sum_{t=0}^{T} \left(\frac{1}{1+r}\right) \left\{ \pi_{a,t+1} + \left[(\delta_{\eta,t}) p_{L,t} \alpha \right] \right\}, \tag{15}$$

The farmer seeks to increase the value of land assets in each production period by undertaking management practices that improve soil quality. The inclusion of the change in land value resulting from the soil productivity index developed in Chapter 4 is reflective of farmers' consideration of the impacts of management practices on soil quality and future land value. Sensitivity testing of the model will be undertaken using a range of discount rates (2%, 5%, and 7%) and varying input costs by 20% to investigate how the discount rate impacts NPV profits, land value, and soil quality, with the results presented in Chapter 6 and discussed in Chapter 7.

5.7 FERTILISER INPUT VARIATION

Australian soils are low in nitrogen, fertilisers contain nitrogen and are critical production inputs to improve crop yields in Australia (Smith et al., 2019). Fertiliser will be applied in each production period according to the NSW DPI recommended application times and quantities are from the NSW Southern Winter East Crop Dryland Budgets 2012 (DPI, 2013).

The recommended fertiliser application rate for wheat is 100kg/ha of Di-Ammonium Phosphate fertiliser (DAP) at sowing, which contains 18% nitrogen, and a further 85 kg/ha of urea, including 46% nitrogen, applied in July applied in each production period. In APSIM and following Mendelsohn and Dinar (2003), fertiliser input quantities remain fixed over the modelling period to focus on the effects of climate shocks in different production periods. A further benefit of a fixed fertiliser input process is that it will enable comparison of the impact of climate shocks with current and hydropriming practices. Using historical and predicted climate change simulation outputs with a fixed production function with current and alternative management practices will provide a robust evaluation of climate shock impacts on wheat yield and farmer income.

Australian dryland crop producers face significant climate production risks, which are exogenous to the crop production function. Farmers seek to maximise the profits derived from land use, and as discussed in Chapter 4, fertiliser is a crucial input to maintain soil productivity. The fertiliser unit price will remain fixed over the production period using prices as presented in Table 5.4. The study is a stylised example seeking to understand the connection between hydro-priming wheat seeds and fertiliser input quantities and what combination can be utilised to minimise wheat crops' climate risk exposure.

Fertiliser input quantities will be varied to investigate the impact on NPV returns, crop yields with climate change, and fertiliser input efficiency using the wheat grain NUE. The amount of fertiliser will increase and decrease the NSW DPI recommended urea and DAP quantities by 20, 40 and 60% in APSIM, with the simulation results incorporated into the soil productivity index, land value, production function, and NPV returns using processes described in Sections 5.5 and 5.6. This process will be repeated for both the hydro-priming and current management practices, with the quantity of fertiliser that maximises farmer profits and fertiliser input efficiency presented in Chapter 6, with the results discussed in Chapter 7.

5.8 HYDRO-PRIMING PRODUCTION COST

As discussed in Chapter 3 hydro-priming is created by dissolving 5 kg of granular DAP fertiliser in 200 litres of water during the summer fallowing.[26] The production function in Section 5.3 outlines the seeding rate per hectare based on GRDC recommendations for the Wagga Wagga region. Three methods of hydro-priming will be investigated: A low-technology solution where seeds are manually hydro-primed, an automated process where the priming and drying processes are undertaken by machinery, and a semi-automated process where the priming is done manually, and the seeds dried using machinery. To allocate costs, from Section 5.1, it

---

[26] Di-Ammonium Phosphate (DAP) fertiliser consists of 18% nitrogen and 20% phosphorus, with an average price of $AUD 664 per metric ton for the period 1/2003 – 1/2023. (IndexMundi, 2023)

is assumed that farmers operate a 500ha area devoted to crop production, and that the farmer allocates the entire 500ha to wheat production using hydro-priming technology.

Low-technology manual hydro-priming is a method that may be suitable for small landholders. Seeds are manually placed in a large receptacle with the liquid fertiliser for 5–24 hours before removal and air drying on a hard surface and stored until required. The costs of manual hydro-priming of 100kg of wheat seeds include the price of the 300L receptacle, the cost of the fertiliser used, the water needed for the process and the labour to complete the process[27], with costs presented in Table 5.5.

For commercial hydro-priming, seeds are automatically processed through drums with 40 – 1,800kg of seed capacity, depending on the configuration. The installed priming drum capacity is 40kg, constraining the volume processed through automatic priming. Therefore automatic priming will be calculated using 40kg of seed with costs presented in Table 5.5. A priming unit costs $51,207 and is capable of priming up to 40kg of seeds at a time.[28] The liquid and seeds remain in the drums for the programmed time before being transferred into a commercial drying machine that utilises heat pumps to extract water from the seeds. A conditioned seed dryer costs $77,168 and can dry up to 100kg of seeds in 3 hours.

---

[27] Using a 300L water tank at a cost of $170.60 (DickSmith, 2023)
Riverina Water supply cost of $1.51 per kL (RiverinaWater, 2023)
DAP fertiliser at a cost of $664.48 per ton (IndexMundi, 2023)

[28] Personal communications with Agratetechniek on 25/2/23 and 6/03/23 for small-scale agriculture found that an osmotic priming unit 5 x 8 litres, VLM-4150 costs $51,207. In personal communication prices were supplied in Euros. Conversion of the prices from Euros to AUD used the average €/$AUD exchange rate for 2020, €1=$1.6561 (ExchangeRates, 2023). The total cost, including the $5,211 shipping cost MoverDB. (2023). *2023 Sea Freight Container Shipping Rates To & From Australia*. MoverDB. Retrieved 6/03/2023 from https://moverdb.com/container-shipping/australia/ for both units, is $133,577.

In the partial budget constructed in this study, all taxes, freight, and purchase costs have been calculated and included in 2020 AUD. However installation costs are site-specific and have been excluded from production cost data. For automated priming the fertiliser, electricity, water, and labour cost for 40kg of seed hydro-primed utilises the same cost assumptions as discussed in the low technology hydro-priming, with the addition of $2.54 of electricity to operate the osmo-priming and seed drying machinery using 3kw/h for 3 hours.[29]

A lower cost option than automated priming is semi-automated priming, with manual priming subsitutued for an automated priming unit. Seeds are manually primed using a 1,000-litre tank (Equip2go, 2023) filled with the fertiliser solution, used to immerse 500kg of wheat seeds in 500L of water, with costs presented in Table 5.5 The solution is manually drained, by removing a plug at the base of the receptacle before a tractor transports the seeds to the drying unit, where seeds are manually loaded for drying.[30] DingXin (2023) has a drying unit which can dry up to 3 tonnes per hour using 3.15kw/h of electricity.[31] Therefore, the drying cost includes electricity to operate the seed drying machinery per 500kg of seed dried.

The marginal cost of automatic hydro-priming is $289 per/ha and semi-automated is $68 per/ha in the first year. In years 2 to 19 the marginal cost is $32 per/ha and $45 per/ha respectively, before equipment is replaced in the 20th year, 1980. The cycle was repeated, and the machinery was replaced in 2000, with all costs inflated using the applicable discount rate. The marginal cost of semi-automated hydro-

---

[29] Wrigley (2023) is used to estimate energy costs with the average cost of electricity in NSW in 2023 is $0.2866 per kw/h.

[30] It is assumed the tractor is a preexisting asset held by the farmer and excluded from cost estimates has a drying unit costing $7,484[30], with shipping from China to Sydney costing $2,511.

[31] In personal communications with DingXin (2023) prices were supplied in $USD, conversion to $AUD used the average $USD/$AUD exchange rate for 2020, $USD 1= $AUD 1.4533 (ExchangeRates, 2023)

priming is higher than the automated cost due to significantly higher labour input costs in Table 5.5. Consistent with this, the highest cost in manual hydro-priming is the labour cost, with the cost in the first year $59 per/ha and $59 per/ha in subsequent years with capital costs allocated across the 500ha equally.

Table 5.5
Seed hydro-priming cost ($/ha)

Input	Manual ($/ha)	Automatic ($/ha)	Semi-automated ($/ha)
Receptacle/machinery	170.60	128,375.00	11,482.00
Fertiliser used	0.90	0.83	0.83
Water	0.15	0.06	0.09
Electricity		2.54	0.90
Labour	58.00	29.00	43.50
Total	229.65	128,407.43	11,527.32
Cost year 1 ($/ha)	59.39	289.18	68.28
Marginal cost (subsequent years) ($/ha)	59.05	32.43	45.32

Hydro-priming seeds may reduce the profit-maximising quantity of fertiliser required while improving crop nitrogen use efficiency. The quantity of fertiliser required to maximise returns from land use will be investigated by simulating a range of input quantities using the NSW DPI (2013) recommended fertilisers (urea and DAP) and crop application times, with economic analysis following the process presented in Sections 5.5 and 5.6. A further benefit of hydro-priming may be improved crop nitrogen use efficiency (NUE) and grain protein content. Following the process by Moll et al. (1982), the NUE of hydro-priming with wheat will be evaluated with different quantities of fertiliser using the process outlined in Section

5.6 to determine the NPV profitability of hydro-priming and any soil productivity benefits.

5.9 CARBON PRICING OF FERTILISER EMISSIONS

Fertiliser nitrous oxide emissions, EF, are calculated using the method for calculating fertiliser emissions in the Australian Government, *2020 National Inventory Report Volume 1* (DCCEEW, 2022). The quantity of nitrogen in a fertiliser, M_t ,depends on the fertiliser type, ϑ ,with urea containing 46% nitrogen, whilst DAP fertiliser contains 18% nitrogen, and quantity applied (kg/ha) in a production period, $\frac{df_t}{dx_{f,t}}$. Carbon emissions permits are issued in tons, therefore M_t will be converted into tons per hectare by dividing the value by 1,000.

$$M_t = \left(\frac{\frac{df_t}{dx_{f,t}} \times \vartheta}{1{,}000} \right), \tag{16}$$

In each production period, the number of fertiliser emissions will be estimated in tons per hectare using the National Inventory Report 1 Method for inorganic fertilisers by DCCEEW (2022, Volume 1, p. 338). The amount of nitrogen in the fertiliser will be multiplied by the nitrous oxide emission factor, 0.2 for urea and 0.002 for other fertilisers applied, which includes DAP (p. 379 & p. 339, DCCEEW, 2022) and a conversion factor of 44/28 to convert the elemental mass of N_2O to molecular mass.

$$x_{\propto}(t) = M_t \times EF \times \frac{44}{28}, \tag{17}$$

The cost of fertiliser emissions will be calculated using (17) applied to the average market price per tonne of carbon emissions from three different markets in 2021. The World Bank's (2023) average carbon prices for 2021, presented in Table 5.6, for the European Union (EU), New Zealand Emissions Trading Scheme (NZ ETS) and Australian Carbon Credits Units (ACCU) were utilised and harmonised into 2020 prices using the RBA deflation rate. Carbon markets are relatively recent, with different inception dates and considerable market volatility. To ensure the prices used in modelling reflect current market conditions, the average 2021 prices in AUD are used and calibrated to 2020 prices using the RBA deflation rate.

The EU carbon market was established in 2005, with low prices resulting from an overallocation of carbon permits, the EU has subsequently addressed this. The EU carbon market is the largest and most mature of all carbon markets, while the New Zealand market commenced in 2008.[32]. ACCU's are what farmers will be eligible for and were first issued in 2011 and are an offset market with voluntary participation, unlike the EU market which trades permits to allow an entity to emit pollution (Clean Energy Regulator, 2022). Using the 2021 average annual price reflects current market value for a carbon permit but extrapolates away from daily market fluctuations over a calendar year.

---

[32] The New Zealand market is relatively mature but to achieve a desired reduction in carbon pollution the New Zealand government is more involved in managing the market than the EU.

Table 5.6

Carbon emission permit prices per tonne in 2020 $AUD[33]

Source	Price ($/t)
EU average price 2021	70.17
ACCU average price 2021	19.16
New Zealand ETU average price 2021	36.31

Source: (CER, 2022; WorldBank, 2022)

The carbon price, $\boldsymbol{w}_{\propto}$, is an exogenous variable fixed across the modelling period to focus on the impact of a policy shift on farmer profits and fertiliser input management decisions. However, given that we are only interested in examining how a carbon price will impact a farmer’s fertiliser input decisions and subsequent profits, the analysis does not consider the costs of soil carbon emissions. The carbon price on fertiliser nitrous oxide emissions is known *ex-ante* when fertiliser input decisions are made. Applying a cost to nitrous oxide emissions from fertiliser will increase production costs. For every additional unit of fertiliser used, production costs increase, increasing the marginal production cost and decreasing the marginal benefit of other fertiliser inputs compared to a world without an emissions pricing policy. The farmer will then choose the quantity of fertiliser that maximises NPV returns from wheat production:

$$\max \sum_{t=0}^{T} \left(\frac{1}{1+r}\right) \left\{ \left(p_{Y,t+1} y_t - (1+r)[\boldsymbol{xw} + x_{\propto} w_{\propto}] \right) + (\delta_{\eta,t})\, p_{L,t} \alpha_t \right\}, \qquad (18)$$

---

[33] Prices are in 2020 AUD are taken from the first quarter data in 2021 from the World Bank Carbon Pricing Dashboard (2023)

Modelling will be undertaken by applying the carbon prices presented in Table 5.6 using current and hydro-priming management practices and varying the quantity of fertiliser as described in Section 5.7 to determine the amount of fertiliser and management method to maximise NPV returns from wheat production.

5.10 CROP ROTATION

Continuous wheat production differs from current crop production land use in Wagga Wagga. Farmers rotate crops to prevent pest and disease infestation that occurs with continuous monoculture crop production and negatively impacts crop profitability. Field peas are suitable crops to grow in rotation with wheat as the pests and soil diseases common in cereal crops do not thrive in leguminous crops (Xing et al., 2017). A further benefit of field peas is the ability to deposit atmospheric nitrogen in soil via nodules on the root systems, reducing nitrogen fertiliser inputs and regenerating soil nitrogen content (Chaudhary et al., 2008; Matthews & Maccaffery, 2019). A simulation with a crop rotation commonly grown in the region will be used to investigate the impact of climate shocks on NPV of soil quality and land value, with the crop rotation sequence, wheat, wheat and field pea (Heenan, 1995).

The field pea cultivar *Kaspa (Butler*) is selected from the New South Wales Winter crop variety sowing guide 2019 for its site suitability, growth characteristics and availability within the APSIM crop modelling software (Matthews & Maccaffery, 2019). The sensitivity of *Kaspa (Butler)* to pest and disease predation is considered in cultivar selection, however the effects of pest and disease occurrence on crop productivity are not modelled. This is left for future research endeavours. The management practices used to calibrate APSIM will follow NSW DPI's (2013) recommended cultivation, sowing time, and fertiliser inputs, presented in Table 5.7.

Table 5.7

Field pea management characteristics for APSIM calibration

	Field pea
Cultivar	Kaspa
Sowing time	June
Sowing depth	30mm
Row Spacing	200mm
Plant population	30 m^2
Fertiliser quantity	100kg/ha legume starter (DAP) at sowing

Source: NSW DPI (2013), Matthews & Maccaffery (2019).

The production function follows the crop production function described in Section 5.4, with the Net Present Value described in Section 5.6 incorporating variable input cost and revenue data in Table 5.8 to estimate the NPV returns from land use, wheat grain protein content and Nitrogen Use Efficiency (NUE) of fertiliser inputs with the crop rotation sequence wheat, wheat, field pea. The crop rotation sequence is repeated iteratively over the modelling period from 1960 – 2015.

Table 5.8

Crop Production Cost Data

Production Cost ($)	Field Pea
Weed control	107.07
Sowing	65.33
Pest & disease control	30.05
Cultivation	0
Fertiliser	33.30
Contract harvest	56.81
Crop levies & insurance	21.97
Total variable production cost ($)	**332.86**
Transport, port terminal fees ($/t)[34]	60.39
Revenue ($/t)	**420.00**

Source: NSW DPI (2013), GrainTrade (2021)

The crop rotation sequence will be repeated using a range of fertiliser inputs and simulated to investigate how crop rotations impact soil productivity and returns from land use with climate shocks, using historical climatic conditions and predicted lower and upper-bound climatic conditions. The crop rotation process will be repeated with all processes remaining identical, however using the hydro-primed wheat scenario to investigate how field pea and wheat crops interact and the impact on soil productivity and NPV returns. The impact of the crop rotations sequence of profits derived from land use, soil productivity and land value will be compared to the results obtained with continuous wheat production to evaluate how crop rotations impact soil productivity. Sensitivity testing will be undertaken by varying input costs by 20% and using a range of discount rates (2, 5, 7%).

---

[34] Transport from Cootamundra to Port Kembla by road or rail, port terminal fees include intake fee, 1 month storage fee, booking, loading and out loading fees (GrainTrade, 2021).

5.11 LIMITATIONS

Several simplifications are made to enable analysis of climate risks across different management methods, fertiliser inputs and with predicted climate change. It is unknown what future global wheat supply will be and the impact of climate change on current wheat-producing regions is not well understood. Wheat demand is relatively inelastic using fixed prices does not accommodate future population growth and wheat demand trend impacts on market prices. The future market price for wheat will be impacted by wheat supply, with this relatively unknown thus, using a fixed price for wheat across the modelling process removes uncertainty.

A critical limitation is using a fixed production function with continuous wheat production. Using a fixed production function will enable evaluation of the economic impact of climate shocks' on NPV for simulations comparing historical crop yields and returns from wheat production to wheat yield generated with predicted climate change. A fixed production function will help identify how climate shocks impact wheat yield and farmer income with hydro-priming and current management conditions. A further benefit of the fixed production function is that it will identify if fertiliser input variation can mitigate the severity of climate shocks on soil and wheat yields experienced with historical data and predicted climate change.

Using fixed inputs and output prices applied to hydro-priming will support the economic analysis of how hydro-priming impacts economic returns with historical climate and predicted climate change. This is important to evaluate the net benefits of hydro-priming as a technique to mitigate climate shocks and determine whether fertiliser input efficiency can be improved to reduce agricultural contribution to climate change.

A further benefit of using fixed prices for wheat outputs and production inputs is that it enables comparison of historical NPV returns with predicted future NPV returns. Removing price variation enables comparison of climate shocks in different years to investigate how varied rainfall in germination impacts wheat yields and profits from land use. As stated previously future output prices are unknown and this is also true for production input prices. Fertiliser input prices increased in 2022 due to the Ukraine war, which is unlikely to have been considered in many agricultural economic research analyses in the 5 years before the conflict commenced. Historical market factors that influence past input price variations cannot be replicated hence, using fixed input prices remove the market fluctuations from the analysis and enable focus on the economic impact of climate shocks on returns from land use.

Wheat prices fluctuated significantly between 1974 -1995 and included the impact of historical agricultural policies such as US government agricultural support (Jacks et al., 2011). Future agricultural policy is unknown, however applying historical price variation to predicted climate change simulations with step changes in climate will skew results and detract from economic analysis of how climate shocks change with progressive step changes in predicted climate change. By utilising fixed input and output prices, economic analysis of the impact of climate shocks on biophysical data can be evaluated.

Including market price fluctuations was considered in previous iterations of the thesis however fertiliser and wheat prices were the only prices with data for the entire modelling period. Some results were skewed due to the aforementioned agricultural policies impacting global wheat prices. Fertiliser input price variation did not significantly impact annual wheat profits from land use. The quantity of DAP and urea used compared to the price per ton did not materially impact annual profits or change farmer management decisions. However, using annual price data for wheat, urea and DAP fertiliser inputs added a layer of complexity when analysing climate shocks' impact on land use profits. Therefore, price variation was removed by holding prices fixed to facilitate analysis of the economic and biophysical impact of climate shocks in different periods.

5.12 SUMMARY

Climatic variation is the most significant risk to dryland crop production in Australia, affecting crop yield, soil productivity and profits from wheat production. The modelling presented in this chapter investigates how climate shocks impact profits from land use and proposes methods to mitigate climate shock impacts on crop yields and profits. The novel technique of hydro-priming wheat seeds before sowing is explored and partial cost budget for three different hydro-priming methods presented. The impact of hydro-priming seeds will be combined with fertiliser input variation to explore the most efficient and profit-maximising quantity of fertiliser. The effectiveness of hydro-priming wheat seeds with predicted climate change will be evaluated by applying two scenarios. Developing new methods to address the impact of excessive or insufficient rainfall on crop yields will support dryland crop production to become more resilient.

Biophysical modelling will create a soil productivity index to evaluate the impact of hydro-priming wheat seeds on soil productivity and investigate how climate shocks interact with management practices to impact soil quality. The soil productivity price function developed in this chapter and used to evaluate the impact of management on soil quality decrease can be employed to address a wide variety of land use research questions, including crop production, financial analysis of farmer wealth, land assets and soil carbon sequestration estimations. To determine soil carbon and productivity variation, the soil productivity model can be calibrated with simple biophysical data to investigate various research questions, including livestock land use and forestry simulations. The economic model focuses on the interactions between the soil nutrient variables, periodic soil carbon and nitrogen, and land value to evaluate the effectiveness of the land price function with the findings presented in Chapter 6 and discussed in Chapter 7.

Fertiliser nitrous oxide emissions are contributing to climate change. Creating and applying a carbon price on fertiliser inputs will increase crop production costs linearly with increasing fertiliser inputs. This internalises the externality of nitrous oxide emissions and their environmental impact. The effect on fertiliser input management decisions of a policy shift to place a carbon price on fertiliser emissions will be investigated.

Chapter 6: Results

This chapter presents the results of the economic model described in Chapter 5 for the NPV of a dryland production system in south eastern Australia exposed to climate shocks. The effect of climate shocks on soil productivity, wheat yields and land use gross margins are explored. The new method of varying land value developed in Chapter 4 was applied to soil carbon and nitrogen variations evaluated using data from APSIM simulations. The modelling process was repeated for current management practices and compared to the new hydro-priming management method presented in Chapter 3. Simulations incorporated hydro-primed wheat into a simple crop rotation system to investigate how hydro-priming effects farmers’ NPV returns from land use. The simulations also considered how the soil’s productive capacity effects climate shocks on wheat yield, gross margin, soil productivity and land value.

Current exposure to climate shocks, the effect on wheat yields, soil productivity and NPV returns are presented in Section 6.1. Varying fertiliser inputs can increase farmer gross margin and NPV returns and the effect of this on soil productivity and land value is explored in Section 6.2. Predicted climate change is expected to increase climate shocks’ effect on soil productivity and NPV returns (presented in Section 6.3) while mitigating climate change through fertiliser input variation is explored in Section 6.4.

The biophysical and economic effect of hydro-priming wheat seeds is presented in Section 6.5. Section 6.6 discusses the effect of a change in emissions policy placing a carbon price on fertiliser emissions with current and hydro-priming management processes. The NPV returns, soil productivity and land value variation with a crop rotation are presented in Section 6.7. A scenario where wheat crops within a crop rotation are hydro-primed is explored in Section 6.8. The chapter concludes with a summary of the findings and how they fit within the existing literature in Section 6.9.

6.1 CURRENT MANAGEMENT PRACTICES

Wheat production was simulated in APSIM annually for the period 1960–2015, with crops sown in March–April each year. Wheat planting data was sourced from the Grains Research Development Corporation's *2020 Winter Crop Variety Sowing Guide* (Matthews et al., 2020) and used with management practices recommended by the NSW DPI (2013). Wheat simulations in APSIM use wheat sowing time, row spacing and plant population for low-rainfall dryland wheat production information from the guide. Yields were generated in APSIM and exported into Microsoft Excel for analysis.

The economic model was calibrated using the World Bank (2020) average US hard red wheat market price for 2020 of AUD 336 p/t.[35] The revenue per hectare using the World Bank (2020) wheat price per ton and the production cost data of AUD 236.84 plus the cost of fertiliser applied, as discussed in Chapter 5, were used to determine annual profits from land use (see Table 6.1). This model did not include fixed costs such as mortgage repayments and capital expenditure however, it does consider variable production costs, including transport, shipping, maintenance and repairs of capital infrastructure, farm labour used in the production process and direct inputs.

---

[35] All prices are in 2020 AUD with prices harmonised using the Reserve Bank of Australia's inflation rates and the average annual exchange rate for USD to AUD in 2020, which was USD 1 = AUD 1.45. Reserve Bank of Australia (2023). *Measures of Consumer Price Inflation, Historical Series and Explanatory Notes*. Retrieved 15/3/2023 from https://www.rba.gov.au/inflation/measures-cpi.html

Table 6.1

Wheat Results with New South Wales Department of Primary Industries-Recommended Management Processes for 1960–2015

Wheat attribute	Results
Cultivar	Trojan
Sowing time	March–April
Sowing depth (mm)	70
Row spacing (mm)	180
Plant population (per 1 m^2)	100
N applied (kg/ha)	57.10
Average wheat yield (t/ha)	4.08
Average protein content wheat (%)	11.90
Average wheat price 2020 ($/t)	336
Production cost ($/ha)	237
Urea fertiliser cost ($/t)[a]	229
DAP fertiliser cost ($/t)	312
Average break-even ($/t)	143
Average gross margin ($/ha)	838
Gross margin standard deviation ($/ha)	384

[a] The fertiliser prices are taken from the World Bank (2020) Pink Sheet Commodity price data for 2020 and converted from USD to AUD using the average annual exchange rate for 2020 of 1.45.

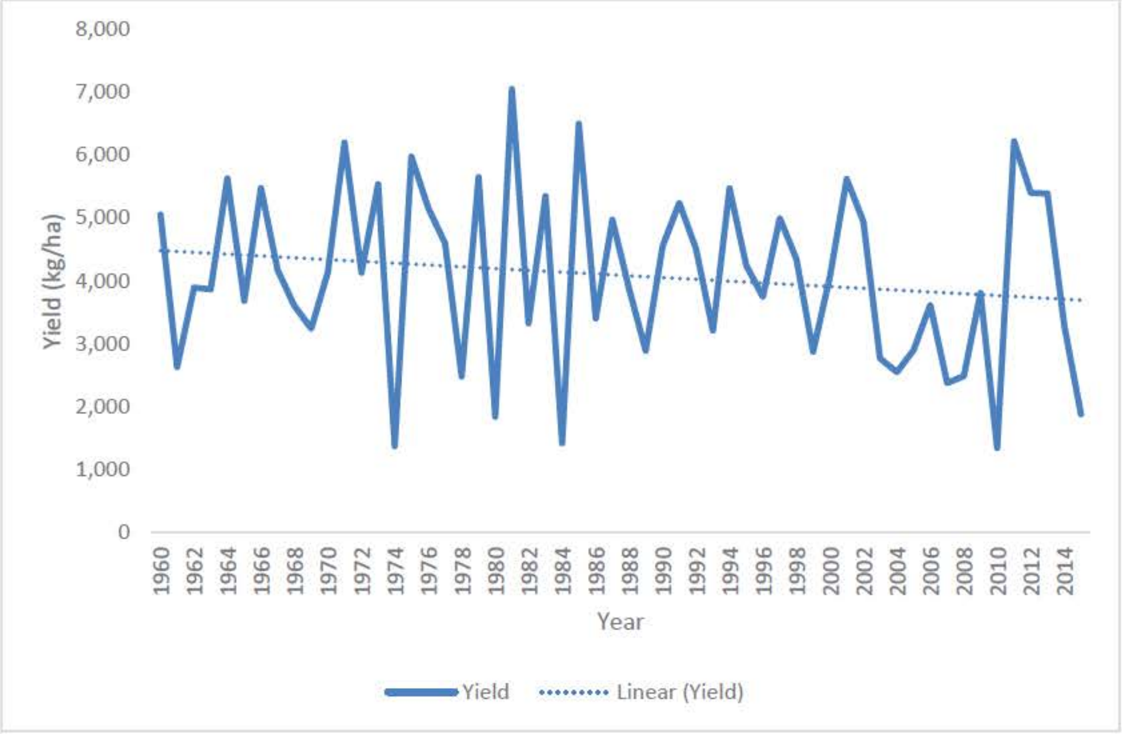
Note: All prices in AUD 2020

Wheat production simulations generated an average wheat yield of 4.08 (t/ha) over the modelling period 1960–2015. The results are consistent with Harris et al.’s

(2019) field studies in Wagga Wagga 2016–2017 that found the LRPB Trojan wheat planted from March to April generated an average yield of 3.58–6.1 t/ha. In Figure 6.1, the average yield trend line declines over the modelling period, which is consistent with Armstrong et al.'s (2019) finding that continuous wheat production over 17 years in Western Victoria resulted in declining yields. The simulations with APSIM using the NSW DPI's (2013) recommended inputs produced results consistent with field trials.

Figure 6.1

Wheat Yields 1960–2015 With New South Wales Department of Primary Industries-Recommended Inputs and Management Practices



Source: APSIM (2019), MS Excel (2021)

The annual wheat yields were incorporated into the economic model using NSW DPI-recommended fertiliser inputs and management processes. The average yield of 4.08 t/ha had an average break-even price of $143 t/ha, with an average gross margin of $838 p/ha (*SD* $384). Significant variations in farmer gross margin and income affected the NPV returns. In 2020 AUD, continuous annual wheat production from 1960 to 2015 had an NPV between $95,619 and $759,188 using discount rates of 2%, 5% and 7%

(see Table 6.2). These baseline results were used to evaluate input variation, hydro-priming and predicted climate change effects on farmer income.

Table 6.2

Continuous Wheat Net Present Value (1960–2015) With New South Wales Department of Primary Industries-Recommended Fertiliser Inputs and Management Practices

Net present value (NPV) percentage	NPV in 2020 ($/ha)
2%	$95,619
5%	$319,622
7%	$759,188

Source: APSIM (2019), MS Excel (2021)

Production input prices have a significant effect on profits from wheat production (see Table 6.3). As noted in Chapter 5, production input prices were fixed across the modelling period to focus on the effect of climate shocks on farmer profits and input efficiency. Production costs were increased and decreased by 20% to evaluate how production cost variation effects NPV returns from wheat production. A decrease in variable input prices by 20% increases profits by 13% across the discount rates. Increasing costs by 20% decreases profits by 12%. One of the largest production input costs is fertiliser. Holding the quantity of fertiliser applied as fixed a 50% increase in fertiliser prices decreases NPV returns by 2%–2.5%, decreasing NPV returns by 2%–2.5%. A 50% decrease in fertiliser input price variation is not a significant driver of NPV income from land use.

Table 6.3

Net Present Value in 2020 With a Change in Variable Production Costs Continuous Wheat Production 1960–2015 With New South Wales Department of Primary Industries-Recommended Fertiliser and Management Practices

NPV %	Net present value (NPV)			
	–20% costs	+20% costs	50% decrease fertiliser cost	50% increase fertiliser cost
2%	$107,941	$83,803	$98,715	$93,029
5%	$359,653	$280,174	$329,213	$310,615
7%	$853,499	$665,520	$781,461	$737,558

Another driver of wheat profitability, also affected by variations in rainfall and soil quality, is the wheat grain protein content. Wheat protein content effects the price the farmer receives for wheat grown and is affected by soil nutrient and water content. Wheat grown and exported in the Wagga Wagga region includes Premium Prime Hard, which requires a minimum 13% protein content, Australian Hard wheat, with a protein content of 11.5%, and Australian Premium White, with a protein content of 10% (AEGIC, n.d., p. 4). Field experiments in 2009-2010 in the Wagga Wagga region by Maphosa et al. (2015, p. 149), measuring the protein content of high-yielding hard wheat cultivars found the average protein content was between 10% and 15%. In the simulation results in this study the average protein content of wheat with current management practices is 11.9% (see Table 6.1), which is sufficient for wheat to be sold internationally as Australian hard wheat (AEGIC, n.d., p. 4) and validates the decision to use the World Bank (2020) US hard wheat price in the profitability analysis.

Fertiliser is one of the most critical inputs to increase wheat biomass and profits from wheat production. The net nitrogen (N) applied is 57.1 kg/ha in each production period (see Table 6.1), consisting of 100 kg/ha of DAP fertiliser with a nitrogen content of 18% applied at sowing and an additional 85 kg/ha of urea with a nitrogen content of 46% applied in July in each production period as recommended by the NSW DPI.

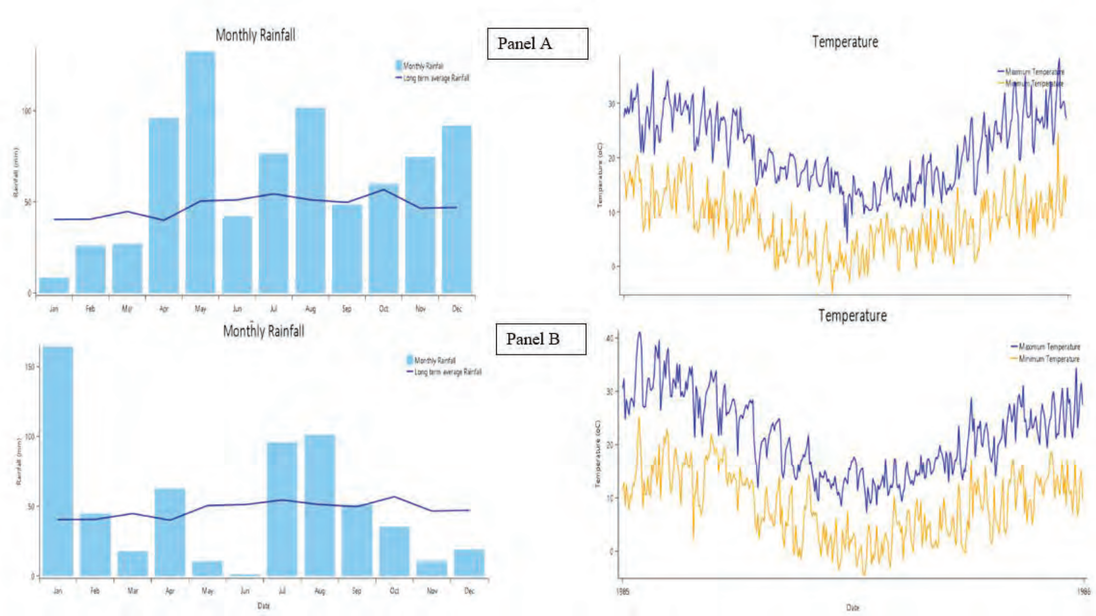
6.1.1 Identifying and Exploring Drivers of Climate Shocks on Wheat Production

Wagga Wagga dryland crop producers are exposed to several climate risks, including drought, heat stress, and above-average rainfall events that affect crop yields, annual returns from crop production, and the soil's productive capacity. The Wagga Wagga region is exposed to recurring droughts and infrequent flooding events (Sewell et al., 2016), creating interannual yield variations, as shown in Figure 6.1. The most significant yield variance over the modelling period was during the Millennium Drought, with the lowest rainfall for the modelling period (BOM, 2020), resulting in a 32% decline in wheat yields. Other periods with below-average rainfall decreasing wheat yields in Figure 6.1 include the 1982 drought (BOM, 2023), where wheat yield was 18.5% below the average. Periods with above-average rainfall include the floods experienced in Wagga Wagga in 1974, resulting in a 65% reduction in wheat yield. Farmers are exposed to significant risks that effect their periodic wheat yield and profits from agricultural land use.

Combining hotter temperatures with above-average rainfall increases wheat yield while decreasing soil carbon and nitrogen content generating a significant shock to long-run soil productive capacity. In the latter half of 1984, temperatures exceeded 30 °C several times during the critical grain-filling period, concurrent with above-average rainfall (see Figure 6.2). The combination of hotter-than-average temperatures and higher rainfall increased the conversion of soil carbon into carbon dioxide, resulting in a decline in soil carbon over the summer months of December 1984 to February 1985. A dry early growth period in 1985, with warmer temperatures, promoted above-average crop biomass and strong crop production. Above-average rainfall during flowering and grain set in July–August 1985 generated a 6.49 t/ha yield. Although this was the largest yield achieved over the modelling period 1960–2015, it resulted in a sharp drop in soil carbon and nitrogen, with wheat yields remaining below 6 t/ha for the following 25 years.

Figure 6.2

Wagga Wagga Monthly Rainfall and Annual Temperature 1984 (Panel A) and 1985 (Panel B)



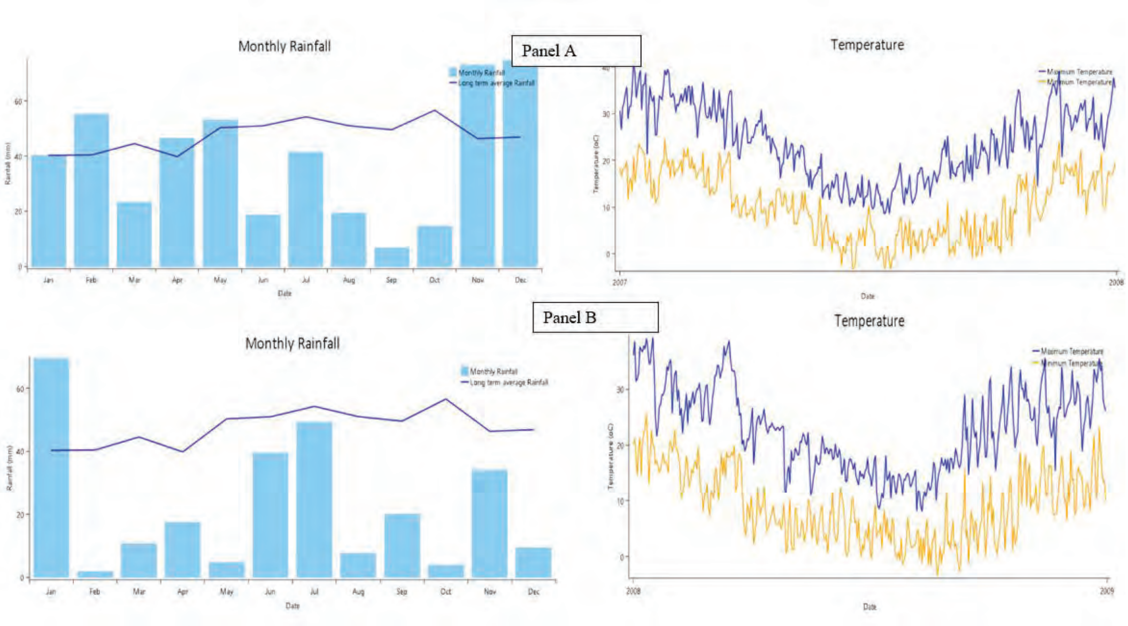
Source: BOM, 2020

Climate shocks affect soil carbon and nitrogen content and, therefore, profits from land use. Rainfall varied significantly between 1984 and 1985, generating a negative soil productivity shock with above-average rainfall occurring during the early crop growth stages of April–May, in July–August during wheat flowering and over the harvest period November–December, as illustrated in Figure 6.2. Wheat yield in 1984 was affected by rainfall during flowering, which reduces grain fertilisation and, subsequentially, potential yields. The above-average rainfall affects crop yield, soil carbon and nitrogen balances with the 1.41 t/ha achieved in 1984 significantly lower than the long-run average of 4.08 t/ha yield (see Figure 6.1). Despite the low crop yields, soil carbon increased in 1984, resulting from the decomposition of the previous crop residue, where 5.3 t/ha was achieved in 1983 (see Figure 6.1). Soil nitrogen balances were reduced in 1984, with rainfall moving nitrogen through the topsoil into the subsoil, reducing nitrogen available for crop production. Variation in precipitation affected the soil nutrient availability for subsequent soil production periods thus impacting future crop yields and returns from land use.

During the 2007 production period, rainfall was the lowest the study site received over the modelling period (see Figure 6.3). In 2008, rainfall was below average at 466 mm (see Figure 6.3), compared to the long-term average of 571 mm. Despite the significantly below-average rainfall, soil carbon decreased by 4% in 2007, compared to a 12% decline in 1985. Over the production period, the drier conditions of 2007–2008 reduced the soil carbon decomposition rate (as discussed in Chapter 4, moisture is critical for soil carbon decomposition). The effect of the above-average temperature spikes at the end of 2007 and the start of 2008 is shown in Figure 6.4. Soil carbon increased by 0.89% between 2007 and 2008, with a net 1.3% decline in soil carbon over the Millennium Drought period 1997–2009. In contrast, the higher rainfall and temperatures for 1984–1985 reduced soil carbon by 1.2% within two seasons, suggesting that above-average rainfall combined with hotter temperatures are drivers of soil carbon losses. Drought conditions reduce soil carbon losses compared to production periods with similar temperatures and higher rainfall with the effects likely to be exacerbated with predicted climate change.

Figure 6.3

Rainfall and Daily Temperature Data for 2007 (Panel A) and 2008 (Panel B)



Source: BOM, 2020

Like soil carbon, soil nitrogen is heavily influenced by seasonal rainfall, with above-average rainfall significantly decreasing soil nitrogen. The reduction in rainfall compared to the long-term average does not reduce soil nitrogen as expected. By maintaining soil nitrogen through continued fertiliser applications annually throughout the Millennium Drought years, wheat demand for nitrogen was reduced, and the soil nitrogen balance declined by 1.9% from 1997 to 2009. In contrast, the soil nitrogen declined by 2% in 1984–1985 (shown in Figure 6.4). Drought conditions have less effect on soil nitrogen balances than seasonal rainfall with above-average rainfall and temperature, generating a significant negative climate shock to soil nitrogen balances. Finding methods to address this will reduce potential wheat yield shocks with the current climate and predicted climate change.

The soil productivity index described in Chapter 4 combines soil carbon and nitrogen to enable the evaluation of both components' contribution to productive land use. Agricultural land is the most significant asset a farmer controls therefore, evaluating soil productive capacity changes can support strategic land use planning. As discussed in Chapter 4, soil carbon content influences the volume of soil nutrients stored within the soil. This study used soil nitrogen as a proxy for a matrix of wider nutrients necessary for crop production. Dalal and Chan (2001) identified a link between loss of soil carbon and reduced quantities of accessible soil nutrients for crop production, which includes nitrogen. The decline in soil carbon reduces the soil's ability to mineralise nutrients, or its cationic exchange capacity, reducing soil fertility.

The effect of soil carbon and nitrogen variation over the 56-year modelling period was a 7.5% reduction in soil carbon and an 8.1% reduction in soil nitrogen (see Table 6.4). A reduction in soil carbon corresponded with a reduction in soil nitrogen, reducing the soil's productive capacity, which is consistent with Chan et al.'s (2003) findings. The productive capacity of the soil changes according to climatic conditions and management decisions. The net change from one production period to the next provides a mechanism for farmers to evaluate the effect of their management decisions on soil productivity.

Table 6.4

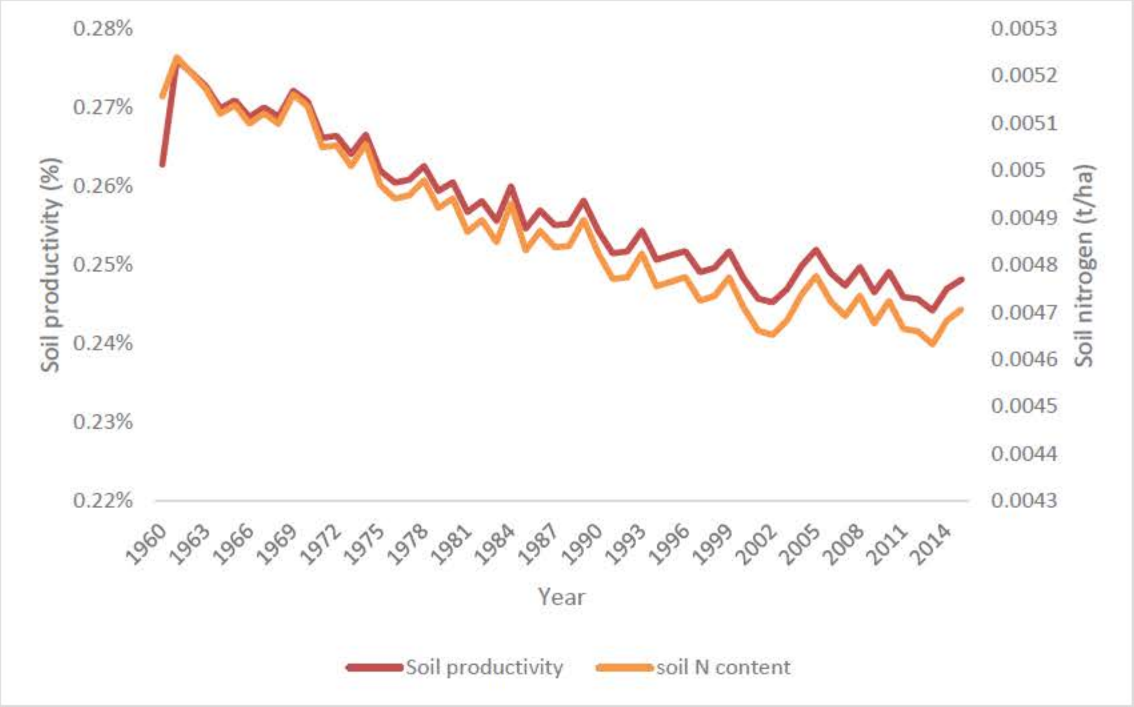
Change in Soil Nitrogen, Carbon and Productivity 1960–2015 with Department of Primary Industries New South Wales Management Practices and Historical Climate Data

Soil variable	Change (%)
Change in soil productivity	–5.6
Change in soil carbon	–7.5
Change in soil nitrogen	–8.1

The soil productivity index movement is nonlinear and consistent with soil nitrogen movement and as such, the soil productivity variable provides a reliable estimation of the soil's productive capacity change, as shown in Figure 6.4. The soil productivity index incorporates periodic variation in two critical indicators of agricultural land quality, soil carbon and nitrogen. The soil productivity index in Figure 6.4 converges with soil nitrogen until 1975, after which soil nitrogen losses exceeded the soil productivity index variation.

Figure 6.4

Soil Nitrogen and Productivity 1960–2015 with New South Wales Department of Primary Industries-Recommended Management Practices

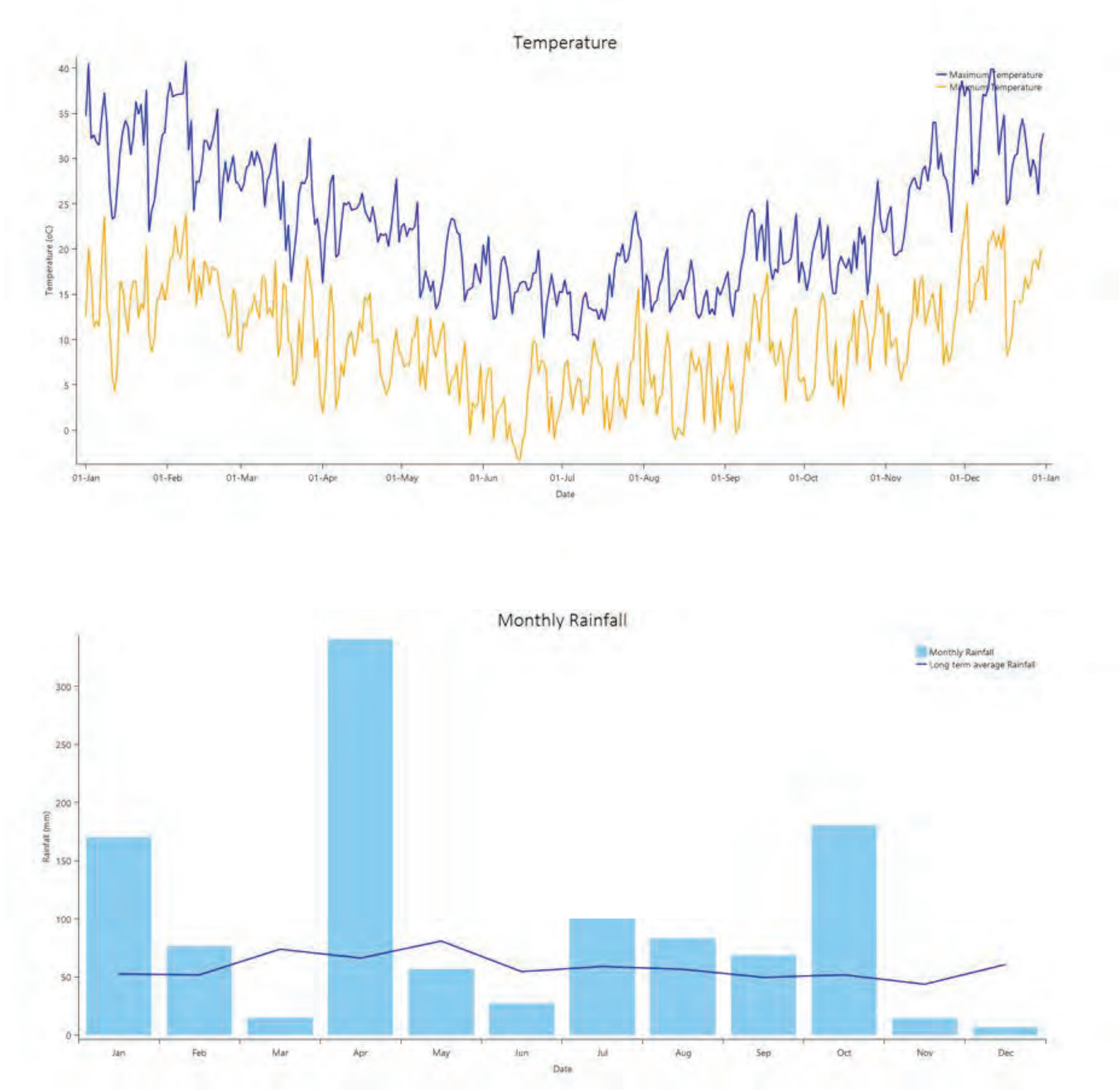


Source: APSIM (2019), MS Excel (2021)

Soil productivity diverged from soil nitrogen in 1975 due to a climate shock. The rainfall in the early crop growth stage in April 1975 was more than four times the long-term average rainfall (see Figure 6.5). Flooding of the Murrumbidgee River in Wagga Wagga occurred in 1974, with five floods all over 8 m and again in 1975, with flooding in June (Anon., 2023). In APSIM, the wheat sowing window is from 1 April to 1 June. APSIM does not recognise any externalities, such as flooding associated with rainfall events. The effects of flooding on the landscape are seen in APSIM through soil nitrogen denitrification, reducing the topsoil nitrogen by 1.6%, significantly more than soil carbon losses (1%) in the same period. The soil productivity index combines soil carbon and nitrogen to estimate soil productive capacity with climatic shocks more reliably than using soil nitrogen or carbon individually.

Figure 6.5

Wagga Wagga 1975 Daily Temperature (Top Panel) and Monthly Rainfall (Bottom Panel)



Source: BOM (2020)

Estimating the effect of management processes on the future productive capacity of the soil provides a method to determine land asset value. Agricultural land markets are traditionally thin with land value influenced by site-specific characteristics. Using historical sales data for properties in the region incorporates market factors and site-specific characteristics that may not accurately reflect the carrying value of the evaluated land asset. The change in the soil productivity index applied to land value using the process described in Chapter 4 provided a site-specific method to evaluate the effect of management practices and rainfall shocks on land value.

Utilising the index with a discount rate, as presented in Chapter 5, adjusts the land value in a method consistent with financial literature. The real value of land in 2020 using the soil productivity index declined by 5.2%–5.5% (see Table 6.5), which is less than the reduction in soil nitrogen (8.1%) or carbon (7.5%) content variation over the same period. The variations in nominal land value using discount rates of 2%, 5% and 7% were explored. The change in nominal land value was between 5.2% and 5.5% across the discount rates. This finding suggests the soil productivity index is robust with various discount rates when used with historical climate data and the NSW DPI's (2013) recommended fertiliser inputs.

Table 6.5

Net Present Value in 2020 for Soil Productivity Variation 1960–2015 Using the Soil Productivity Index to Vary Land Value

Variable	Land value	2%	5%	7%
Nominal land value in 2020 ($/ha)	2,742	2,590	2,590	2,598
Change (%)		–5.5	–5.3	–5.2

6.2 FERTILISER INPUT VARIATION

The quantity of fertiliser applied can be increased to potentially improve the soil productivity index and wheat production NPV returns. Simulations were undertaken in varying DAP and urea fertiliser input quantities to model this, using the method described in Chapter 5 and the input quantities illustrated in Table 6.6.

Table 6.6

Variation in Fertiliser Quantities

Fertiliser	Department of Primary Industries New South Wales	–20%	–40%	–60%	20%	40%	60%
Urea (kg/ha)	85	68	51	34	102	119	136
Di-ammonium phosphate (kg/ha)	100	80	60	40	120	140	160

The quantity of fertiliser that maximises NPV from wheat production and land value is higher than the NSW DPI's (2013) recommended fertiliser application rate. The profit-maximising quantity of fertiliser with NSW DPI-recommended production management practices is to increase fertiliser by 60% to 136 kg/ha of DAP at sowing and 160 kg/ha of urea in July for each production period (see Table 6.7). The simulation results, including yield, profits, and soil productivity for each fertiliser quantity modelled, are presented in Table 6.7. Increasing fertiliser inputs by 60% reduces the soil carbon losses by 60% and nitrogen losses by 52%, increasing NPV returns from wheat production land use by 57%.

Table 6.7

Wheat Production Net Present Value Profits in 2020 AUD for 1960–2015 With Varied Fertiliser Input Quantities

Fertiliser quantity	Net present value 2020 ($/ha)			Change in soil (%)			Average				Gross margin *SD* ($/ha)
	2%	5%	7%	Carbon	Nitrogen	Productivity	Crop yield (t/ha)	Protein content (%)	Grain NUE (%)	Break-even price ($/t)	
+60%	144,211	479,059	1,133,573	–3.0	–3.9	–0.9	5.7	12.9	11.6	124	546
+40%	129,825	431,618	1,022,227	–4.3	–5.1	–2.2	5.3	12.5	8.1	130	512
+20%	113,450	378,877	899,763	–5.7	–6.4	–3.6	4.7	12.2	7.3	136	467
Recommended	95,872	319,914	759,509	–7.5	–8.1	–5.6	4.1	11.9	6.5	143	384
–20%	107,293	358,902	852,902	–8.0	–8.6	–6.1	4.0	11.9	7.7	143	459
–40%	59,090	201,544	483,593	–12.9	–13.4	–11.4	2.8	11.4	4.9	163	206
–60%	40,146	141,105	343,315	–16.7	–17.3	–15.8	2.2	11.2	4.4	187	149
Nil	-4,281	-1,051	13,755	–23.5	–23.9	–23.0	0.9	10.2	0.0	349	93

Note. NUE = nitrogen use efficiency.

As fertiliser inputs increase, wheat yields and grain nitrogen use efficiency (NUE) increase. With a 60% increase in fertiliser, the average crop yield increases from 4.08 t/ha to 5.7 t/ha and the grain NUE increases from just under 6.5% to 11.6% (see Table 6.7). Increasing fertiliser increases the soil nitrogen accessible to plants, grain NUE and gross margins from wheat production. A further benefit of increasing fertiliser quantities is the improvement in wheat protein. With a 60% increase in fertiliser inputs, the wheat grain protein content increases from an average of 11.9% with recommended fertiliser inputs to 12.9% when the DAP and urea applied are increased by 60%. The results are consistent with Mahjourimajd et al. (2016) findings of a positive relationship between Australian wheat protein content and nitrogen inputs.

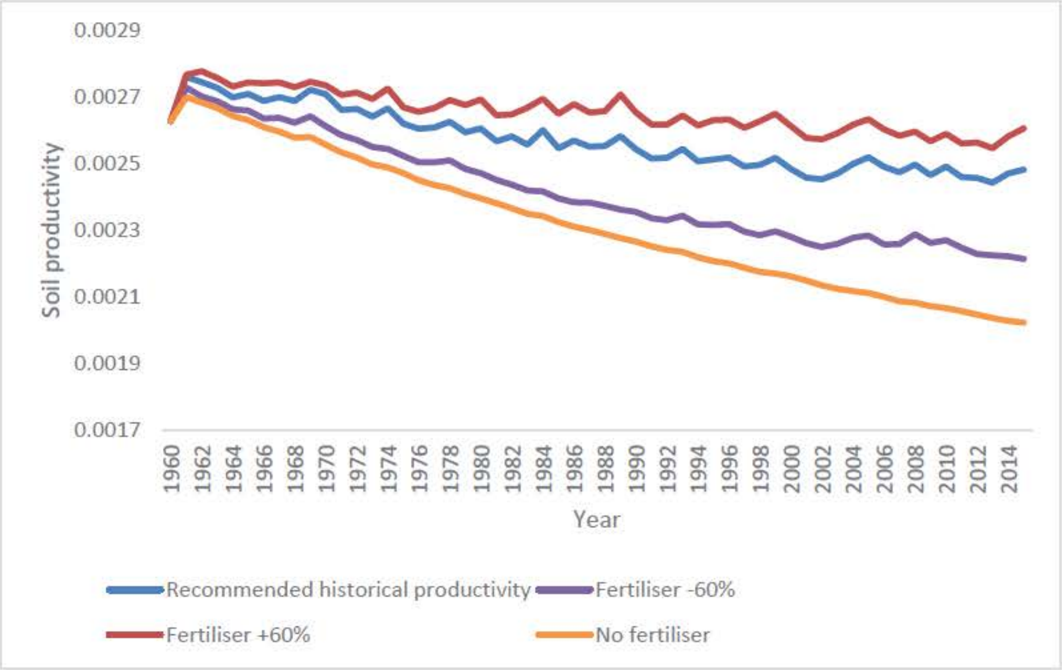
A 60% increase in fertiliser inputs increases the land use returns from wheat production. Increasing crop yield with increased fertiliser inputs decreases the average break-even price from $143 to $124 p/ha; however, it increases the standard deviation in the average gross margin from $384 to $546 (see Table 6.7). Increasing fertiliser inputs increases NPV returns and soil productivity; however, it also increases the effect of climate shocks on annual gross margins. Decreasing fertiliser inputs decreases the NPV returns and interannual variance in gross margins.

When fertiliser inputs were increased by 60%, the NPV profits in 2020 increased from $358,902 p/ha to $479,059 p/ha with a discount rate of 5%. In contrast, when fertiliser inputs were decreased by 60%, the NPV profits declined to $141,105 p/ha with a discount rate of 5%, and the average break-even price increased to $187 p/ha (see Table 6.7). Decreasing fertiliser inputs by 20% results in an exact break-even price as the recommended fertiliser input rates. There is no effect on grain protein content with a 20% decrease in fertiliser inputs; however, there is a slight increase in soil carbon and nitrogen depletion (see Table 6.7). A 20% increase in fertiliser inputs decreases the break-even price by $7 per hectare. It improves soil nitrogen and carbon balance compared to recommended fertiliser inputs and increases grain protein content (12.2%) and crop yields (4.7 t/ha). Increasing fertiliser inputs increases farmer profits from wheat production while reducing the net soil carbon and nitrogen losses.

Increasing fertiliser inputs reduces soil nitrogen and carbon loss, improving soil productivity and reducing climate risk exposure and gross margins generated from wheat production. Farrell et al. (2021) found that as crop yields increased, so did soil carbon content. Soil carbon is a key component in generating wheat yields and reducing climate risk exposure through increased soil water holding capacity, as discussed in Chapter 4. As illustrated in Figure 6.6, increasing fertiliser inputs by 60% increases soil productivity compared to the existing management practices. With a 60% increase in DAP and urea inputs, soil carbon decreases by 3% and soil nitrogen by 3.9%. Higher fertiliser inputs increase wheat yields, supporting findings by Hunt (2021) that maintaining higher soil nitrogen content promotes more robust crop production and maintains soil fertility. Increasing nitrogen inputs generates co-benefits of increased organic material supporting the maintenance of soil quality which is considered valuable in the competitive market for agricultural land.

Figure 6.6

Soil Productivity 1960–2015 Simulations With Various Quantities of Fertiliser



Source: APSIM (2019), MS Excel (2021)

Evaluating the effect of management practices on the marketable land value can support farmer land management decisions. Market value captures risk premiums associated with assets and a range of non-monetary benefits not considered in this analysis. The focus of the soil productivity index applied to land value provides farmers with an economic tool to evaluate the effect of their management decisions on soil productivity. Increasing soil productivity improves the lands' future productive capacity and value. Using simulations to estimate soil carbon, nitrogen variation and changes in land value with different management practices can support farmers' decision-making. Discounting enables the present value comparison of the effect of different fertiliser input quantities on the land value and validates the effectiveness of the soil productivity index applied to land value.

With a 60% reduction in fertiliser inputs and a 5% discount rate, the NPV of land in 2020 declined over the modelling period by 15% compared to the Rural Bank

(2020) value of $2,742 (see Table 6.8). Using the recommended fertiliser inputs, the NPV of the land decreases by 5.5%, while increasing fertiliser by 60% decreases the land value by 1%. When no fertiliser is applied, productivity declines by 23% and land value by 22%. The soil productivity index captures the variation in land productive capacity and estimates how *certeris paribus* changes in soil productivity effect the land value. This finding is consistent with Phipps (1984), who identified a relationship between returns from land and land value. The long-run cumulative effect of fixed management processes results in a decline in real land value when the recommended fertiliser input quantity or a 60% reduction in fertiliser inputs is simulated. Consistent with King and Sinden (1988), increasing the fertiliser inputs maintains the productive topsoil's productive capacity, which is valuable in a competitive market.

Table 6.8

Nominal Land Values 2020 Using Historical Climate Data and Varied Fertiliser Input Quantities

	Land value ($/ha)		
Fertiliser input quantity	2%	5%	7%
+60%	2,716	2,712	2,718
Recommended	2,590	2,590	2,598
–60%	2,315	2,322	2,334
Nil	2,119	2,131	2,145

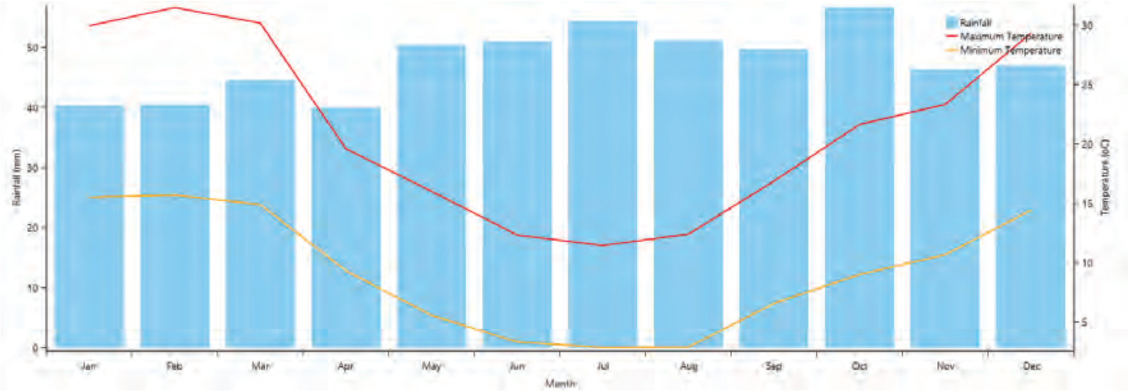
6.3 PREDICTED CLIMATE CHANGE IMPACT ON WHEAT PRODUCTION WITH EXISTING MANAGEMENT PRACTICES

Climate change is predicted to effect dryland crop production, increasing farmers' exposure to climatic risks and negative returns from dryland wheat production.

Therefore, an investigation of management treatments to mitigate the effects of climate risk on wheat production is required. This study simulated climate change by varying daily historical climate data records using Jeffrey et al.'s (2001) statistical downscaling methods. The varied climate data shown in Figure 6.7, Figure 6.8 and Figure 6.9 was applied to wheat production simulations in APSIM using the method described in Chapter 5.

Figure 6.7

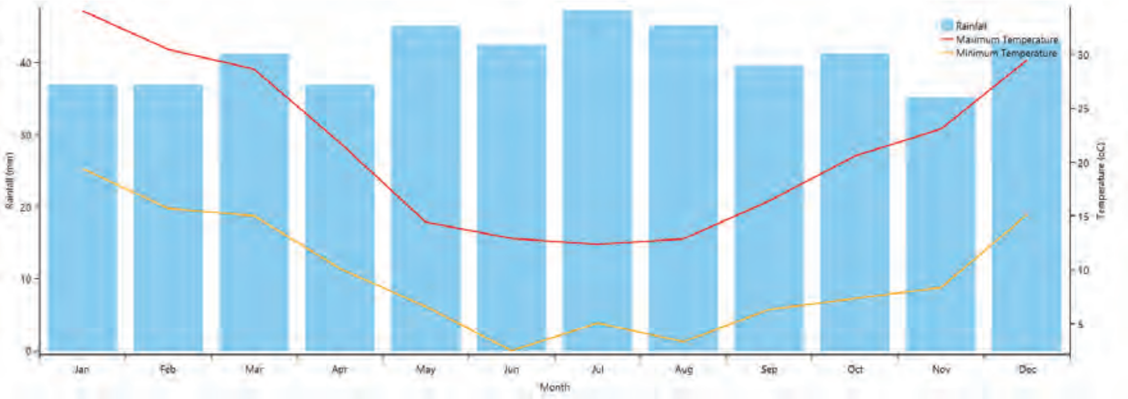
Wagga Wagga Historical Average Climate Data 1960–2015



Source: BOM (2020)

Figure 6.8

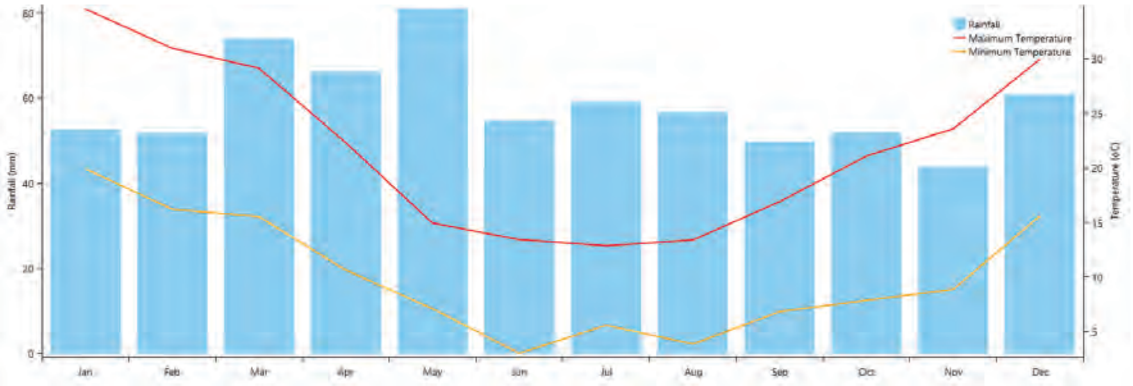
Wagga Wagga Average Climate Data 1960–2015 With Lower-Bound Predicted Climate Change



Source: BOM (2020)

Figure 6.9

Wagga Wagga Average Climate Data 1960–2015 With Upper-Bound Predicted Climate Change

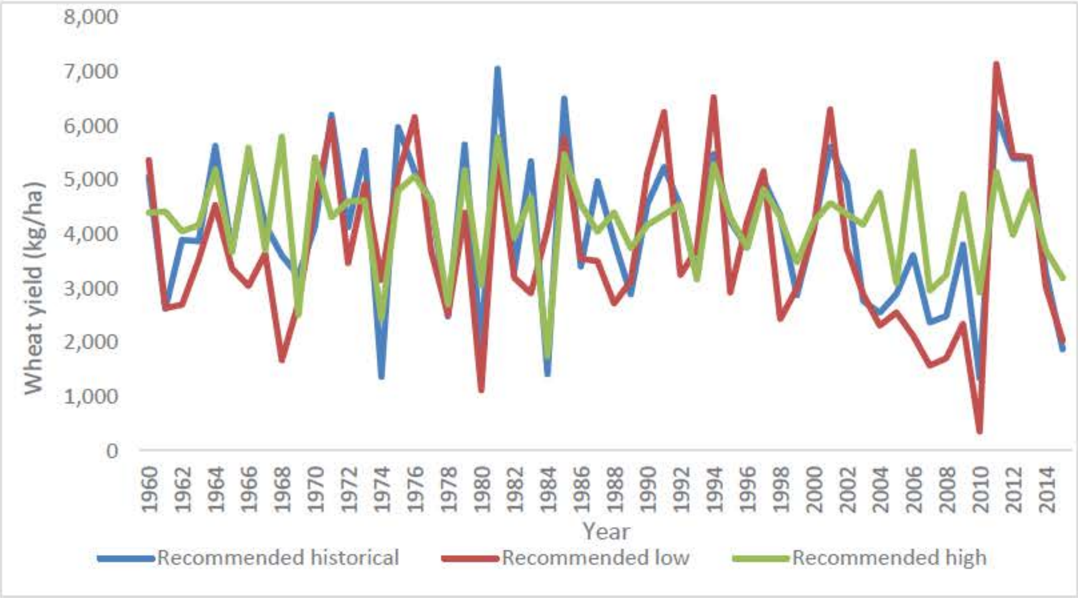


Source: BOM (2020)

There is significant uncertainty around predicted climate change; the predicted variability in rainfall will affect future wheat yields for the study site (see Figure 6.10). If the lower bound of predicted climate change occurs, average annual rainfall will decline, as will wheat yields compared to yields obtained with historical climate data. Due to increased precipitation, wheat yields with upper-bound rainfall are comparatively higher during drier periods, such as the Millenium Drought of 1997–2009. As identified earlier, rainfall variation has a significant effect on wheat yields. The BOM (2020) rainfall data shows a cumulative 5,281 mm of rain between 1960 and 1970 with statistical downscaling this falls to 4,473 mm for the lower-bound scenario and increases to 6,370 mm for the upper-bound scenario. Significant yield variation resulted from varied rainfall in 1968 with lower-bound climate change reducing wheat yield to 1.67 t/ha in 1968, while upper-bound climate change increased it to 5.80 t/ha from the 3.69 t/ha. The data suggests that the uncertainty around predicted future climatic rainfall patterns increases the farmers' exposure to climate risk yield variability.

Figure 6.10

Wheat Yield 1960–2015 With New South Wales DPI-Recommended Fertiliser Inputs With Historical, Lower- and Upper-Bound Predicted Climate Change



Source: APSIM (2019), MS Excel (2021)

Investigating rainfall variation in 1968 in more detail, as identified in Section 6.1, found that a reduction in rainfall in crucial crop growth periods significantly effects wheat yield. This result occurred in 1968 during the germination and establishment phases. As discussed in Chapter 5, climate change was predicted to significantly affect summer and autumn rains, thereby affecting crop germination, establishment, and grain filling. Germination and establishment in simulations occur April–May each year, with precipitation data from statistical downscaling presented in Table 6.9. Rainfall in the lower-bound scenario is reduced by 15% in May during the establishment phase and 26% in October during the grain development phase compared to historical rainfall (see Figure 6.11). Whereas with the upper bound scenario rainfall is unchanged in October and increases by 54% in May. Wheat yield with historical data is 3.69 t/ha, with the lower-bound scenario 1.67 t/ha and 5.80 t/ha, with the upper bound suggesting that rainfall variation during establishment and grain filling effects yield potential. These findings are consistent with field results for Wagga Wagga by Gomez-Macpherson and Richards (1995).

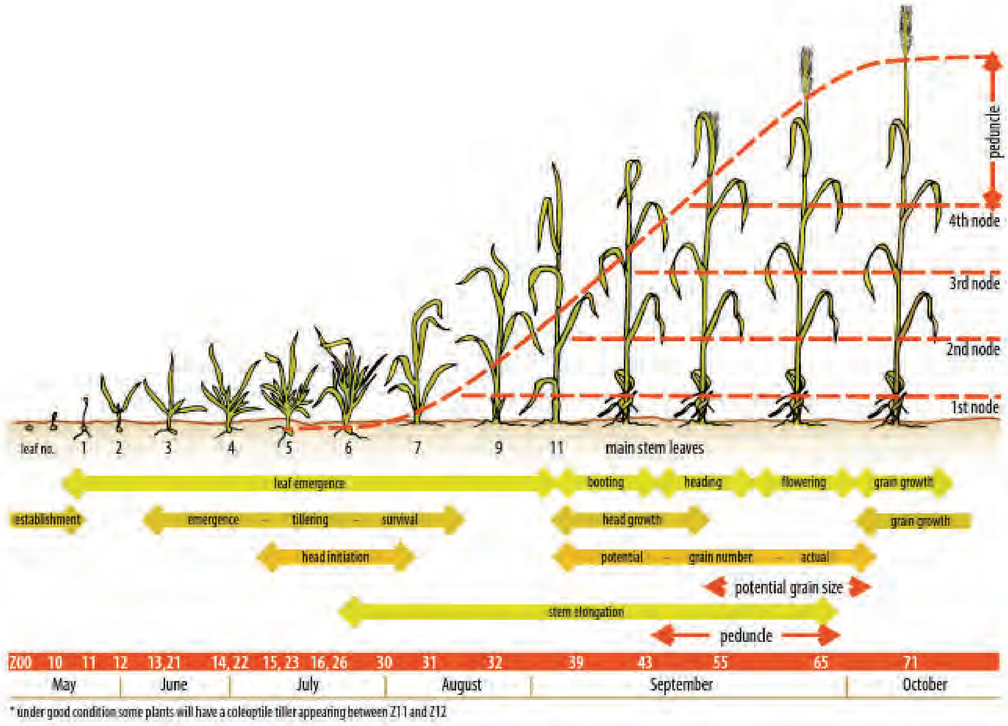
Table 6.9

Wagga Wagga, New South Wales Rainfall March–May 1968 Under Different Climate Scenarios Using Statistical Downscaling

Climate scenario	Precipitation (mm)			
	April	May	August	October
Historical data	0.5	26	38	30
Lower-bound climate change	0.4	22	35	22
Upper-bound climate change	0.8	40	40	30

Figure 6.11

Life Cycle of Winter Wheat in New South Wales



Source: White & Edwards (2007)

Germination and establishment phases are critical stages of wheat production to maximise yield and profits. Wheat yields in Figure 6.10 remained largely convergent throughout the 1970s and 1980s, with upper- and lower-bound yields diverging in 1988. As Table 6.10 illustrates, the rainfall variation in 1988 during germination, emergence, grain development and filling during April, May, August and October, respectively, had a significant effect on crop yields in 1988, with lower-bound crop yields 31% lower than yields with historical data and 38% lower than wheat yield with the upper-bound climate scenario. Increased precipitation increases wheat yield by 13% in the upper-bound scenario compared to wheat yield with historical data. Management methods to reduce the adverse effect of rainfall deficits are required to support farmers in addressing the challenge of climate change and reducing wheat production yield and profit variation.

Table 6.10

Wagga Wagga, New South Wales, Rainfall March–May 1988 Under Different Climate Scenarios Using Statistical Downscaling with New South Wales DPI-Recommended Fertiliser Inputs and Management Processes

Climate scenario	Wheat yield (t/ha)	Precipitation (mm)			
		April	May	August	October
Historical data	3.9	23	50	38	23
Lower-bound climate change	2.7	21	45	33	18
Upper-bound climate change	4.4	37	81	42	22

Using the NSW DPI-recommended fertiliser inputs, profits increase with the upper-bound climate scenario. Under all discount rates in Table 6.11, the NPV of wheat production increases with the upper-bound climate scenario compared to historical climate data or the lower-bound climate scenario. The break-even price declined by $10 to $133, as did the variance in annual returns. The gross margin variance decreased to $248—a decrease in NPV returns is correlated with a decrease in interannual gross margin variance. With declining gross margins, there is a slight increase of 0.2% in the grain protein content and just over a 2% improvement in the wheat NUE with upper-bound climate change (see Table 6.11).

Table 6.11

Wheat Results 1960–2015 Using New South Wales Department of Primary Industries-Recommended Fertiliser Inputs and Alternative Climate Scenarios

Fertiliser quantity	Net present value ($/ha)			Change in soil (%)		Average				Gross margin *SD* ($/ha)
	2%	5%	7%	Carbon	Nitrogen	Crop yield (t/ha)	Protein content (%)	Grain NUE (%)	Break-even ($/t)	
Upper	98,187	328,182	781,952	–14.5	–15.3	4.2	12.1	67.0	133	248
Historical	95,872	319,914	759,509	–7.5	–8.1	4.1	11.9	64.7	143	384
Low	83,366	274,813	647,364	–5.3	–5.7	3.7	12.8	60.9	162	413

Note. NUE = nitrogen use efficiency.

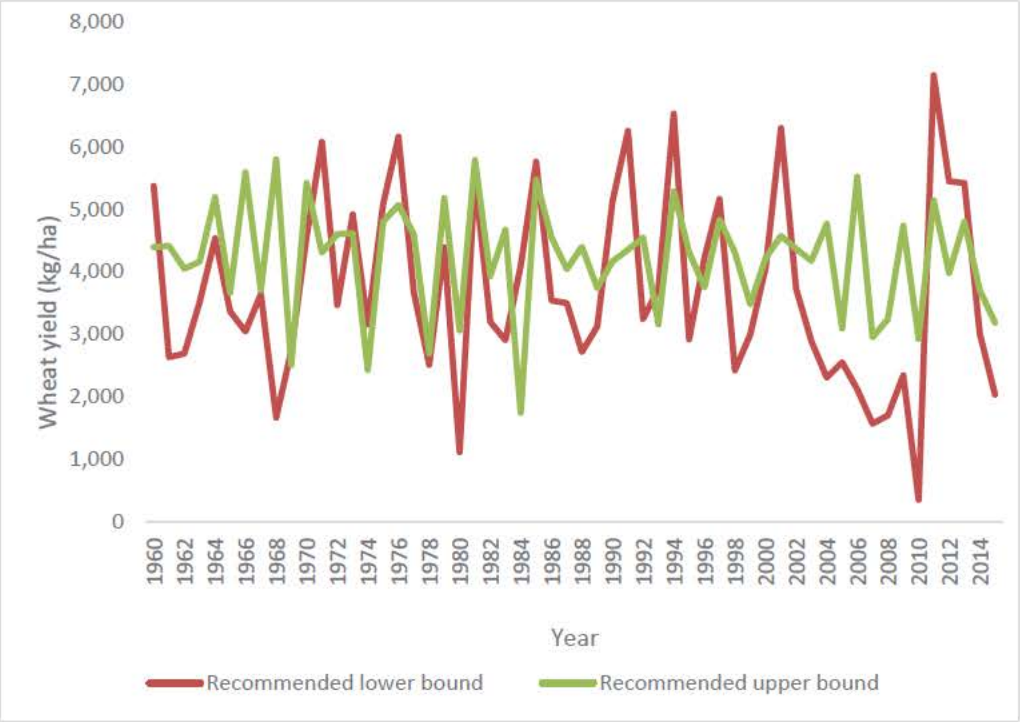
As identified previously, rainfall is critical to wheat production. Lower bound average wheat yield declined by 10%, with NPV profits decreasing by 13%–15% across the discount rates and increasing the break-even price by $19 to $162 p/ha and standard deviation in annual gross margin. Despite reduced rainfall, the lower-bound scenario increases the average grain protein content compared to historical or upper-bound simulations (see Table 6.11), suggesting that *ceteris paribus*, a reduction in rainfall increases the protein content and wheat quality. Using the outcomes of the APSIM climate change simulations, predicted rainfall variation significantly effects NPV returns from wheat production.

Climate change scenarios effect wheat yield, NPV returns, soil carbon and nitrogen content. In the upper-bound scenario, increased precipitation combined with warmer temperatures increases the soil carbon decomposition rate (see Table 6.11). Despite increased profits, there is a 14.5% decline in soil carbon and a 15.4% reduction in nitrogen with the upper-bound climate scenario. As discussed in Chapter 2 and Section 6.1, higher rainfall increases the movement of nitrogen through the soil profile into the subsoil rendering it inaccessible to crops. In contrast, the lower-bound climate simulation using the same midpoint temperature increase has a 2.2% reduction in soil carbon loss and a 2.4% reduction in soil nitrogen loss compared to historical climate simulations. This finding confirms that rainfall variation is the most significant driver of climate change-induced effects on wheat production in Wagga Wagga.

As previously discussed, rainfall in 1984–1985 was above average, with historical data leading to reduced soil carbon, nitrogen and wheat yields with NSW DPI-recommended fertiliser inputs. In Figure 6.12, climate change wheat yields diverge after 1985, suggesting that yield potential decreases as soil quality declines. Climate shocks have a significant effect on wheat yields and land use income.

Figure 6.12

Wheat Yield 1960–2015 (kg/ha) With Lower- and Upper-Bound Climate Change Scenarios

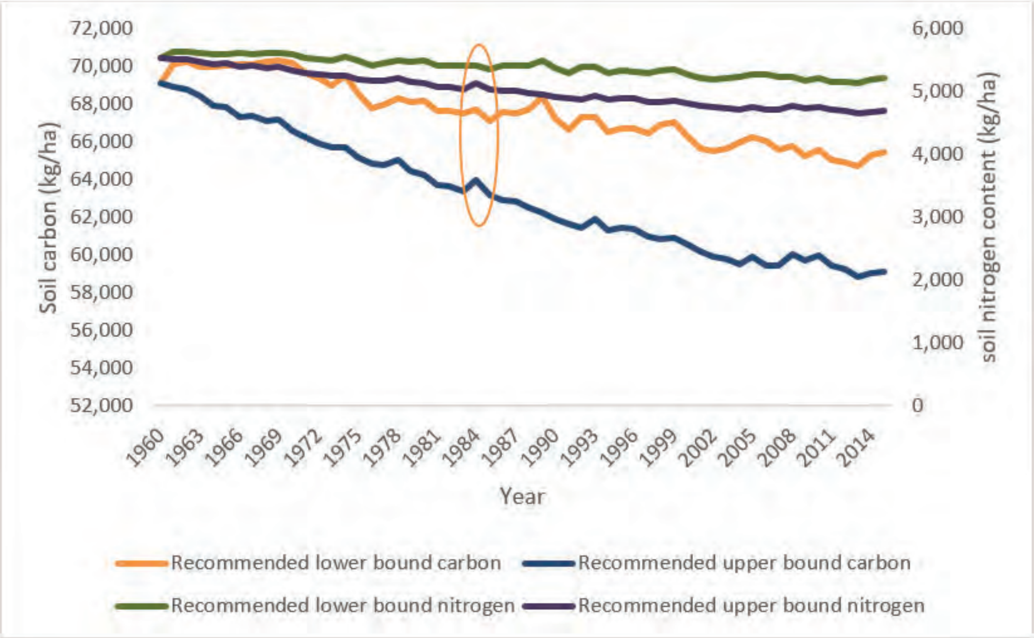


Source: APSIM (2019), MS Excel (2021)

The effect of climate change on land productivity is highlighted in Figure 6.13. In 1984–1985, soil carbon with upper-bound climate change declined more than historical or lower-bound soil carbon variation for the same period. With upper-bound climate change, the higher rainfall and temperature increased soil nitrogen losses. Lower-bound climate change has higher soil carbon content and a smaller decline in soil carbon than the upper bound. The net loss in soil nitrogen for lower-bound climate change in 1984–1985 is lower for the same period, suggesting a relationship between soil carbon and nitrogen. The development of the soil productivity index in Chapter 4 linking variables provides explanatory power to the results. A negative climatic shock occurs with long-run yield effects using identical production processes and temperatures with higher rainfall and warmer temperatures.

Figure 6.13

Upper- and Lower-Bound Scenario Soil Carbon and Nitrogen Variation 1960–2015 With New South Wales Department of Primary Industries-Recommended Fertiliser Inputs



Source: APSIM (2019), MS Excel (2021)

Alternative climatic conditions affect land value; the market value of land is affected by precipitation variation. The variation in soil productivity effects future land productive capacity and the land market value. With a reduction in rainfall, soil productivity losses are minimised, resulting in a 2020 land value of \$2,938–\$3,739 (see Table 6.12). In this study, land value variation only considers the variation in soil productivity. The changing tastes and preferences for agricultural land resulting from climate change-induced rainfall variation are beyond the scope of this work and were not considered.

Table 6.12

Nominal Land Value With New South Wales Department of Primary Industries-Recommended Fertiliser Inputs Using Different Climate Scenarios

Land value 2020 ($/ha)	Compound annual growth rate[a]	Discount rate 2%	5%	7%
Historical	4.90%	$2,859	$3,305	$3,643
Lower bound	4.95%	$2,938	$3,393	$3,739
Upper bound	4.74%	$2,622	$3,038	$3,355

[a] Using a discount rate of 5%

The Rural Bank (2020) estimated a compound annual growth rate of 7.5% for Australian agricultural land from 20 years to 2020. Using the land value with a 5% discount rate across climate simulations, the compound annual growth rate for the study site in Table 6.12 is 4.90% with the historical climate, increasing to 4.95% with lower-bound climate change and declining to 4.74% with upper-bound predicted climate change. Ignoring the market effect of changing commodity prices and market participant preferences the soil productivity index to vary land value provides a realistic estimate of the effect of management practices on soil productivity.

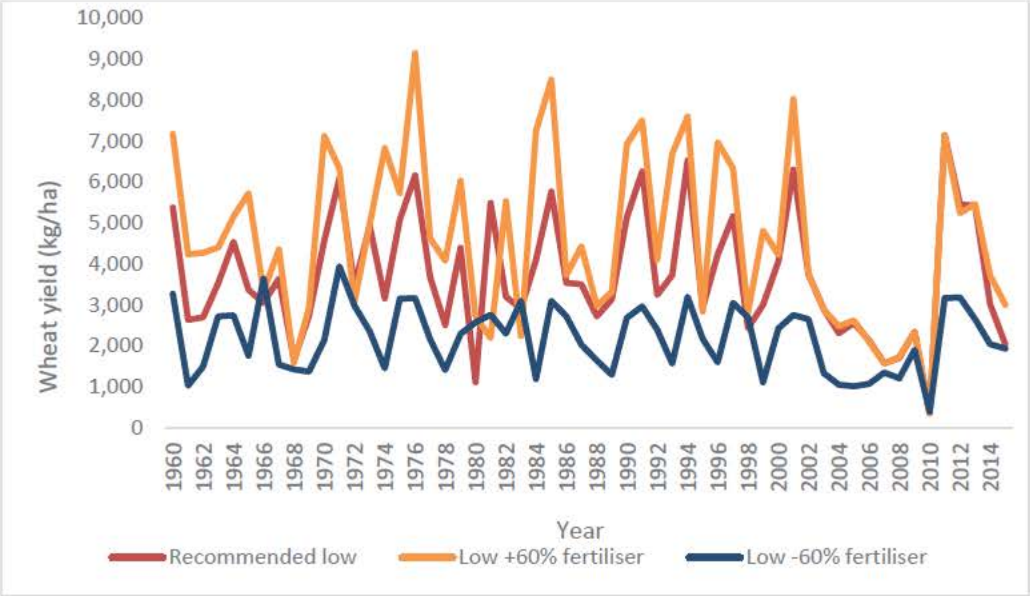
6.4 CLIMATE CHANGE AND FERTILISER INPUT VARIATION

6.4.1 Lower-Bound Predicted Climate Change Scenario

Wheat yields are exposed to climate shocks, with predicted climate change expected to increase the frequency of shocks farmers are exposed to. Variations in fertiliser inputs may reduce the effect of climate shocks on wheat yields and the income derived from land use. Wheat yields in the lower-bound climate scenario decline to 1–3 t/ha when urea and DAP fertiliser inputs are reduced by 60% (see Figure 6.14). Increasing fertiliser inputs in the lower-bound climate scenario increases the wheat yields by less than those achieved with historical climate data. Despite comparatively more productive soil, a reduction in rainfall reduces wheat yields and NPV returns.

Figure 6.14

Wheat Yields 1960–2015 Using Lower-Bound Predicted Climate Change



Source: APSIM (2019), MS Excel (2021)

The NPV of annual returns from wheat production with lower-bound climate change are presented in Table 6.13 and are consistent with results generated with historical climate data. Decreasing fertiliser inputs decreases the NPV of wheat production returns and increases the variance in returns thus, the higher the input quantity, the more variable gross margins become (see Table 6.13). With a 60% reduction in fertiliser inputs, the NPV returns decline by 56%–58%, with a break-even price of $203 and an average yield of 2.2 t/ha. With a 20% reduction in fertiliser inputs, there is less than a 1% reduction in the NPV profits across all discount rates used, requiring a break-even price of $162 p/ha and an average yield of 4.1 t/ha (consistent with historical climate yields with the same fertiliser input quantity). The most significant result is that when no fertiliser inputs are applied, a negative NPV is returned from annual wheat production for the modelling period with lower-bound climate change (see Table 6.13). Increasing the fertiliser inputs by 60% increases NPV returns by 34%–39%, with an average yield of 4.6 t/ha and a break-even price of $158. Varying fertiliser inputs significantly effects NPV returns with lower-bound rainfall than returns simulated by historical rainfall data.

The most efficient fertiliser input quantity with lower-bound climate change is to reduce fertiliser inputs by 20%. The grain NUE is 7.3%, an increase of almost 13% above the recommended input grain NUE and 6% higher than the grain NUE with a 60% increase in fertiliser inputs with lower-bound climate data. Reducing fertiliser inputs by 20% decreases the break-even price to $237 per/ha, the lowest of the fertiliser input quantities modelled for lower-bound climate change with current management practices. However, there is a 0.1 t/ha reduction in average yield, a 1.2% decrease in profits and a 0.1% reduction in grain protein content with a 20% reduction in fertiliser inputs. Hence, there is a trade-off between efficient fertiliser usage and profit maximisation.

Table 6.13

Results for Wheat Production 1960–2015 With Lower-Bound Climate Change

	Net present value ($/ha)			Change in soil (%)			Average				
Fertiliser quantity	2%	5%	7%	Carbon	Nitrogen	Productivity	Crop yield (t/ha)	Wheat protein (%)	Wheat NUE	Break-even price ($/t)	Gross margin *SD* ($/ha)
+60%	109,371	369,588	881,053	–2.4	–3.5	–0.3	4.6	14.3	6.66	244	563
+40%	104,684	350,737	832,146	–2.8	–3.8	–0.7	4.4	13.8	6.56	238	518
+20%	94,628	313,665	740,614	–3.2	–3.8	–0.7	4.1	13.3	6.38	240	462
Rec.	83,366	274,813	647,364	–5.3	–5.7	–2.9	3.7	12.8	6.09	241	413
–20	82,320	271,556	639,906	–5.9	–6.4	–3.6	3.6	12.7	7.30	237	413
–40	56,579	188,451	445,187	–10.6	–11.0	–8.7	2.8	11.5	5.05	255	301
–60	39,211	133,620	318,835	–14.8	–15.4	–13.6	2.2	11.2	4.54	275	223
Nil	4,219	23,795	67,777	–23.1	–23.6	–22.7	0.9	9.8	0	407	86

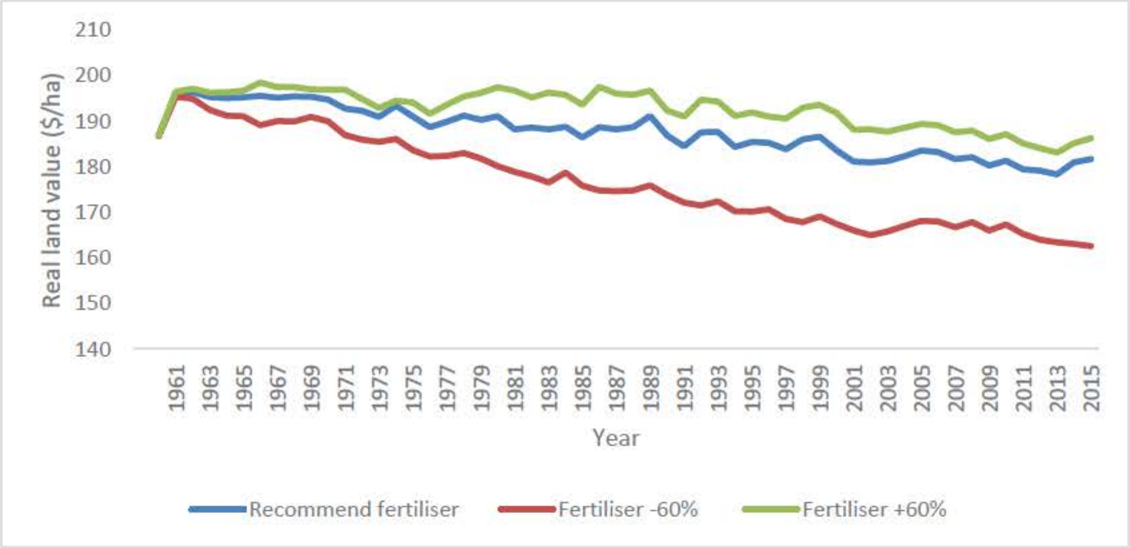
Note. NUE = nitrogen use efficiency; Rec. = recommended fertiliser input quantity.

The effect of variation in fertiliser input quantities is reduced with lower-bound climate scenarios compared to simulations using historical climate data, as illustrated in Figure 6.15. With lower-bound climate change, a 60% increase in DAP and urea from the NSW DPI-recommended inputs maximises profits, as shown in Table 6.13. A further benefit is that soil productivity is maintained over the simulation period (1960–2015) with a 60% increase in DAP and urea inputs with lower-bound climate change. This finding is consistent with results generated with historical climate data that is, increasing fertiliser inputs above the recommended rate increases nitrogen retained in the soil thereby reducing soil productivity losses to just 0.3% over the modelling period with lower-bound climate change. Reducing fertiliser inputs in lower-bound climate simulations has less effect on soil productivity than historical climate data, further supporting the link between seasonal precipitation and soil productivity variation.

The soil productivity variable applied to land value with climate change simulations provides consistent results to those obtained using historical climate data. Figure 6.15 shows that with a discount rate of 5% using NSW DPI-recommended fertiliser inputs, there is a 2.5% improvement in land value with the lower-bound scenario that also employs the NSW DPI-recommended fertiliser inputs. Increasing fertiliser inputs increases the real land value compared to the recommended fertiliser input quantity, consistent with findings using historical climate data. The variation in land value generated with lower-bound climate change simulations is consistent with soil nitrogen and carbon variation. This finding suggests that the soil productivity index developed in Chapter 4 reliably estimates the effect of climatic and fertiliser input variation consistent with expectations.

Figure 6.15

Real Land Value 1960–2015 in $1960 Using Lower-Bound Predicted Climate Change With a 5% Discount Rate



Source: APSIM (2019), MS Excel (2021)

6.4.2 Upper-Bound Predicted Climate Change Scenario

With the upper-bound climate change scenario, increased rainfall increases crop yields compared to historical and lower-bound climate simulations. Wheat yields increase across all scenarios when increasing the volume of precipitation with daily temperatures identical to lower-bound climate simulations, *certeris paribus*. Increasing urea and DAP fertiliser inputs increases crop yields, with upper-bound wheat yields on average between 4.8 t/ha and 5.8 t/ha, compared to lower-bound climate change and wheat yields with historical climate data.

The quantity of fertiliser used in simulations effects environmental outcomes. Improving fertiliser efficiency to reduce nitrous oxide emissions is a key research theme. Reducing fertiliser inputs reduces yield consistently across all climate scenarios. Reducing DAP and urea inputs by 20% below the NSW DPI-recommended application quantity reduces crop yields by 0.1 t/ha across all climate scenarios. The decrease in wheat yield converges across scenarios when fertiliser inputs are reduced by 40%, with average wheat yields of 2.8–2.9 t/ha across climate scenarios. With a 60% reduction in fertiliser, the average wheat yield is 2.2 t/ha regardless of climate. The results suggest that a maximum 20% reduction in fertiliser inputs, regardless of the climate scenario, is recommended to maintain profits from land use at the study site.

Increasing fertiliser inputs increases crop yield and fertiliser efficiency across all climate scenarios. Efficient fertiliser application is a global research theme (Angus & Grace, 2017). Testing the NSW DPI (2013) recommended fertiliser inputs by varying inputs to determine if an alternative quantity can increase crop yields efficiently in the future with climate change can support farmers in implementing the most efficient and profitable management processes. The DAP and urea inputs are more efficient in the upper-bound climate scenario with a wheat grain NUE of 7.4–8.7 with increased fertiliser inputs than in wheat grain NUE of 6.4–6.7 with the lower-bound scenario, as shown in Table 6.14. Lower-bound grain NUE is lower than the historical grain NUE with increased fertiliser inputs generating a grain NUE of 8.6–11.3 while the upper-bound grain NUE improves by 0.1% with a 20% increase in fertiliser and is identical to the historical grain NUE with a 40% increase in fertiliser. The results suggest that increasing fertiliser inputs by 60% is inefficient and may increase the rate of fertiliser loss either through conversion to nitrous oxide and vaporised into the atmosphere or moved through the soils into subsoil with increased precipitation.

Table 6.14

Wheat Nitrogen Use Efficiency and Protein Content 1960–2015 With Varied Fertiliser Inputs Across Different Climate Scenarios

	Average					
Fertiliser input quantity	Protein: upper bound (%)	NUE: upper bound	Protein: historical (%)	NUE: historical (%)	Protein: lower bound (%)	NUE: lower bound
+60%	12.9	8.7	12.9	11.6	14.3	6.7
+40%	12.7	8.1	12.5	8.1	13.8	6.6
+20%	12.4	7.4	12.2	7.3	13.3	6.4
Recommended	12.1	6.7	11.9	6.5	12.8	6.1
–20%	12.1	8.0	11.9	7.7	12.7	7.3
–40%	11.8	5.2	11.4	4.9	11.5	5.1
–60%	11.7	4.6	11.2	4.4	11.2	4.5
Nil	10.0	0	10.2	0.0	9.8	0

Note. NUE = nitrogen use efficiency.

Wheat grain production is linked to nitrogen availability so that varying fertiliser inputs will affect the grain protein content. As discussed in Section 6.1, grain protein content determines the price a farmer can obtain for wheat produced with higher grain protein content increasing the price received (AEGIC, n.d.). Upper-bound climate change increases grain protein content compared to historical simulations for all fertiliser input quantities excluding a 60% increase in fertiliser where grain protein content is identical for both climate simulations (see Table 6.14). Increasing fertiliser inputs by 60% from the recommended quantity despite lower grain yields in the lower-bound scenario increases the grain protein content to an average of 14.3%, enabling it to be sold as Australian Prime Hard wheat at a premium price. Fertiliser input quantities between a 20% reduction to the maximum modelled are above the 11.5% threshold for grain to be classified as Australian Hard wheat. Varying nitrogen inputs effects grain protein content and the price farmers receive.

Profits are maximised with a 60% increase in DAP and urea fertilisers applied across all discount rates when using the Australian hard price for wheat with upper-bound climate change. Despite increased fertiliser input costs, the increased wheat yield increases profits by 47% - 49% depending on the discount rate. Consistent with lower-bound climate change, increasing fertiliser input quantities increases the variance in gross margin returns. Increasing fertiliser inputs by 60% decreases the break-even price to $120/ha from $133/ha with the recommended quantity of fertiliser inputs (see Table 6.15). In contrast, decreasing fertiliser inputs by 60% increases the break-even price to $179 while increasing fertiliser inputs increased wheat yield and decreased the average break-even price.

Table 6.15

Results for Wheat Production 1960–2015 With Upper-Bound Climate Change

Fertiliser input quantity	Net present value ($/ha)			Soil change (%)			Avg. break-even price ($/t)	Gross margin *SD* ($/ha)
	2%	5%	7%	Carbon	Nitrogen	Productivity		
+60%	145,850	484,246	1,148,738	–9.7	–10.7	–8.4	120	431
+40%	130,446	432,734	1,026,465	–10.9	–11.9	–9.8	123	366
+20%	114,692	381,361	906,020	–12.4	–13.3	–11.3	127	303
Rec.	98,187	328,182	781,952	–14.5	–15.3	–13.5	133	248
–20%	95,904	320,860	764,969	–15.3	–16.3	–14.6	132	247
–40%	60,709	207,489	499,618	–19.6	–20.4	–19.2	155	129
–60%	40,966	143,591	349,960	–21.7	–22.4	–21.4	179	98
Nil	2,467	19,161	58,701	–25.5	–25.9	–25.3	348	72

Note. Rec. = recommended fertiliser input quantity.

Decreasing fertiliser inputs reduces the grain NUE and NPV returns from continuous wheat production with upper-bound climate change. As shown in Table 6.15, decreasing fertiliser inputs by 60% decreases the 2020 NPV profits from continuous wheat production by 55%–58% compared to 2020 NPV profits with recommended fertiliser inputs (see Table 6.15). Reducing DAP and urea applied by 20% decreases 2020 NPV profits from continuous wheat production for 1960–2015 by an average of 2% across the three discount rates utilised. Despite a reduction in profits, the break-even price decreases from $133 to $132 with a 20% reduction in fertiliser inputs used in the upper-bound simulation. This finding is consistent with lower-bound simulation results (see Table 6.13). Therefore, reducing the break-even price by reducing fertiliser inputs by 20% reduces wheat yields and does not increase profits from wheat production. This lends support to the previous finding that reducing fertiliser inputs reduces wheat NUE.

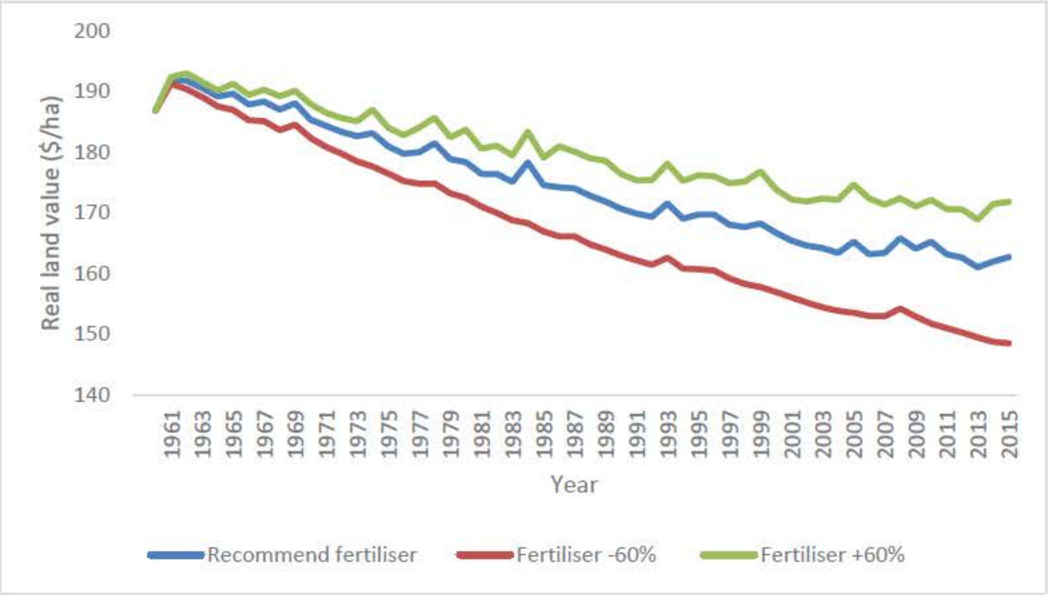
Decreasing fertiliser inputs decreases grain NUE and NPV profits from wheat production and increases soil nitrogen losses with upper-bound climate simulations. Decreasing the fertiliser applied increases soil nitrogen extraction to compensate for inadequate fertiliser input quantities. The soil nitrogen losses with upper-bound climate change are between 16% and 22% when fertiliser inputs are reduced by 20%–60% (see Table 6.15). Increasing fertiliser inputs above the recommended rate decreases soil nitrogen losses to 10%–13%. Soil nitrogen losses with upper-bound climate change increase compared to lower-bound soil nitrogen losses (see Table 6.13). Precipitation is the only climate variable that changes between climate simulations (temperature increases are identical). The change in soil nitrogen losses between climate simulations supports the findings in Section 6.1 that identified rainfall as the critical driver of soil nitrogen losses.

Consistent with the previous results for soil nitrogen variation, increased precipitation with upper-bound climate change increases soil carbon losses. With a 20%–60% decrease in fertiliser inputs applied, soil carbon content declines by 15%–22% (see Table 6.15), compared to 6%–15% with lower-bound climate change (see Table 6.13) and 9%–18% with historical climate data (see Table 6.7). These findings reinforce the fact that soil carbon losses increase with increased precipitation and higher temperatures over the modelling period thus, decreasing future land productivity. Increasing fertiliser inputs by 20%–60% decreases the soil carbon losses with upper-bound climate change by 10%–12%, compared to just 0.3%–0.7% with lower-bound climate change simulations. Rainfall is a crucial driver of soil carbon losses and this is consistent with the results from historical climate data.

The decline in soil productivity with upper-bound climate change is reflected in the change in real land value illustrated in Figure 6.16. The downward trend in real land value over the modelling period reflects declining soil carbon and nitrogen across all scenarios. Predicted upper-bound climate change significantly effects future land productivity, reflected in the land value in Figure 6.16. With a 60% reduction in fertiliser inputs, real land value steadily declines over the modelling period with upper-bound climate change (see Figure 6.16). Using the NSW DPI-recommended fertiliser inputs, with upper-bound climate change, the land value declines. There was an increase in 1984 followed by a sharp decline in 1985, consistent with historical simulations that identified the above-average rainfall and warmer temperatures in 1985 as a critical driver of soil productivity losses and land value. There was a downward trend in land value from 1985 to 1994, Using historical climate data (BOM, 2020) shows that soil productivity increased with reduced rainfall in 1994. This result suggests that a negative climate shock can trigger ongoing soil productivity losses, reflected in the land value in Figure 6.16. The variation in real land value shown in Figure 6.16 with upper-bound climate simulations supports the finding that rainfall variation is a significant driver of soil productivity and land value. Using the soil productivity index to vary land value is a valuable tool to support land management decision-making.

Figure 6.16

Real Land Value Variation 1960–2015 With Upper-Bound Climate Simulation Using a Discount Rate of 5% in $1960



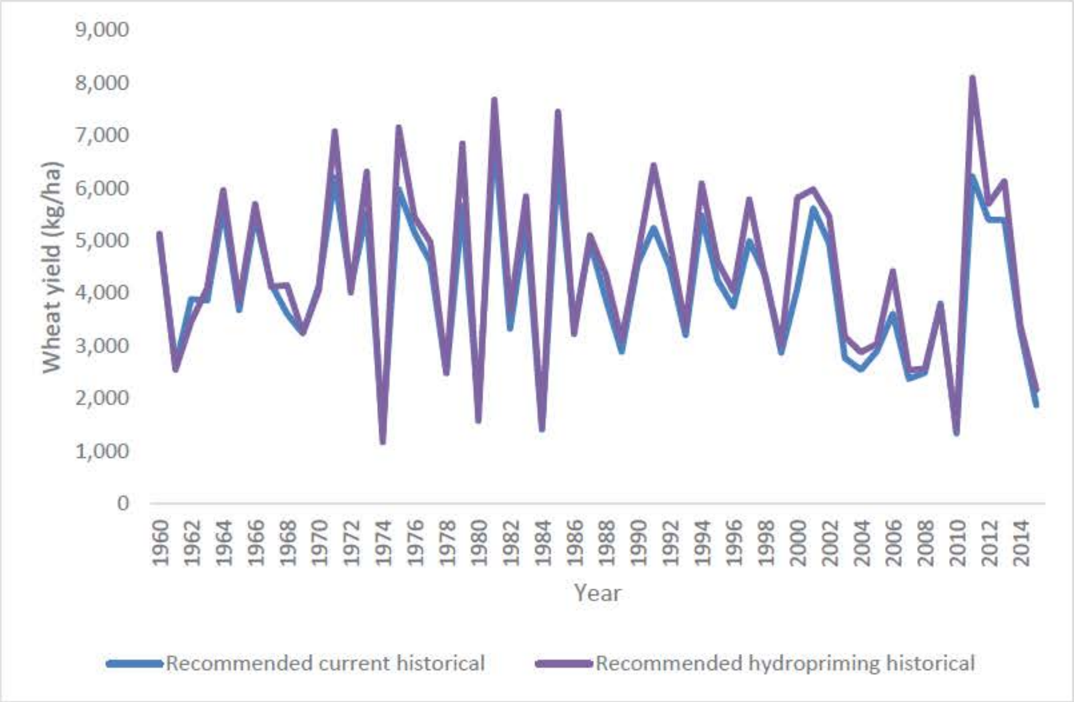
Source: APSIM (2019), MS Excel (2021)

6.5 HYDRO-PRIMING MANAGEMENT PRACTICE

As discussed in Chapter 3, hydro-priming is an alternative management practice of imbuing seeds with fertiliser before sowing. This practice is common in the horticultural industry and may increase wheat early growth rates and improve fertiliser efficiency and wheat yields. The wheat yields for hydro-priming and current management practices with historical climate data are shown in Figure 6.17, using identical wheat cultivars, planting times, row spacing and depth as current management practices (see Section 6.1). The average increase in wheat yields over the modelling period was 358 kg/ha. Hydro-priming wheat seeds with fertiliser prior to sowing increases yield, *certeris paribus.*

Figure 6.17

Current and Hydro-Priming Management Practices Wheat Yield 1960–2015 With New South Wales DPI-Recommended Fertiliser Inputs and Historical Climate Data



Source: APSIM (2019), MS Excel (2021)

Over the modelling period 1960–2015, wheat yields show 22%–43% yield increases in 1971, 1975, 1979, 1991, 2000 and 2011. Investigating the links between BOM (2020) rainfall records and simulated hydro-priming yields provided insight into hydro-priming seasonal yield variation. Rainfall was lower than the long-term average for the modelling period of 1971. Despite this, hydro-priming crop yields are 0.88 t/ha higher than current management practices with identical urea and DAP fertiliser application rates. Precipitation in 1975 was lower than average during the wheat production season however, with hydro-priming, wheat yields were 1.17 t/ha higher than with current management practices (see Figure 6.17). In 1979, rainfall was lower than average in the wheat germination and establishment period of April to May with simulated hydro-primed seeds wheat yields being 1.20 t/ha compared to yields with current management practices. In 1991, rainfall was above average for the wheat establishment period of April to May, and the grain setting period of August and hydro-primed seeds generating wheat yields 1.19 t/ha higher than current management practices. Similarly, in 2000, rainfall was above average in April and May, with higher rainfall recorded in September and October (BOM, 2020) and hydro-priming illustrates a 1.73 t/ha improvement in wheat yields. The results suggest that hydro-priming increases wheat yields compared to current management practices with seasonal rainfall variation during critical wheat growth stages.

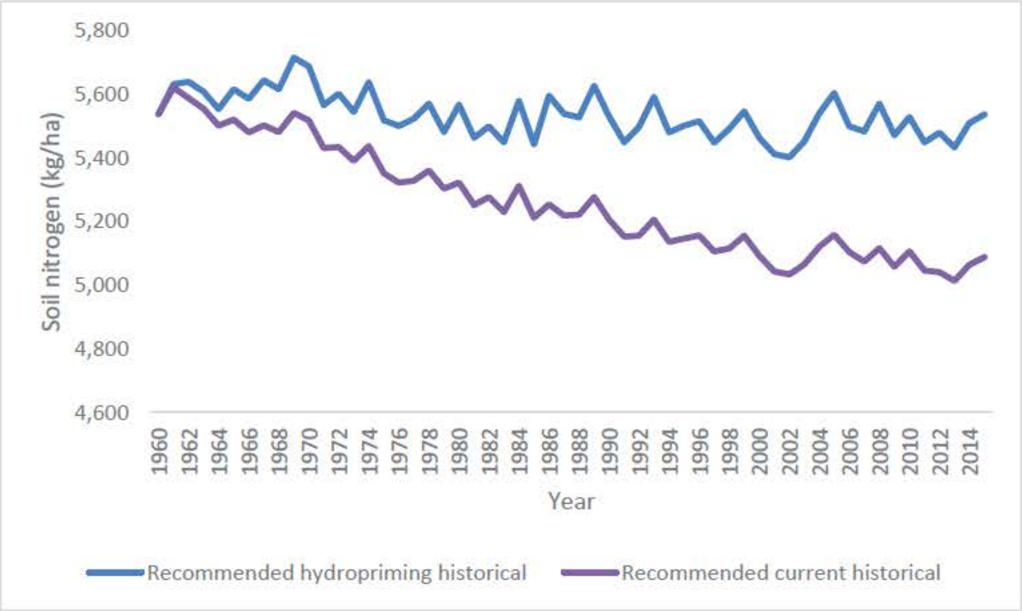
Hydro-primed wheat yields were 45–425 kg/ha or 1%–3% lower than yields with current management practices in 1961, 1962, 1967, 1972, 1974, 1980, 1986, 1999 and 2009. Above-average rainfall was recorded each of these years during June–July (BOM, 2020). As the lifecycle of the wheat plant in Figure 6.11 illustrates, June–July is a significant period when biomass production occurs. Hydro-priming accelerates wheat crop growth so that above-average rainfall may damage head growth and effect yield potential.

Hydro-priming wheat seeds in drought periods increases wheat yields. For example, hydro-primed wheat yield in the 1982–1983 drought was 330 kg/ha and 498 kg/ha or 9.3% and 9.9% higher, respectively, than with current management practices. During the Millennium Drought, there was an average 8% increase in wheat yield. The results suggest that hydro-priming wheat seeds before planting in seasons with predicted lower rainfall can marginally improve wheat yields. Further, the improvement in wheat yields across with seasonal rainfall variation suggests that hydro-priming wheat seeds effectively reduces climate risks to wheat yields.

With increased wheat yields, soil nitrogen content may decline with hydro-priming compared to current management practices. Figure 6.18 shows that soil nitrogen content follows a similar pattern for hydro-priming and current management practices thereby, confirming that soil nitrogen content is driven by climatic variation. Figure 6.18 illustrates soil nitrogen variation—with the alternative management practices, soil nitrogen diverged after 1962 when above-average rainfall was recorded (BOM, 2020). In 1962–1963, hydro-priming soil nitrogen increased by 0.1% compared to a 0.5% decline with current management practices. Rainfall and temperatures in 1964 experienced above-average temperatures during March and April, with a maximum temperature of 36.9 °C recorded on 13 March 1964 and 34.4 °C recorded on 23 March 1964 (BOM, 2020). In 1964, there was a 1.1% improvement in soil nitrogen with hydro-priming compared to a 0.3% increase with current management practices. Wheat harvest and yields were similar in 1964, with 5.9 t/ha harvested on 15 December for hydro-priming and 5.6 t/ha harvested on 14 December with current management practices. The results are consistent with the findings of Patra et al. (2016) that demonstrate hydro-priming seeds will increase early wheat root growth and support soil nitrogen retention.

Figure 6.18

Soil Nitrogen Content 1960–2015 With Hydro-Priming and Current Management Practices Using Historical Climate Data



Source: APSIM (2019), MS Excel (2021)

Soil carbon increases over the modelling period with hydro-priming compared to current management practices (shown in Table 6.16) consistent with the soil nitrogen and results generated in Section 6.1 with current management practices. Historical climate data shows soil carbon increases by 0.9% with hydro-primed seeds compared to the 8.1% loss with current management practices. The combined effect of improved soil nitrogen and carbon results is a 3.4% increase in soil productivity with hydro-priming with historical climate data. Soil productivity with lower-bound climate change increases by 4.5%, with soil carbon increasing by 1.8%. This exponential relationship between soil carbon and nutrient retention aligns with De Neve and Hofman (2000) findings. Hydro-priming increases soil productivity with an exponential improvement over the modelling period in the historical and lower-bound climate simulations.

Table 6.16

Current Management Practices and Hydro-Priming 1960–2015 Soil and Yield Statistics

Recommended fertiliser input quantity and climate scenario	Soil change (%)			Average			Land value 2020 ($/ha) 5%
	Carbon	Nitrogen	Productivity	Crop yield (t/ha)	Wheat protein content (%)	Wheat NUE	
Current Upper	–14.5	–15.3	–13.5	4.2	12.1	6.70	3,038
Current Historical	–7.5	–8.1	–5.6	4.1	11.9	6.47	3,305
Current Lower	–5.3	–5.7	–2.9	3.7	12.8	6.09	3,393
Hydro-priming upper	–8.1	–9.5	–7.1	4.5	12.1	7.89	3,255
Hydro-priming historical	0.9	0.0	3.4	4.4	11.8	7.81	3,605
Hydro-priming lower	1.8	0.9	4.5	4.1	12.8	7.56	3,639

Note. NUE = nitrogen use efficiency.

With upper-bound climate change, soil productivity increases in the hydro-priming scenario by 7.1%. In comparison, with current management practices, it declines by 13.5%. These findings are consistent with the work of Williams et al. (1989), who identified a link between soil carbon, temperatures, and economic returns from land use. The soil productivity variable applied to hydro-priming with alternative climatic scenarios suggests that increases in soil carbon increase soil productivity. Hydro-priming improves soil productivity and land asset values across all climatic scenarios modelling. This finding suggests that hydro-priming is reliable for increasing soil productivity and land value under various climatic conditions.

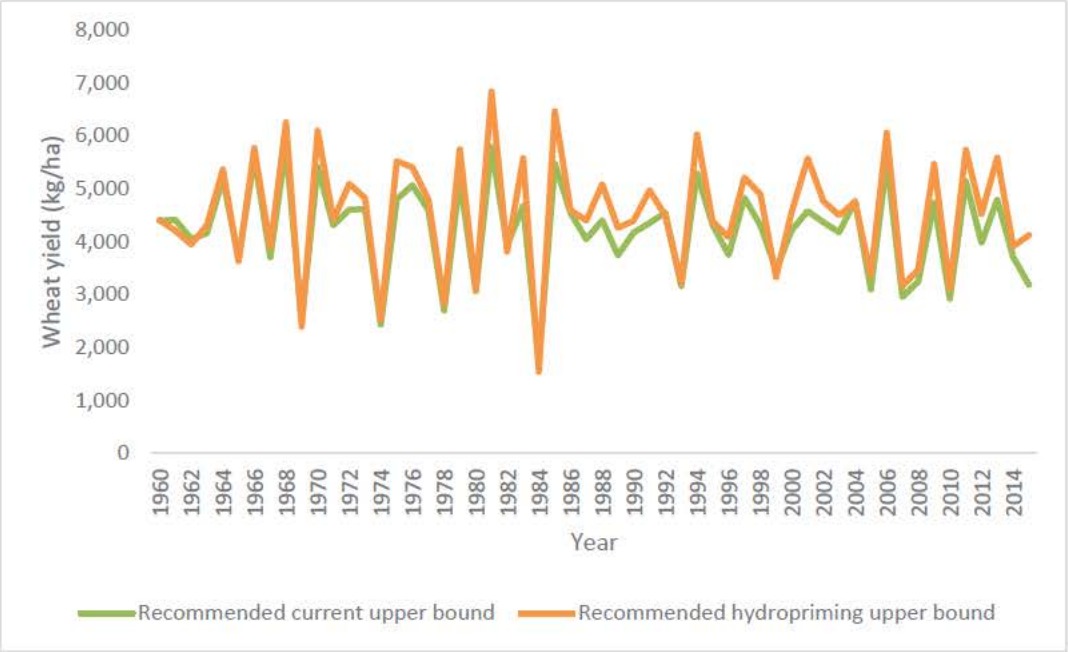
Hydro-priming improves relative wheat yields, soil productivity and grain NUE. With lower-bound climate change, increased urea and DAP fertiliser inputs are more effective than current management practices (see Table 6.16). Hydro-priming seeds accelerates early crop root growth, increasing the wheat plant’s ability to access fertiliser applied across the soil surface. With lower-bound climate change, grain NUE increases from 6.47 to 7.56 and from 6.09 to 7.89 with upper-bound climate change. Holding fertiliser inputs fixed and hydro-priming increases the effectiveness of wheat fertiliser usage. Despite increased grain NUE with hydro-priming, the wheat protein content declines with historical and upper-bound scenarios. With historical climate data, hydro-priming reduces wheat protein content from 12.1% to 11.8% and from 12.8% to 12.1% with upper-bound climate change. Hydro-priming with lower-bound climate change increases wheat protein content from 11.9% to 12.8%, suggesting that with lower-bound climate change, hydro-priming improves wheat quality. Nonetheless, this improvement is insufficient to change the wheat class and thus, its selling price.

There is a direct link between average wheat yield and soil productivity with hydro-priming. With historical climate, soil productivity and wheat yields increased to 4.4 t/ha compared to current management practices. However, with lower-bound climate change, average wheat yields are not immediately improved despite improved soil productivity, with average wheat yield across both scenarios at 4.1 t/ha. With upper-bound climate change, the average wheat yield is increased to 4.5 t/ha compared to 3.7 t/ha with current practices. In the hydro-priming scenario, soil productivity is correlated with an increased average wheat yield for the modelling period.

The net improvement in wheat yield in the upper-bound climate scenario with hydro-priming compared to current management practices is illustrated in Figure 6.19. There was a 0.99 t/ha increase in wheat yield in 1983 and a 0.99 t/ha increase in 1985 with hydro-priming. Between 1985 and 1992, hydro-priming yields exceeded the yields obtained using current management practices. During this period, the adjusted rainfall falls within one standard deviation of the long-term average rainfall for upper-bound climate change, downscaled using the method described in Chapter 5. The results suggest hydro-priming improves crop yields in seasons with long-run average rainfall in the upper-bound climate scenario. Hydro-priming wheat seeds is a strategy that mitigates the effect of climate risks on wheat yields.

Figure 6.19

Wheat Yield (kg/ha) 1960–2015 With Upper-Bound Climate Change for Current and Hydro-Priming Management Practices



Source: APSIM (2019), MS Excel (2021)

6.5.1 Sensitivity Testing Hydro-Priming Root and Shoot Growth Rates

As discussed in Chapter 3, hydro-priming wheat field studies produced a range between 6% and 26% increased root and shoot growth rates. To evaluate the effectiveness of the hydro-priming process on crop yield, soil carbon, nitrogen, and productivity, the APSIM wheat file was calibrated using the different growth rates taken from the lower and upper bounds of the field study results (see Chapter 5). The critical results for the simulations are presented in Table 6.17, including yield and soil content. Across the different simulations using 6% and 26% root and shoot growth rates with identical climate data and fertiliser inputs, wheat yields vary by less than 0.5%. The average yields in Table 6.17 have minor variation across the field study root and shoot growth rates, suggesting that the midpoint growth rate used in the hydro-primed wheat seeds scenario is robust.

Table 6.17

Shoot and Root Growth Rates Increase With Hydro-Priming Using Recommended Fertiliser Inputs and Historical Climate Data 1960–2015

Variable	Hydro-priming recommended		
	6%	13%	26%
Average annual yield (kg/ha)	4,434	4,443	4,455
Soil carbon variation (%)	0.9%	0.9%	1.0%
Soil nitrogen variation (%)	–0.1%	0.0%	0.1%
Soil productivity (%)	3.4%	3.4%	3.6%

6.5.2 Hydro-Priming Production Cost-Effectiveness

As discussed in Chapter 5, hydro-priming seeds can be undertaken manually or automatically. Sowing 1 hectare of land for wheat production requires 60 kg/ha of wheat seed while sowing multiple fields with hydro-primed seeds requires automated processes to hydro-prime seeds effectively. The cost of hydro-priming seeds is discussed in Chapter 5 (the table from Chapter 5 is reproduced in Table 6.18). The farmer is assumed to allocate 500 ha of their property to wheat production. A further simplifying assumption is made with the hydro-priming scenario that all crops sown will utilise hydro-priming technology therefore, in the first year, the capital cost of purchasing machinery in the automated method is allocated across all 500 hectares.

Table 6.18

Seed Hydro-Priming Cost ($/ha)

Variable	Manual ($/ha)	Automatic ($/ha)	Semiautomated ($/ha)
Receptacle/machinery	170.60	128,375.00	11,482.00
fertiliser used	0.90	0.83	0.83
Water	0.15	0.06	0.09
Electricity		2.54	0.90
Labour	58.00	29.00	43.50
Total	229.65	128,407.43	11,527.32
Cost per ha (year 1)	59.39	289.18	68.28
Marginal cost p/ha (subsequent years)	59.05	32.43	45.32

Evaluating the most cost-effective hydro-priming method using break-even prices per hectare applied to the NSW DPI-recommended fertiliser input quantities provides a method of evaluating the cost-effectiveness of hydro-priming compared to current management practices. As Table 6.19 shows, using the marginal cost for years without a capital cost, hydro-priming increases the break-even price by $18–$21 or 13%–15.8% with historical climate data. With lower-bound climate data, the break-even price increases by $30–$36 or 21%–25%. With upper-bound climate change, the effect of the increased crop yield with hydro-priming reduces the break-even price from $162 to $140–$143, a reduction in the break-even price of 11.7%–13.5%. The most cost-effective hydro-priming method is for automated hydro-priming across all climatic scenarios.

Table 6.19

Hydro-Priming Alternative Methods Break-Even Prices ($/t)

Recommended fertiliser input quantity and climate scenario	Average break-even price ($/t)			
	No priming	Automated	Semiautomated	Manual
Current Upper	162			
Current .Historical	133			
Current Lower	143			
Hydro-priming upper		140	140	143
Hydro-priming historical		151	152	155
Hydro-priming lower		173	175	179

The NPV is maximised for a 1-hectare plot of land with continuous wheat production when seeds are processed using the automated hydro-priming method (see Table 6.21). The findings are robust across the modelled 2%, 5% and 7% discount rates and climate scenarios. This result used ongoing capital investment as set out previously, with costs increasing annually using the discount rate. As Table 6.20 indicates, costs are similar across all the hydro-priming methods considered in this analysis, suggesting that the hydro-priming method had little effect on NPV returns over the 1960–2015 period. Farmers can potentially trial more labour-intensive methods before committing to significant capital investment in automated machinery, potentially increasing the uptake by farmers. Farmers can generate similar NPV returns with hydro-priming across all the priming methods investigated in this analysis.

As Table 6.20 illustrates, the NPV for hydro-priming is higher across all hydro-priming methods when compared to NPV for current management practices using a range of discount rates. Hydro-priming increases returns from wheat production land use by 5.4%–6.8% across the discount rates and hydro-priming methods. With historical climate data, 2020 NPV hydro-priming increases land use profits from continuous wheat production from 1960–2015.

With lower-bound climate change, the NPV returns from one hectare of land devoted to wheat production decrease by 10%–11% across discount rates and hydro-priming methods, compared to NPV returns with hydro-primed wheat using historical data. With upper-bound climate change, hydro-priming increases NPV returns by 1.5%–2.5% across hydro-priming methods and discount rates compared to hydro-primed wheat returns with historical data. However, all hydro-priming methods increase NPV returns by 7 – 9% compared to non-primed continuous wheat across all climate scenarios. The improvement in the NPV returns across climatic scenarios, discount rates and methods suggests that hydro-priming is a profitable alternative land use to increase margins returns from continuous wheat production when NSW DPI-recommended urea and DAP fertiliser inputs are used.

Table 6.20

Net Present Value in 2020 With Historical Climate for Hydro-Priming and Current Management Practices for 1960–2015

Climate scenario and recommended management method	Net present value automatic ($/ha)			Net present value semiautomatic ($/ha)			Net present value manual ($/ha)		
	2%	5%	7%	2%	5%	7%	2%	5%	7%
Current historical (non-primed)	95,872	319,914	759,509						
Hydro-priming historical	100,470	328,066	768,238	99,501	325,560	764,341	100,845	329,846	774,252

Table 6.21

Net Present Value in 2020 Hydro-Priming and Current Management Practices 1960–2015 With New South Wales Department of Primary Industries -Recommended Fertiliser Inputs

Climate scenario and management method[a]	Net present value automated ($/ha)			Net present value semiautomated ($/ha)			Net present value manual ($/ha)		
	2%	5%	7%	2%	5%	7%	2%	5%	7%
Hydro-priming upper	101,937	333,872	785,328	101,562	332,053	782,187	102,906	336,339	792,098
Hydro-priming historical	100,470	328,066	768,238	99,501	325,560	764,341	100,845	329,846	774,252
Hydro-priming lower	89,450	294,913	692,959	88,522	292,454	689,114	89,866	296,740	699,025

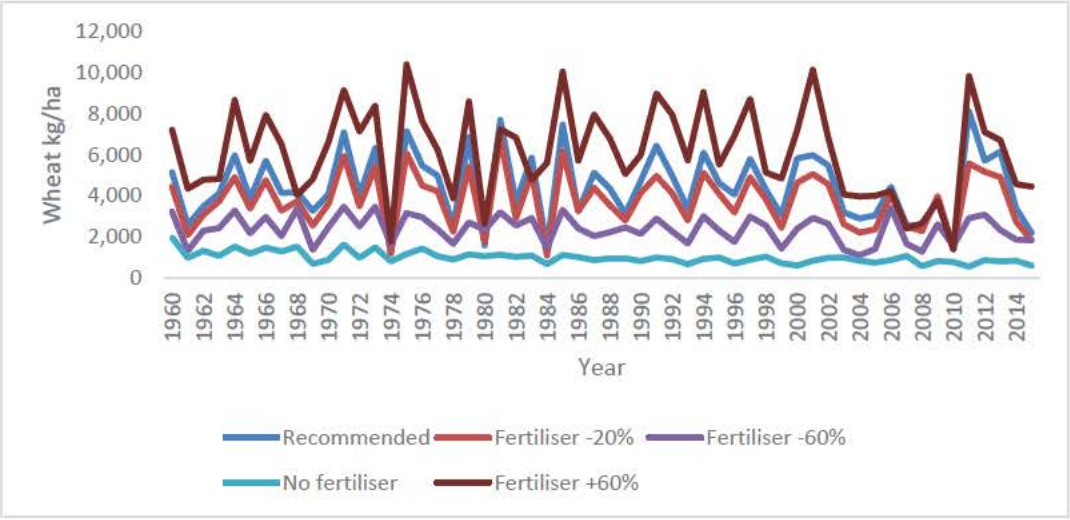
[a] New South Wales Department of Primary Industries-recommended fertiliser inputs.

6.5.3 Hydro-Priming with Fertiliser Input Variation

The yield and NPV return improvement with hydro-primed wheat using NSW DPI-recommended inputs may be enhanced through the variation in fertiliser inputs. As such, simulations were run in APSIM with the same fertiliser input variations used in Section 6.4 but the urea and DAP fertiliser inputs were varied. Consistent with current management practices, wheat yields increase, with a 60% increase in DAP and urea fertiliser wheat yields increase on average by 43% (see Figure 6.20). Similarly, with current management practices, wheat yields by an average of 2.8% when fertiliser inputs are decreased by 20%. However, with hydro-priming, yields decrease by 14% with an identical reduction in fertiliser inputs. With a 60% decrease in fertiliser inputs, wheat yields in hydro-priming and current management practices declined by 43%. Yield variation with alternative fertiliser inputs is consistent across historical, lower, and upper-bound climate scenarios. As Figure 6.21 and Figure 6.22 show, the variation is broadly consistent across all climatic scenarios. Wheat yield variation with alternative fertiliser input quantities is consistent across priming and current management practices.

Figure 6.20

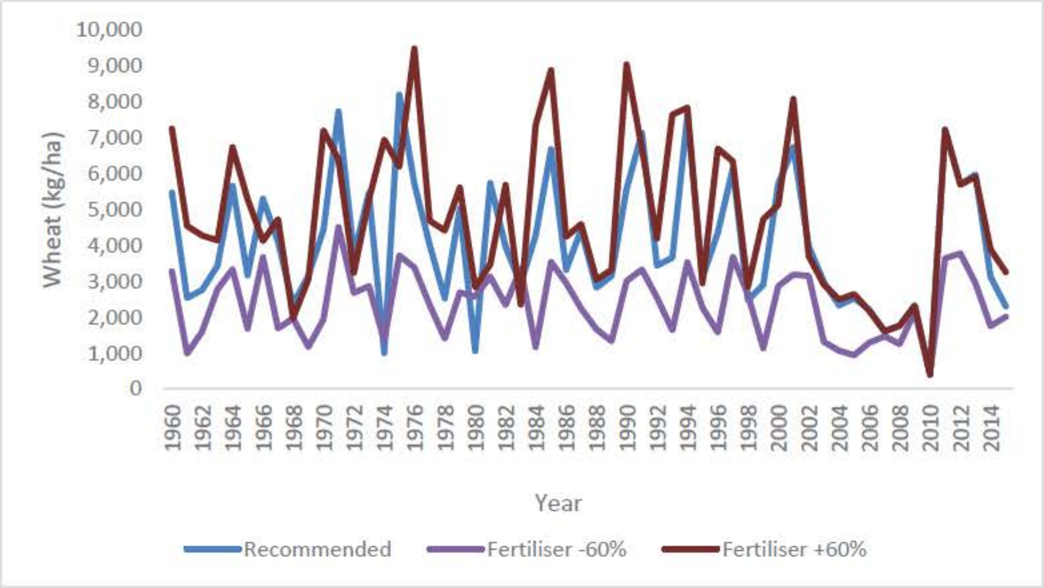
Hydro-Priming Wheat Yields (kg/ha) 1960–2015 With Varied Fertiliser Inputs Using Historical Climate Data



Source: APSIM (2019), MS Excel (2021)

Figure 6.21

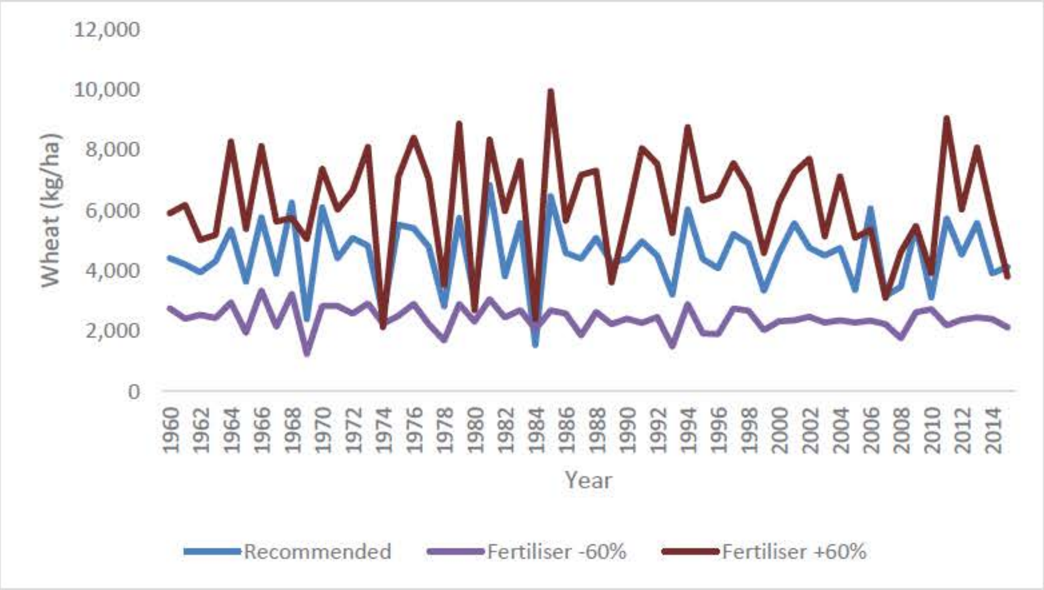
Wheat Yields (kg/ha) With Lower-Bound Climate Change and Varied Fertiliser Inputs



Source: APSIM (2019), MS Excel (2021)

Figure 6.22

Wheat Yields (kg/ha) 1960–2015 With Upper-Bound Climate Change and Varied Fertiliser Inputs



Source: APSIM (2019), MS Excel (2021)

Hydro-priming with historical climate data and fertiliser input variation increases the average wheat yield and varies wheat protein content. For example, a 60% increase in fertiliser increases wheat yields to 6.1 t/ha and wheat grain protein content to 12.98%, just below the lower threshold for Australian Prime Hard wheat. Decreasing fertiliser inputs by 20% decreases protein content to 11.5% compared to 11.9% with the same quantity of fertiliser inputs and current management practices. Similarly, there is a marginal 0.1% decline in grain protein content with hydro-priming compared to current management practices when fertiliser inputs are reduced by 60% with historical climatic conditions. When using the recommended fertiliser input quantity or higher with hydro-priming, wheat protein content remains sufficient to be classed as Australian Hard wheat. Hydro-priming with historical climate data increases wheat yields however it also reduces grain protein content compared to current management practices across the simulated fertiliser inputs.

Production efficiency is maximised by increasing fertiliser inputs by 60%. The decrease in grain protein content is offset by increased crop yields, which reduces the break-even price required. However, it increases the gross margin standard deviation to the highest of all the simulations undertaken. Increasing fertiliser inputs increases farmer NPV returns and yield and income variance with a significant positive correlation. With a 60% increase in fertiliser inputs, the break-even price is between $129 and $132 compared to $124 with the equivalent fertiliser inputs using current management practices (see Table 6.22). With a 20% and 60% reduction in fertiliser inputs, the break-even price increases by 7.5%–13% compared to the equivalent fertiliser input quantity using current management practices. Despite the increase in crop yields, the break-even price increases with the additional cost of hydro-priming across all fertiliser input quantities modelled with historical climatic conditions.

Table 6.22

Hydro-Priming 1960–2015 Soil Statistics, Yield and Break-Even Price

	Soil change (%)			Average attribute			Average break-even price ($/t)			
Fertiliser input quantity and climate scenario (historical)	Carbon	Nitrogen	Productivity	Crop yield (t/ha)	Wheat protein content (%)	Wheat NUE (%)	Automated	Semiautomated	Manual	Gross margin *SD* ($/ha)
+60%	5.6	3.9	7.8	6.12	12.98	13.52	129	130	132	610
+40%	4.0	2.7	6.5	5.61	12.61	9.60	137	138	140	574
+20%	2.8	1.7	5.3	5.08	12.11	8.83	143	143	146	553
Recommended	0.9	0.0	3.4	4.4	11.80	7.81	151	152	155	475
–20%	–2.2	–3.0	0.1	3.76	11.52	6.80	162	163	167	382
–40%	–6.5	–7.2	–4.5	3.07	11.25	5.84	175	176	180	270
–60%	–11.5	–12.2	–7.6	2.36	11.08	5.07	201	202	207	192
Nil	–21.2	–21.8	–20.7	0.97	10.24	0.00	370	375	388	84

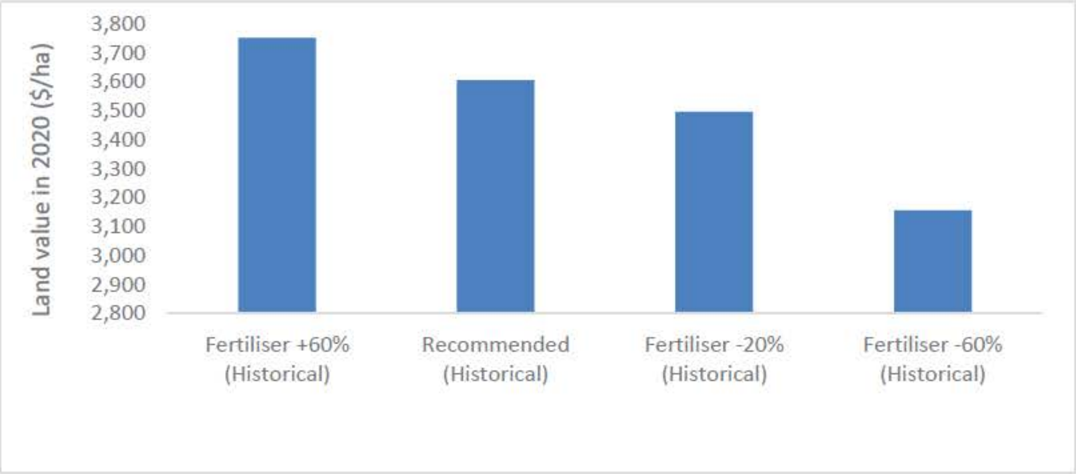
Note. NUE = nitrogen use efficiency.

Soil nitrogen content variation with hydro-priming in Table 6.22 is consistent with current management practices. Increasing fertiliser inputs increases the soil nitrogen content while decreasing fertiliser inputs decrease soil nitrogen content. The quantity of soil carbon is a driver of soil nitrogen content, with soil carbon increasing by 5.8% and soil nitrogen by 3.9%. The overall soil productivity improves by 7.8% with a 60% increase in fertiliser inputs. Conversely, decreasing fertiliser inputs by 60% decreased soil carbon by 11.5% and nitrogen by 12.2%, with soil productivity declining by 7.6%, supporting the earlier findings that soil productivity variation is exponential.

The effect of fertiliser input variation on soil productivity and land values is illustrated in Figure 6.23. The increase in soil productivity, through increased soil nitrogen and carbon with a 60% increase in fertiliser inputs, increases the land value in 2020 for wheat production between 1960 and 2015 to $3,751 compared to $3,155 with current management practice and historical climate data (see Figure 6.23). With a 60% reduction in fertiliser inputs over the modelling period, the land value in 2020 declines to $3,155. Land value variation is consistent with soil productivity and wheat yield variation.

Figure 6.23

Land Value in 2020 ($/ha) With Hydro-Priming and Historical Climate Data 1960–2015



With lower and upper-bound climate change, soil carbon, nitrogen, and productivity vary consistent with previous results. Upper-bound climate change is associated with higher temperatures and rainfall, increasing the soil carbon conversion into carbon dioxide, and reducing the soil carbon available for nitrogen retention. As a result, soil nitrogen losses reduce soil carbon combined with increased precipitation mobilising nitrogen through soils into the topsoil. Lower-bound climate change is associated with warmer temperatures and decreased rainfall, reducing net soil carbon and nitrogen losses (see Table 6.23). The results confirm previous findings and support the hypothesis that warmer temperatures combined with rainfall are the most significant driver of soil productivity losses over the modelling period with continuous wheat.

Table 6.23

Lower- and Upper-Bound Hydro-Priming Soil Statistics and Yield

	Soil change (%)			Average		
Fertiliser input quantity and climate scenario	Carbon	Nitrogen	Productivity	Crop yield (t/ha)	Wheat protein content (%)	Wheat NUE (%)
+60% lower	4.6	3.1	7.0	4.81	14.5	7.6
+60% upper	–1.8	–3.4	–0.3	6.20	13.1	10.1
Recommended lower	1.8	0.9	4.5	4.06	12.8	7.6
Recommended upper	–8.1	–9.5	–7.1	4.55	12.1	7.9
–20% lower	–1.3	–2.0	1.3	3.59	12.1	7.1
–20% upper	–8.7	–10.1	–7.7	4.44	12.0	9.4
–60% lower	–9.1	–9.7	–7.3	2.35	11.1	5.4
–60% upper	–18.0	–19.0	–15.3	2.41	11.7	18.9

Note. NUE = nitrogen use efficiency.

Reduced precipitation with lower-bound climate change reduces wheat yields and increases the grain protein content (see Sections 6.3 and 6.4). Table 6.23 shows there is potential to increase wheat protein content and grain quality with lower-bound climate change. With a 60% increase in fertiliser inputs, the wheat grain content increases to 14.5% with lower-bound climate change and 12.8% with the recommended inputs. Both upper-bound and lower-bound climate scenarios with an increase of fertiliser inputs by 60% improve wheat protein to 13% or higher, the minimum threshold for Australian Hard wheat, potentially increasing wheat production revenue. When combined with lower-bound climatic variation, increasing fertiliser inputs increases grain quality.

Rainfall limits wheat yields with lower-bound climate change decreasing the NPV returns from wheat production compared to historical or upper-bound simulations. Hydro-priming increases farmer NPV returns compared to current management practices across discount rates and fertiliser inputs quantities, as shown in Figure 6.24 and Figure 6.25. Hydro-priming is marginally more profitable with the NPV in 2020 than current management practices when modelled with lower-bound climate data. The NPV returns increase by 1.6% when fertiliser inputs are increased by 60% and decrease by 0.8% when fertiliser inputs are reduced by 20% with lower-bound hydro-priming compared to current management practices. With upper-bound hydro-priming, a 20% reduction in fertiliser inputs increases the NPV returns by 5% compared to current management practices. The most significant improvement is with a 60% increase in fertiliser inputs using hydro-priming with the upper-bound scenario—the NPV returns increase by 14% compared to current management practices. Hydro-priming and increased fertiliser inputs improve the NPV returns from land use with predicted climate change.

Figure 6.24

Net Present Value (NPV) 1960–2015 Wheat Production With Hydro-Priming and Lower-Bound Climate Change

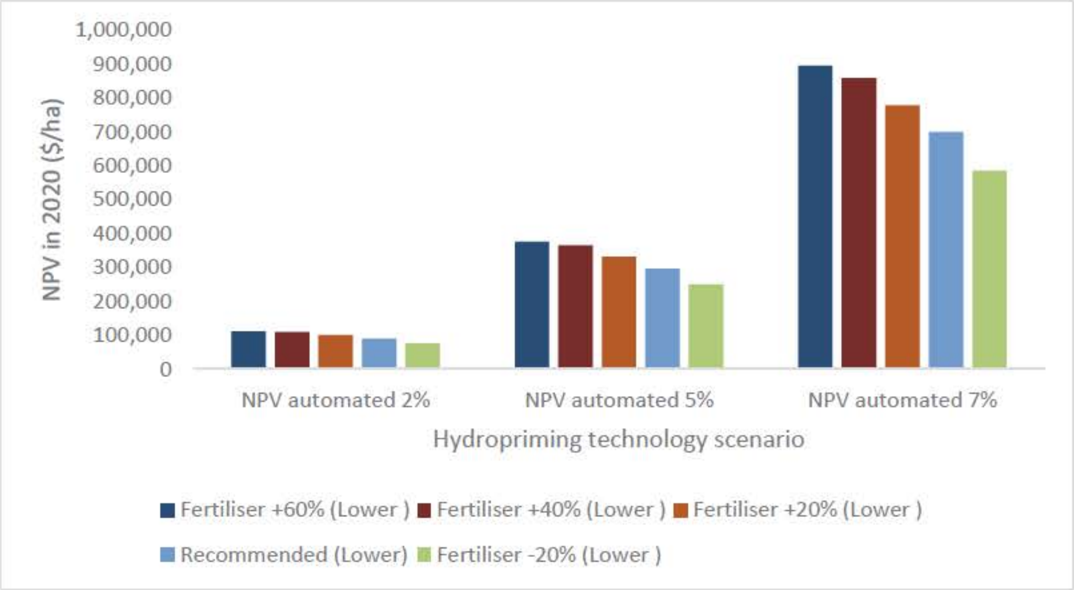
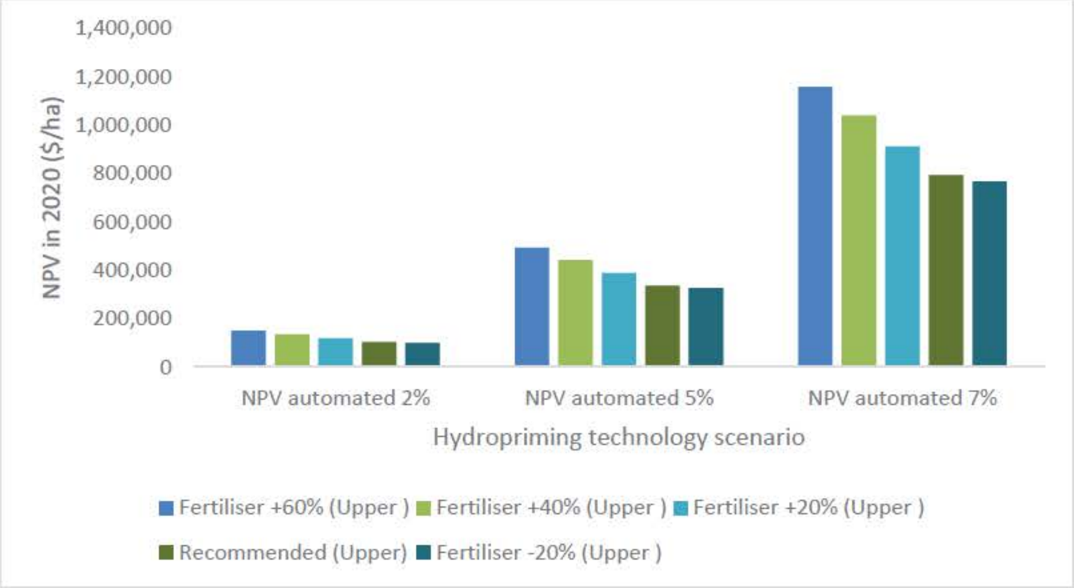


Figure 6.25

Net Present Value (NPV) Wheat Production 1960–2015 With Hydro-Priming and Upper-Bound Climate Change

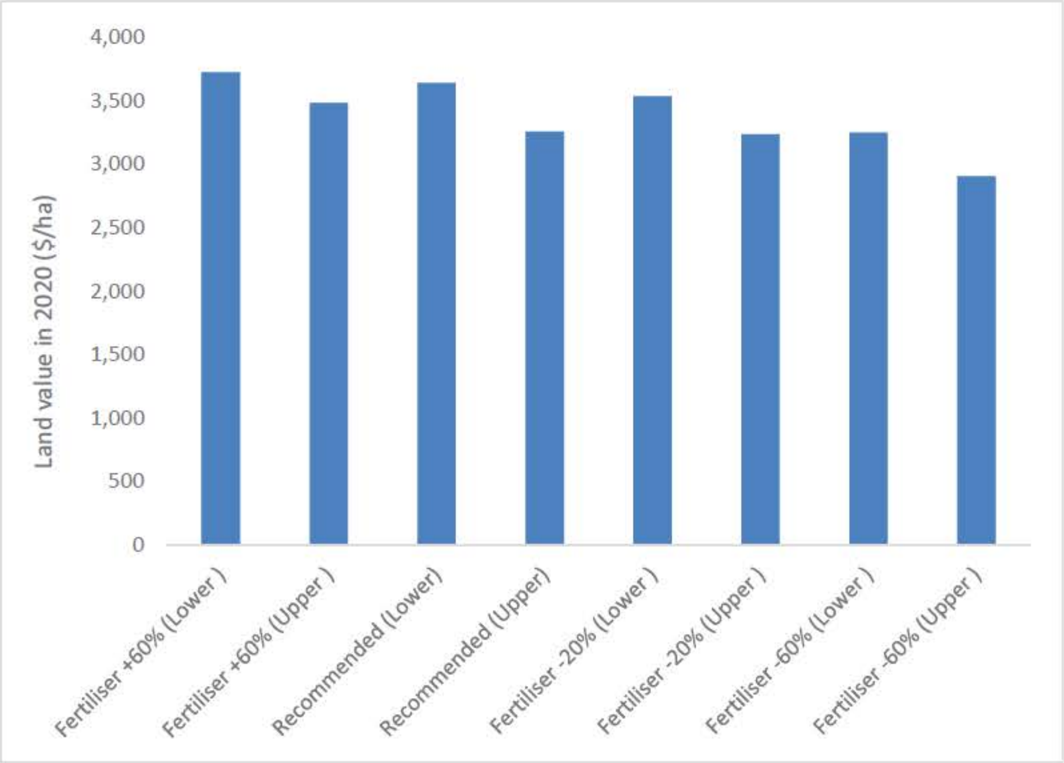


Source: APSIM (2019), MS Excel (2021)

With increased fertiliser inputs, soil nitrogen and carbon are retained, improving soil quality and land value, as shown in Figure 6.26. Across all the fertiliser input quantities modelled, the land value in 2020 with a 5% discount rate with hydro-priming and lower-bound climate change is more significant than the land value with upper-bound climate change for wheat production from 1960 to 2015. The results in Figure 6.26 support the previous findings that soil productivity is improved with reduced rainfall, and rainfall events are the most significant driver of soil productivity variation. Land value with hydro-priming is higher in the lower-bound climate scenario across all fertiliser input variations. Management scenarios that retain soil carbon and nitrogen improve the soil's productivity are reflected in the present land value in Figure 6.26.

Figure 6.26

Land Value in 2020 With Hydro-Priming, Lower- and Upper-Bound Climate Change and Varied Fertiliser Inputs for Wheat Production 1960–2015



Source: APSIM (2019), MS Excel (2021)

The yield and NPV improvements with historical and upper-bound climate simulations suggest that when NSW DPI fertiliser inputs or an increased quantity of DAP and urea are applied, wheat crops respond favourably. However, hydro-priming is ineffective when predicted rainfall declines or the establishment costs for manual, semi-automated, and automated hydro-priming exceed yield improvements. Hydro-priming is not cost-effective with lower-bound predicted climate change.

6.6 CARBON PRICING FERTILISER EMISSIONS

As discussed in Chapter 5, climate change is driven by increased atmospheric emissions. Fertiliser emits nitrous oxide, which are not included d in emissions reduction policies in Australia. The effect of a carbon price on fertiliser emissions was evaluated to determine the farmer profit-maximising fertiliser input quantity towards reducing atmospheric emissions from agricultural crop production. A range of carbon prices per tonne of carbon dioxide equivalent nitrous oxide emissions were modelled and are presented in Table 6.24. The method for applying the carbon price to nitrous oxide emissions is detailed in Chapter 5, with the results incorporated into the economic NPV analysis. A carbon price on fertiliser nitrous oxide emissions will marginally increase production costs compared to periodic returns generated without a carbon price.

Table 6.24

Carbon Prices per Tonne of CO_2e

Carbon Price (\$/t CO_2e)	Price (\$/t)
European Union average price 2020	70.17
ACCU average price 2020	19.16
New Zealand ETS average price 2020	36.31

Source: CER (2022), World Bank, (2022)

Note. CO_2e = carbon dioxide equivalent; ACCU = Australian carbon credit units; ETS = Emissions Trading Scheme.

The carbon price applied to fertiliser inputs is identical across climate scenarios and management practices. The fertiliser input quantities used in modelling are presented in Table 6.25. These fertiliser quantities were converted into carbon dioxide equivalents using the method outlined in Chapter 5 and applied to the carbon price to determine an annual fertiliser carbon emissions production cost.

Table 6.25

Fertiliser Input Quantities Used in a Single Production Period

Fertiliser	Recommended[a]	–20%	–40%	–60%	20%	40%	60%
Urea (kg/ha)	85	68	51	34	102	119	136
Di-ammonium phosphate (kg/ha)	100	80	60	40	120	140	160

[a] Recommended by The Department of Primary Industries New South Wales.

The annual carbon cost of nitrous oxide emissions per hectare using a range of carbon prices applied to the DAP and urea fertiliser inputs in a production period is presented in Table 6.26. The EU carbon price is the highest because the net carbon price per ton of emissions (see Table 6.24) is more than three times the ACCU carbon price and almost double the New Zealand ETS carbon price per tonne of carbon dioxide equivalent emissions. The alternative carbon prices effect the net carbon price per hectare for wheat production for a fertiliser input quantity, with fertiliser emissions using the EU carbon price the highest of the carbon prices modelled. Despite being the highest, the EU carbon prices range from $0.41–$1.63 per hectare for a single production period. The ACCU carbon price is the lowest, with fertiliser emissions costing between $0.11–$0.44 per hectare per production period. The NZ ETS cost of fertiliser emissions for 1 hectare of wheat produced is $0.21–$0.84 per hectare. Therefore, the marginal cost of emissions using a carbon price may have little effect on farmer fertiliser input decisions.

Table 6.26

Annual Emissions Cost per Hectare for Various Fertiliser Input Quantities With Alternative Carbon Prices

Fertiliser input quantity	EU ($/ha)	ACCU ($/ha)	NZ ETS ($/ha)
+60%	1.63	0.44	0.84
+40%	1.43	0.39	0.74
+20%	1.22	0.33	0.63
Recommended	1.02	0.28	0.53
–20%	0.81	0.22	0.42
–40%	0.61	0.17	0.32
–60%	0.41	0.11	0.21

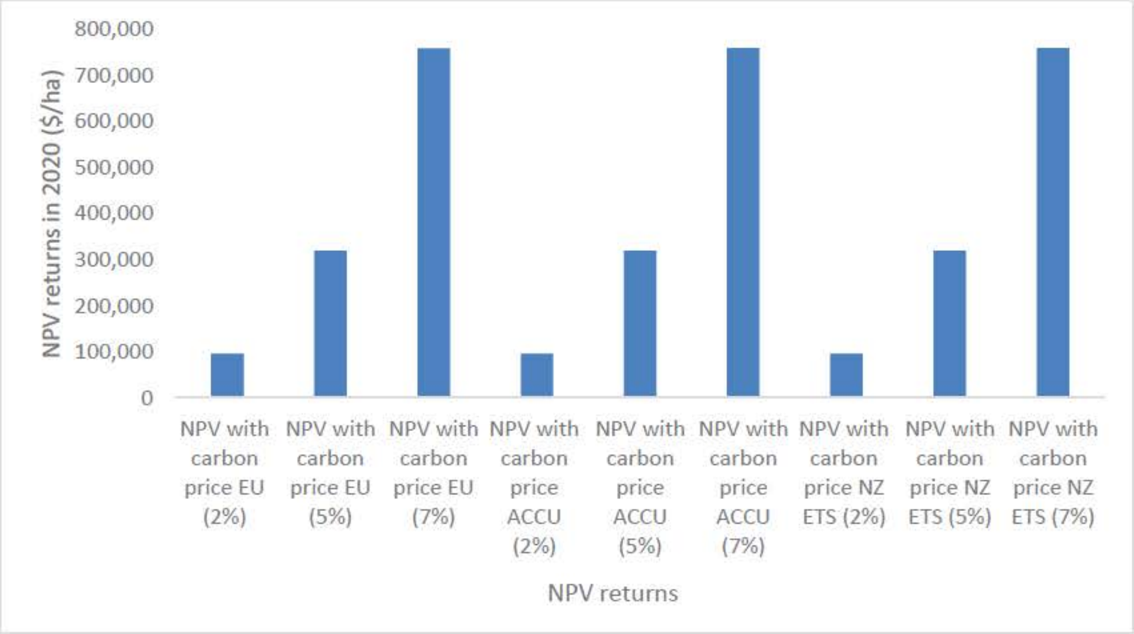
Note. EU = European Union; ACCU = Australian carbon credit units; NZ ETU = New Zealand Emissions Trading Scheme.

6.6.1 NPV Returns with a Carbon Price on Fertiliser Emissions

Using discount rates of 2%, 5% and 7% to compare the effect of the annual emissions costs on the NPV, the current management practices show slight variation across NPV returns with or without a carbon price (see Figure 6.27). Regardless of the carbon price applied, the fertiliser emissions cost is immaterial and does not affect the NPV returns. A carbon price on fertiliser does not change farmer management decisions. Farmers will select the fertiliser input quantity that maximises profits from wheat production.[36]

Figure 6.27

Net Present Value Returns in 2020 for Current Management Practices With a Carbon Price on Annual Fertiliser Emissions from 1960 to 2015 Using Recommended Fertiliser Inputs



Source: APSIM (2019), MS Excel (2021)

6.7 CROP ROTATION

A scenario where wheat crops were interspersed with a leguminous field pea crop was used to investigate the effect of a crop rotation on soil productivity and NPV

---

[36] A range of fertiliser input quantities for historical and predicted climate change were modelled for both hydro-primed and non-primed continuous wheat. The results do not vary and have been excluded for conciseness but are available on request.

returns. Although farmers utilise leguminous crops to reduce pest and disease risk, another benefit from them is their ability to fix atmospheric nitrogen in the soil (see Chapter 5). A crop rotation with wheat, with wheat and field peas planted in ongoing rotations over the modelling period was simulated using historical climate data and the NSW DPI’s (2013) recommended management practices. Wheat crops are planted using the same cultivar and process used in previous simulations. Field peas use the Kaspa cultivar and are planted between mid-April and the end of June, with 100 kg/ha of DAP applied at sowing containing 18 kg/ha of nitrogen. The NSW DPI production costs from field peas inflated to AUD 2020 using the RBA (2023) inflation rate for the period are shown in Table 6.27. Field pea production costs are $548 per/ha, more than double the production cost of wheat. The average 2020 price of $425 per ton for field peas was taken from NSW DPI (2022) cropping pulse price data.

Table 6.27

Crop Rotation Results With New South Wales DPI-Recommended Management Processes for 1960–2015

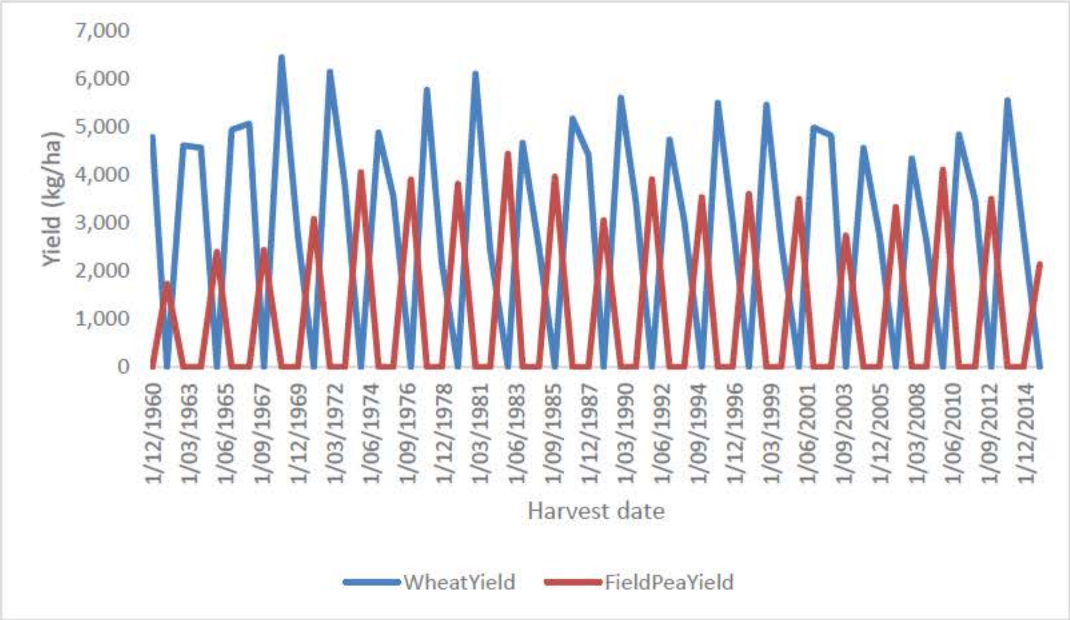
Variable	Wheat	Field pea
Cultivar	Trojan	Kaspa
Sowing time	March–April	Mid-April to end of June
Sowing depth (mm)	70	10
Row spacing (mm)	180	200
Plant population (per 1 m^2)	100	30
N applied (kg/ha)	57	18
Average yield (t/ha)	4.25	3.3
Average protein content (%)	11.90	n/a
Average price 2020 ($/t)[a]	336	426
Production cost ($/ha)[b]	237	548
Average break-even price ($/t)	135	182

[a] Field pea price per ton taken from NSW DPI (2022) Cropping Pulse price data. The average price for 2020 for field peas, excluding June, was used.
[b] Field pea production costs taken from the NSW DPI Winter Crop Budget (2012) and adjusted to $2020 using the RBA (2020) inflation calculator.

Wheat yields are maximised in the season following a field pea rotation (see Figure 6.28). Seasons in which the field pea or wheat yield is nil in Figure 6.28 corresponds to the alternate crop being produced. Figure 6.28 shows a trend towards higher wheat yields in the season following field peas, with the second season after field peas lower, visible in 1974–1975, 1986–1987 and 2002–2003. The seasons with the highest increases in wheat yield were 1969, 1971, 1977 and 1980. The benefits from field peas are not sustained over multiple seasons but allow for a temporary improvement in the wheat yield.

Figure 6.28

Wheat and Field Pea Yields 1960–2015 (kg/ha) With Historical Climate Data and New South Wales DPI-Recommended Fertiliser Inputs



Source: APSIM (2019), MS Excel (2021)

Although field pea yields are variable over the modelling period, the 1976 yield was 3.9 t/ha despite rainfall well below the long-run average in April, May, and June 1976 (BOM, 2020). In 1982, despite drought conditions in the Wagga Wagga region, as discussed in Section 6.1, field peas generated a 4.4 t/ha yield. In 1991 and 2012, floods were recorded in Wagga Wagga (Anon., 2023) and during these seasons, field peas achieved yields of 3.9 t/ha and 3.5 t/ha, respectively. Hence, it appears that field peas are less responsive to rainfall variation than wheat crops.

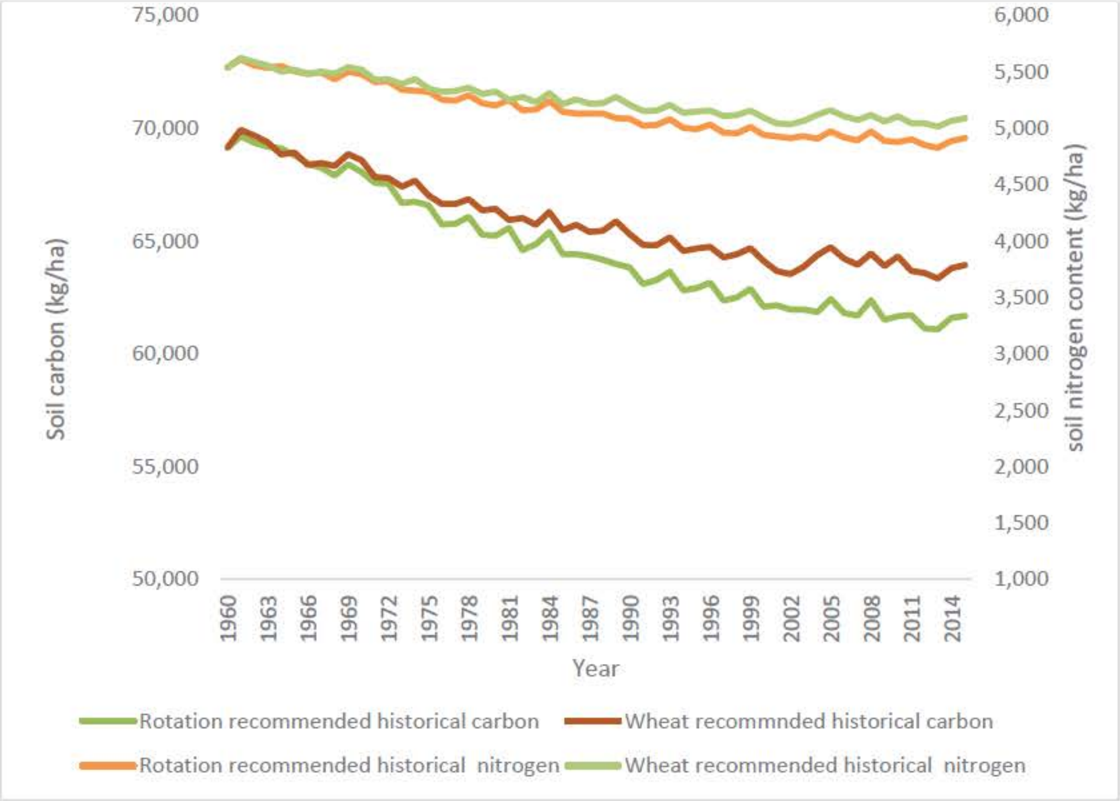
Figure 6.28 shows that high wheat yields occurred in 1968, 1971, 1977, 1980, 1989, 1995 and 1998. Over the modelling period, wheat yields were maximised in 1968 with 6.4 t/ha, following a field pea yield of 2.4 t/ha, which is below average for the simulation. Rainfall in 1968 was significantly below the long-term average over the wheat growth period (BOM, 2020). In 1976 and 1979, the field pea yield was 3.8–3.9 t/ha, with above-average rainfall in June, July, and October in both years. In 1970 and 1988, field pea yields were 3 t/ha, with wheat yields 6 t/ha and 5.6 t/ha, respectively, with above-average rainfall from March to July in 1970 and July in 1988. There is no strong link between rainfall, field pea yield quantity, and subsequent wheat yields.

There is a link between rainfall and soil carbon and nitrogen content, as identified in Sections 6.1 and 6.4. With a crop rotation using historical climate data and recommended inputs, soil carbon and nitrogen declined between 1961 and 1966 (see Figure 6.29). Continuous wheat soil carbon and nitrogen increased between 1968 and 1970 by 1.1%. In the rotation simulation for the same period, soil carbon and nitrogen increased by 0.8%. From 1973 onwards, continuous wheat soil carbon and nitrogen content diverges from the rotation simulation with more variation in rotation soil carbon and nitrogen content than for continuous wheat (see Figure 6.29).

In 1973, field peas achieved 4 t/ha, despite below-average rainfall over the production season every month except August 1973. In 1989, rainfall was below average for the entire production period except for May and July 1989, while in 1974, all months except May in the production period March–December received above average rainfall. Wheat was grown in both simulations with above-average rainfall during June–December 1974. In 1974, continuous wheat soil carbon and nitrogen increased by 0.8% while decreasing by 0.1% with the crop rotation simulation (see Figure 6.29). Between 1988 and 1989, continuous wheat had a 1% increase in soil carbon and nitrogen, while crop rotation carbon and nitrogen declined by 0.8%. In 1974 and 1989, wheat was grown in both simulations; continuous wheat production retains more nitrogen and carbon in the soil with seasonal rainfall variation compared to simulations with field peas grown in rotation with double wheat.

Figure 6.29

Soil Carbon and Nitrogen Content 1960–2015 for Crop Rotation and Wheat Production Scenarios with New South Wales Department of Primary Industries-Recommended Fertiliser Inputs and Historical Climate Data



Source: APSIM (2019), MS Excel (2021)

The periodic change in soil carbon and nitrogen with an iterative crop rotation of wheat, wheat and field peas results in a net decline in soil carbon, nitrogen compared to continuous wheat and, therefore, soil productivity (see Table 6.28). Soil carbon decreases by 10.8%, soil nitrogen by 11.3%, and productivity by 9.1% when using recommended fertiliser inputs with a crop rotation. While with continuous wheat, soil carbon decreases by 7.5%, soil carbon by 8.1%, and soil productivity by 5.6%. Compared to continuous wheat, this relative decline for crop rotation soil carbon is consistent across fertiliser inputs. With a 60% reduction in fertiliser, the difference between the crop rotation, soil carbon change, and continuous wheat is 0.1% increasing to a 4.2% difference with a 60% increase in fertiliser inputs. This pattern is replicated with soil nitrogen, with a 60% increase in fertiliser inputs generating a 4.2% increase in soil nitrogen with continuous wheat compared to the crop rotation soil nitrogen content change. However, with a 60% decrease in soil nitrogen, crop rotation has a loss of 17.2% compared to continuous wheat, which decreases by 17.3%. Crop rotations of wheat, wheat and field peas decrease soil productivity by more than continuous wheat production over the modelling period.

The decline in soil carbon and nitrogen with a crop rotation of double wheat and field peas compared to continuous wheat validates the soil productivity variable described in Chapter 4. Retaining soil nitrogen requires soil carbon inputs from the previous season’s carbon-rich crop stubble, which is left in situ and decomposes, entering the soil in the subsequent crop production period. Brown et al. (1985) found that continuous wheat production with stubble retained in situ reduced run-off compared to peas in the Palouse region of the United States of America because of the higher volume of wheat stubble than field pea stubble. This finding provides insight into the soil productivity losses over the modelling period in all crop rotations compared to continuous wheat in Table 6.28. It suggests that the higher wheat stubble volume is critical in retaining soil nitrogen and productivity.

Table 6.28

Comparison of Crop Rotation and Wheat Production Soil and Crop Statistics Using Historical Climate Data and New South Wales Department of Primary Industries -Recommended Fertiliser Inputs

Scenario and rotation fertiliser input quantity	Soil change (%)			Average				Gross margin *SD* ($/ha)	Wheat fertiliser input quantity	Soil change (%)			Averages for wheat			Gross margin *SD* ($/ha)
	Carbon	Nitrogen	Productivity	Wheat yield (t/ha)	Field pea yield (t/ha)	Wheat protein content (%)	Crop NUE			Carbon	Nitrogen	Productivity	Yield (t/ha)	Protein content (%)	NUE	
+60% historical	–7.3	–8.0	–5.4	6.12	5.26	12.3	10.5	385	+60% historical	–3.0	–3.9	–0.9	5.71	12.9	11.7	546
+40% historical	–8.1	–8.8	–6.3	5.59	4.75	12.0	8.0	372	+40% historical	–4.3	–5.1	–2.2	5.26	12.5	8.1	512
+20% historical	–9.1	–9.8	–7.4	5.02	4.14	11.7	8.1	349	+20% historical	–5.7	–6.4	–3.6	4.69	12.2	7.3	467
Rec. historical	–10.8	–11.3	–9.1	4.25	3.33	11.3	7.9	314	Rec. historical	–7.5	–8.1	–5.6	4.08	11.9	6.5	459
–20% historical	–11.2	–11.7	–9.5	4.13	3.33	11.3	9.6	311	–20% historical	–8.0	–8.6	–6.1	3.98	11.9	7.7	384
–40% historical	–14.1	–14.5	–12.6	3.08	2.29	10.9	9.1	236	–40% historical	–12.9	–13.4	–11.4	2.84	11.4	4 9	206
–60% historical	–16.8	–17.2	–15.7	2.44	1.78	10.8	10.6	186	–60% historical	–16.7	–17.3	–15.8	2.19	11.2	4.3	149
Nil historical	–23.6	–24.0	–23.1	1.01	0.62	10.2	0.0	114	Nil historical	–23.5	–23.9	–23.0	0.89	10.2	0.0	93

Note. NUE = nitrogen use efficiency; Rec. = recommended fertiliser input quantity.

Simulations of rotating double wheat production with field peas increase wheat yields in the season after field peas are grown. Heenan (1995) similarly found that wheat yields increased in seasons after growing field peas. Field peas have an average annual yield of 3.3 t/ha (see Figure 6.28) with a break-even price of $182/ton. Including field peas in rotation with wheat grown with current management practices and NSW DPI-recommended fertiliser inputs increases wheat yields by 4% and reduces the break-even price of wheat by $8 or 5.6%. Comparing the improvement in wheat yields when rotated with field peas, wheat yields increased by 3.6% when grown in rotation compared to continuous hydro-primed wheat yields with identical climate and fertiliser inputs. The break-even price with wheat grown in a crop rotation was 11% lower than the continuous wheat hydro-priming break-even price (see Table 6.19). Therefore, integrating field peas into the production system increases average wheat yields compared to continuous wheat with current hydro-priming management practices.

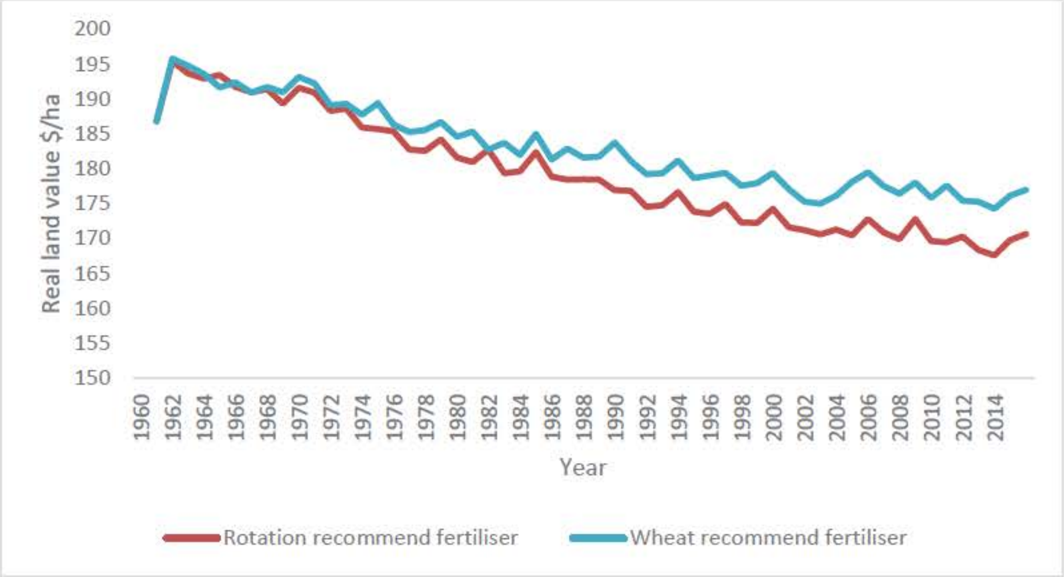
The decrease in soil productivity with crop rotations compared to continuous wheat simulated with historical climate data effected crop yields. When fertiliser inputs are increased, wheat yields increase more in crop rotation simulations than continuous wheat yields. Increasing wheat yields were correlated with declining wheat grain NUE in Section 6.2. Similarly, with increasing wheat yields with crop rotation, wheat grain NUE content is generally lower than wheat grain NUE content with continuous wheat production. With a 40% or 60% increase in fertiliser inputs, wheat NUE grain content decreases by 0.1% and 1.2% with crop rotations compared to continuous wheat. Across other fertiliser inputs, there is an increase between 0.8% and 6.3% in wheat grain NUE content with crop rotation production compared to continuous wheat. The most significant increase in grain NUE content occurs when fertiliser inputs decline by 60%, which is consistent with expectations. Field peas fix atmospheric nitrogen in the soil, mitigating the reduction in fertiliser inputs. Wheat yields and grain NUE are higher with crop rotations than continuous wheat across fertiliser input quantities modelled. Despite reduced soil productivity, the crop rotation simulation increases wheat yields and can increase grain NUE with some fertiliser input quantities.

The grain protein content is a critical determinant of wheat revenue, influenced by soil nitrogen availability. The grain protein content decreases by 0.4%–0.6% with crop rotations, depending on the fertiliser input quantity. Varying wheat prices according to grain protein quality was not considered however, the decline in wheat grain protein content will not negatively affect the grain price received if the recommended rate or an increase in fertiliser inputs occurs. Field pea NUE and legume protein content are unavailable in the APSIM version used for simulations. Therefore, whether variation in fertiliser inputs effects field pea protein content is unknown nevertheless, increasing fertiliser increases wheat grain protein and soil productivity.

The effect of soil carbon, nitrogen and soil productivity periodic variation on land value is illustrated in Figure 6.30. These findings are consistent with the results in Figure 6.29 and Table 6.28. Using a discount rate of 5%, real land value declines over the modelling period. The variations in land value are consistent with the soil carbon and nitrogen changes. Excluding any pest or disease effects on soil and crop productivity, with the associated effects on land value, crop rotations with historical data and recommended fertiliser inputs reduce land value compared to land utilised for continuous wheat production over the modelling period.

Figure 6.30

Real Land Value 1960–2015 (where 1960 =100) for Crop Rotation and Wheat Production With New South Wales DPI-Recommended Fertiliser Inputs and Historical Climate Data,



Source: APSIM (2019), MS Excel (2021)

When simulated with historical climate data, the NPV returns for crop rotations increase compared to continuous wheat (see Table 6.29). These results are consistent with Chan and Heenan's (1999) findings that wheat, wheat and field pea rotations in southern NSW improved farmer profits from land use. Across all discount rates and fertiliser input quantities with the crop rotations simulations, NPV returns in 2020 increased by 4%–13% compared to continuous wheat. Another benefit is that the field peas decrease the variance in gross margin returns, with decreased standard deviation across all fertiliser inputs. The most significant improvements in NPV returns were realised when fertiliser inputs were increased by 60%. The smallest increases in land use profits occurred with recommended fertiliser inputs or a 20% decline in fertiliser inputs. Concurrently, the break-even prices declined by 7%–17% with crop rotation simulations compared to continuous wheat production. When no fertiliser is applied, the average break-even price decreases by 38% with a crop rotation compared to continuous wheat. Introducing a leguminous crop increases wheat yields, decreases break-even prices and increases NPV returns compared to continuous wheat results.

Sensitivity testing of the crop rotation results was undertaken, varying production costs and crop prices. It was found that because wheat is the dominant crop in both production processes, any variation effects NPV returns and break-even prices for both production processes, consistent with the results presented in Section 6.1. For brevity, the results presented have been restricted to a sensitivity analysis using discount rate variation, which found that the results were as expected and robust across all production processes, fertiliser input quantities and discount rates.[37] The effect of field pea rotations on soil productivity was unexpected because it was anticipated that soil nitrogen would increase. However, as identified earlier, soil nitrogen retention is driven by soil carbon content, which declined with crop rotation production processes. Crop rotations increase land use returns but decrease soil productivity and land value over the modelling period. Periodic real land value changes with crop rotations are minor and not considered in land management decisions.

---

[37] Results are available upon request.

Table 6.29

Comparison of Break-Even Prices and 2020 Net Present Value for Crop Rotation and Wheat Production 1960–2015 With New South Wales DPI-Recommended Fertiliser Inputs and Historical Climate Data

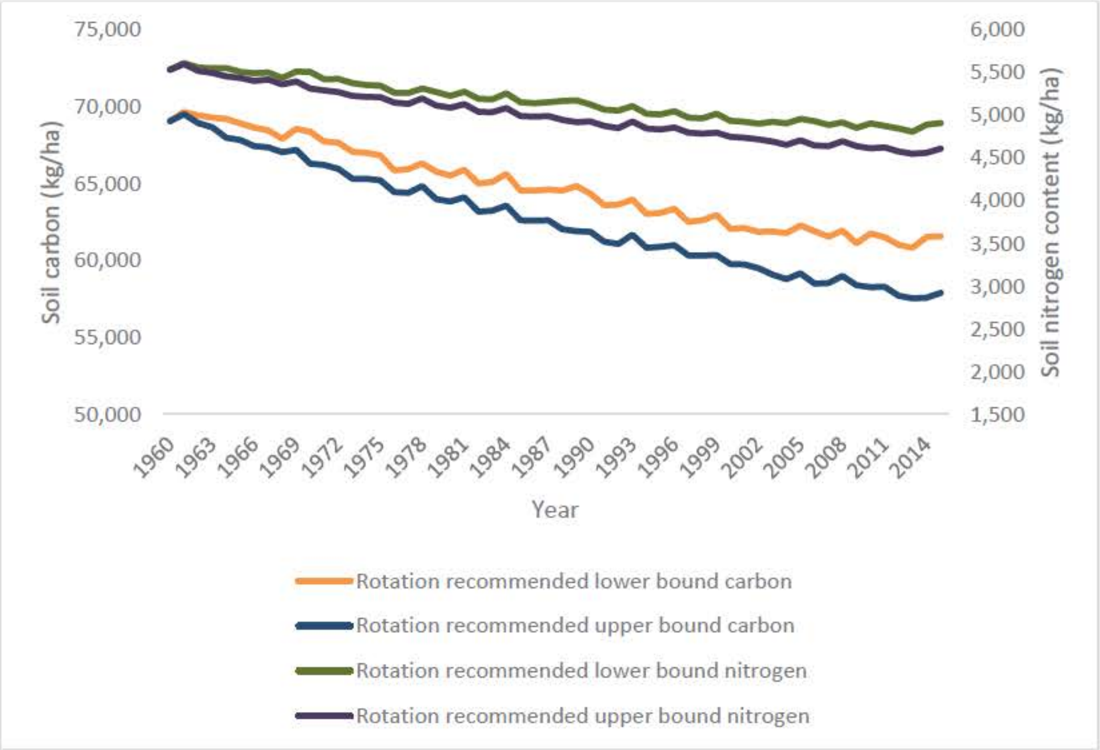
Scenario and rotation fertiliser input quantity	Rotation net present value			Average break-even price ($/t)	Scenario and wheat fertiliser input quantity	Wheat net present value			Average break-even price ($/t)
	2%	5%	7%			2%	5%	7%	
+60% historical	169,677	562,080	1,323,785	122	+60% historical	144,211	479,059	1,133,573	124
+40% historical	152,047	501,904	1,181,235	129	+40% historical	129,825	431,618	1,022,227	130
+20% historical	133,481	437,672	1,026,984	136	+20% historical	113,450	378,877	899,763	136
Recommended historical	112,303	366,921	859,456	150	Recommended historical	95,872	319,914	759,509	143
–20% historical	88,845	290,867	681,761	149	–20% historical	107,293	358,902	852,902	143
–40% historical	66,537	220,240	519,105	181	–40% historical	59,090	201,544	483,593	163
–60% historical	42,830	145,764	348,131	209	–60% historical	40,146	141,105	343,315	187
Nil historical	-2,429	2,044	16,766	442	Nil historical	-4,281	-1,051	13,755	349

6.7.1 The Impact of Predicted Climate Change on Crop Rotation Production with Existing Management Practices

The predicted lower and upper-bound climate change applied to the crop rotation simulations soil carbon and nitrogen are shown in Figure 6.31. Lower-bound soil carbon and nitrogen content are higher than upper-bound content, consistent with the continuous wheat results presented in Section 6.4. Upper-bound soil carbon and nitrogen decline more than the lower-bound due to increased precipitation and higher temperatures. The higher temperatures and soil moisture increases the rate of carbon dioxide and nitrogen mineralisation emissions from soils. As expected, soil carbon and nitrogen declined over the modelling period, with a sharp decline in soil carbon in 1976 associated with above-average rainfall in July and August 1976. There was a more significant increase in soil carbon between 1968 and 1969 with lower-bound climate change than upper-bound simulation results, consistent with continuous wheat results in Section 6.3 and crop rotation results with historical climate data in Section 6.7. Rainfall variation is a crucial determinant of soil carbon variation, driving soil nitrogen variation.

Figure 6.31

Soil Carbon and Nitrogen Content 1960–2015 With Double Wheat and Field Pea Rotation and New South Wales Department of Primary Industries-Recommended Fertiliser Inputs with Lower- and Upper-Bound Climate Simulations



Source: APSIM (2019), MS Excel (2021)

As identified previously, soil carbon is a critical driver of soil nitrogen retention. Figure 6.31 shows a 1% increase in soil carbon between 1983 and 1984, generating an 0.7% increase in soil nitrogen. In 1984–1985, with upper-bound climate change, there was a decrease in soil carbon of 1.5%, with a 1.8% decline in soil nitrogen over the same period. Between 1993 and 1994, with lower-bound climate change, there was a 1.4% reduction in soil carbon and a 1.6% decline in soil nitrogen over the same period. The exponential relationship between soil carbon and nitrogen described in Chapter 4 is captured in the APSIM simulation results in Figure 6.31, validating the soil productivity variable developed in Chapter 4.

The effect of soil carbon, nitrogen and soil productivity variation is reflected in the land values presented in Figure 6.32 and Figure 6.33. Soil productivity and land value benefits are associated with continuous wheat production with lower-bound climate change, with land values with recommended fertiliser inputs diverging by $10 in 2015 from crop rotation with identical fertiliser inputs in Figure 6.32.[38] The pattern with upper-bound climate change in Figure 6.33 is less readily identifiable. Both crop rotation and continuous wheat have similar variations in soil productivity content, suggesting that variation in land value is driven by fertiliser input variation. This finding suggests that with increased precipitation and temperature, any benefits from increased wheat stubble are nullified, potentially through increased conversion of soil carbon into carbon dioxide. The results in Figure 6.33 support the previous findings that soil carbon and, therefore, soil productivity changes are linked to climatic variation. With upper-bound climate change, land use management decisions to vary fertiliser inputs to retain soil productivity are the key driver of soil productivity and land value.

Figure 6.32

Real Land Value 1960–2015 (where 1960 =100) Comparison Between Wheat and Crop Rotation With Lower-Bound Climate Simulations With Varied Fertiliser Inputs in $1960

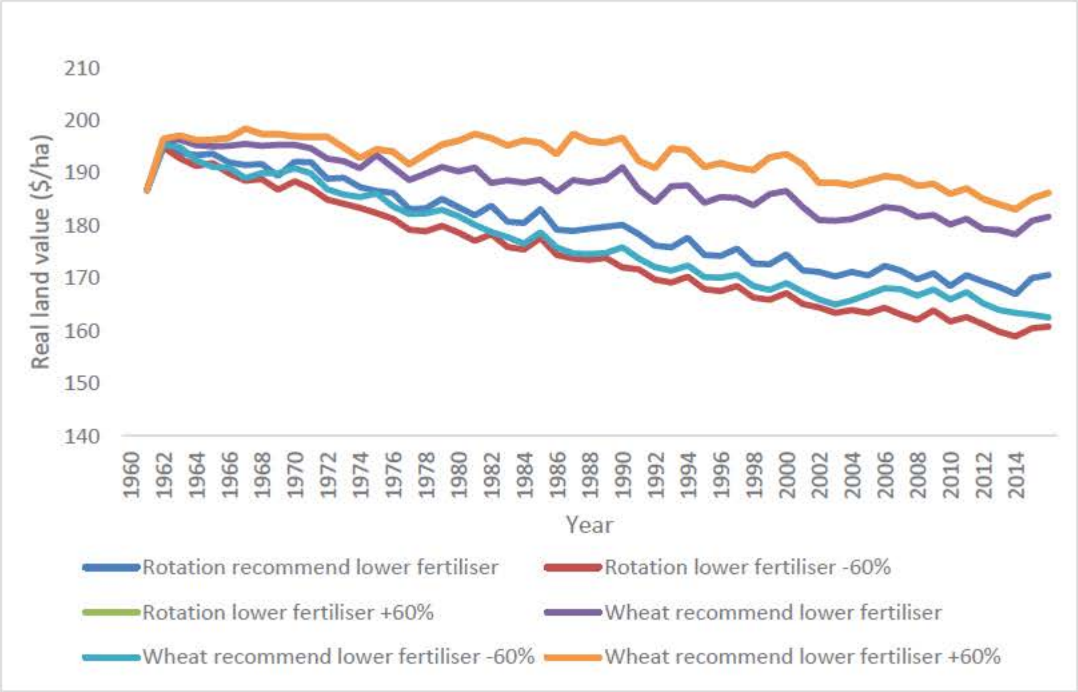
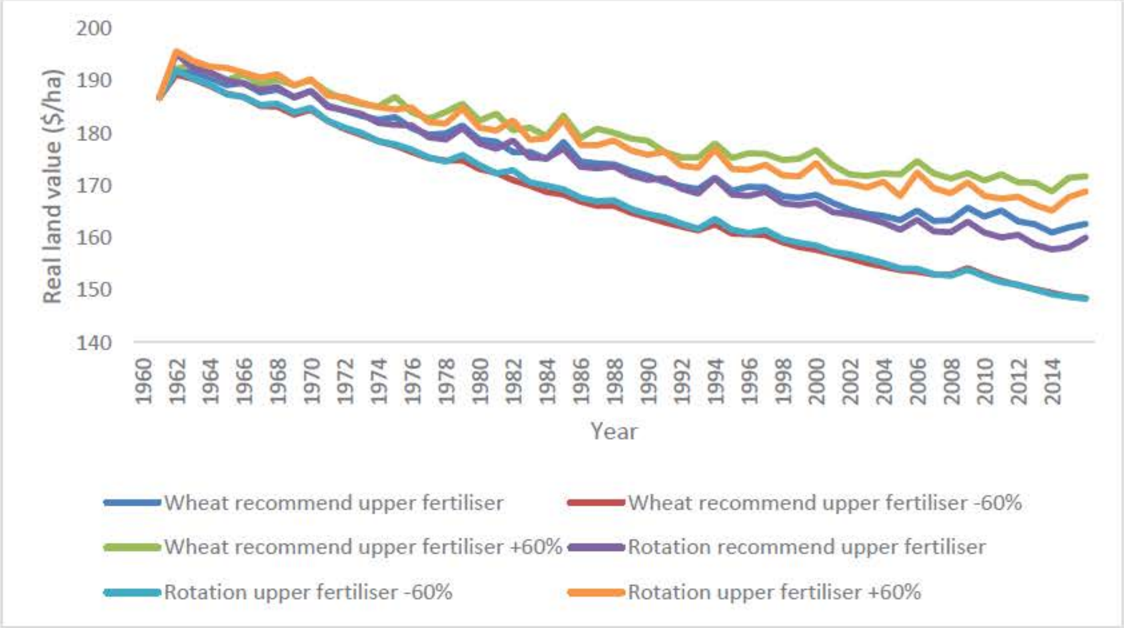


Figure 6.33

Real Land Value 1960–2015 (where 1960 =100) Comparison Between Wheat and Crop Rotation With Upper-Bound Climate Simulations With Varied Fertiliser Inputs in $1960



With predicted climate change, the NPV returns from land use with crop rotations are higher than continuous wheat regardless of the predicted climate change scenario and fertiliser input quantity (see Table 6.30). Crop rotations increase the NPV returns between 0.5% and 744% with upper-bound climate change compared to continuous wheat across discount rates modelled. Excluding a 60% reduction in fertiliser, NPV returns increase by 0.5%–9%; a 60% decrease in fertiliser field pea nitrogen fixation increases soil nitrogen. Lower-bound climate change crop rotation simulations increase NPV returns by 3%–39%, with the largest improvements in NPV returns occurring with a 60% increase in fertiliser. Across both predicted climate change simulations, increasing fertiliser inputs by 60% with the crop rotation simulation maximises land use NPV returns.

Table 6.30

Comparison of 2020 Net Present Value Returns From Land Use 1960–2015 With Crop Rotations to Continuous Wheat With Existing Management Practices

Fertiliser input quantity	Rotation net present value ($/ha)			Wheat net present value ($/ha)		
	2%	5%	7%	2%	5%	7%
+60% upper	157,648	517,497	1,220,786	145,850	484,246	1,148,738
+60% lower	148,133	485,113	1,139,357	109,371	369,588	881,053
+20% upper	121,702	399,390	941,154	114,692	381,361	906,020
+20% lower	120,143	391,694	917,284	94,628	313,665	740,614
Recommended upper	97,957	323,504	764,913	98,187	328,182	781,952
Recommended lower	98,127	321,200	753,738	83,366	274,813	647,364
–20% upper	96,428	318,469	753,186	95,904	320,860	764,969
–20% lower	84,584	278,594	655,567	82,320	271,556	639,906
–60% upper	42,194	146,371	355,016	40,966	143,591	349,960
–60% lower	42,839	145,830	348,349	39,211	133,620	318,835
Nil upper	355	12,682	43,871	2,467	19,161	58,701
Nil lower	1,637	13,277	39,865	4,219	23,795	67,777

6.8 CROP ROTATION WITH HYDRO-PRIMED WHEAT

Using field peas grown in rotation with hydro-primed wheat, APSIM was calibrated using the field pea processes described in Section 5.10 and the process for wheat hydro-priming using the automated priming process described in Section 5.8. Wheat yields increase in the hydro-primed crop rotation simulation by 1%–9% compared to crop rotations using current management practices. The largest yield improvements occur in the simulations where no fertiliser is applied, as shown in Table 6.31. The smallest yield increases for wheat in the hydro-primed crop rotation simulation occur when fertiliser inputs are increased by 60%. This finding confirms previous results in Section 6.5 that a positive relationship exists between wheat hydro-primed with fertiliser and realised yields. Despite field peas not being hydro-primed and the production processes identical in both simulations, field pea yields increase in the hydro-priming crop rotation by 1%–6% when fertiliser inputs are used. The largest increase in field pea yields occurs with a 20% increase in fertiliser inputs and the smallest with a 60% reduction. When no fertiliser is applied, field pea yields decline by 3% in the hydro-priming management treatment scenario compares to non-primed rotations without fertiliser. Field peas benefit from hydro-primed wheat when fertiliser inputs are used *certeris paribus.*

Using hydro-primed wheat seeds in crop rotation simulations with historical climate data and varied fertiliser inputs increases the NPV returns. The NPV returns in the hydro-priming crop rotation scenario increase by 10%–14% compared to hydro-priming crop rotations when fertiliser is applied as recommended or increased. Comparing the primed to non-primed crop rotations, when the recommended fertiliser input quantity is applied, or fertiliser inputs are increased, the hydro-primed crop rotation NPV returns exceed non-primed crop rotations. However, with reduced fertiliser inputs, the non-primed rotation generates higher returns. Compared to non-primed wheat rotations, there is an increased variance in gross margin returns with hydro-primed rotations. Wheat yields increase with hydro-priming in the production period following field peas. When comparing crop rotations with hydro-primed wheat to crop rotations with current management practices using historical climate data, the profit-maximising decision is to utilise hydro-primed wheat and increase fertiliser inputs for both crops by 60%.

Table 6.31

Wheat Hydro-Priming Within the Crop Rotation Net Present Value and Break-Even Prices, 1960–2015, Compared to Current Management Practices Crop Rotation With Historical Climate Data in $2020

Hydro rotation fertiliser input quantity and climate scenario	Net present value automated			Average yield (t/ha)		Scenario and rotation fertiliser input quantity	Rotation net present value			Average yield (t/ha)	
	2%	5%	7%	Wheat	Field pea		2%	5%	7%	Wheat	Field pea
+60% historical	169,677	562,080	1,323,785	6.2	5.5	+60% historical	160,683	531,769	1,257,279	6.12	5.26
+20% historical	133,481	437,672	1,026,984	5.2	4.4	+20% historical	123,736	406,096	954,976	5.02	4.14
Hydro rotation recommended historical	112,303	366,921	859,456	4.4	3.5	Rotation recommended historical	98,244	323,215	760,654	4.25	3.33
–20% historical	88,845	290,867	681,761	4.3	3.5	–20% historical	96,837	318,904	750,884	4.13	3.33
–60% historical	42,830	145,764	348,131	2.5	1.8	–60% historical	43,014	146,644	351,398	2.44	1.78
Hydro rotation nil fertiliser historical	-2,429	2,044	16,766	1.1	0.6	Rotation nil fertiliser historical	202	11,613	40,618	1.01	0.62

Soil productivity increases by 1.2%–6% with crop rotations using hydro-primed seeds compared to crop rotations with current management practices or continuous hydro-primed wheat. The most significant improvement in soil productivity occurs with crop rotation simulations with the recommended fertiliser inputs. Hydro-priming wheat increases soil productivity by 6%, with a 5.4% improvement in soil carbon and a 5.3% improvement in soil nitrogen compared to current management practices in crop rotations. The smallest improvement occurs when comparing continuous hydro-primed wheat to hydro-primed crop rotations. Field peas generate co-benefits through nitrogen fixation in the soil, and hydro-primed wheat improves soil productivity.

The wheat grain protein content increases compared to crop rotations with current management practices and continuous hydro-primed wheat across fertiliser inputs used except for no fertiliser, where wheat grain protein content is identical in both simulations. Wheat grain protein content increases by 0.1%–0.5% in continuous hydro-primed wheat compared to hydro-primed rotations. As discussed in Section 6.5, there are improvements in grain protein content with hydro-priming compared to current management practices between 0.4% and 0.6% (these results are replicated in Table 6.32). The wheat grain protein content must have marginal variation for wheat to be classed as Australian Hard wheat and that requires fertiliser inputs at the recommended rate or higher. Reducing fertiliser inputs below the recommended rate will downgrade the wheat protein quality and the price farmers receive. Farmers can increase wheat grain protein content by hydro-priming wheat seeds before planting.

Contrary to results in Section 6.5, the NUE decreases as fertiliser inputs increase in hydro-primed wheat grain (see Table 6.32). With continuous hydro-primed wheat, there is a positive correlation between fertiliser inputs and wheat grain NUE. With hydro-primed wheat in crop rotations, there is a negative correlation between wheat grain NUE and fertiliser input quantity. The reasons for this are uncertain but may be related to average crop yield. Crop rotations with hydro-priming management practices have the highest wheat grain NUE, suggesting that a further positive externality of crop rotations is field pea nitrogen fixation increasing wheat grain NUE.

With predicted climate change, hydro-primed wheat and field pea crop rotations generate higher NPV returns than non-primed or continuous wheat rotations. The results in Table 6.33 validate the findings with historical climate data. Hydro-primed wheat increases soil productivity compared to non-primed rotations and continuous wheat. The variance in annual returns increases for lower- and upper-bound climate changes with hydro-primed crop rotations. Hydro-primed crop rotation variance more than doubles the variable with continuous wheat using current management practices. However, hydro-primed continuous wheat improves soil productivity more than hydro-primed rotations. The results add robustness to the findings that hydro-priming wheat seeds reduces climate risks and improves farmer NPV returns despite an increased variance in gross margin returns.

Table 6.32

Comparison of Hydro-Priming With Non-primed and Wheat Soil Statistics and Wheat Quality 1960–2015 With Historical Climate Data and Varied Fertiliser Inputs

Hydro rotation fertiliser input quantity and scenario	Soil change (%)			Average		Scenario and rotation fertiliser input quantity	Soil change (%)			Average		Hydro wheat fertiliser input quantity	Soil change (%)			Average	
	Carbon	Nitrogen	Productivity	Wheat protein content (%)	Wheat NUE (%)		Carbon	Nitrogen	Productivity	Wheat protein content (%)	Crop NUE		Carbon	Nitrogen	Productivity	Wheat protein content (%)	Wheat NUE
+60% historical	–2.0	–2.9	0.3	12.6	7.60	+60% historical	–7.30	–8.00	–5.40	12.3	10.5	+60% historical	–3.0	–3.9	–0.9	12.9	11.7
+20% historical	–3.8	–4.5	–1.5	11.8	8.51	+20% historical	–9.10	–9.80	–7.40	11.7	8.1	+20% historical	–5.7	–6.4	–3.6	12.2	8.1
Hydro rotation rec. historical	–5.4	–6.0	–3.1	11.4	8.31	Rotation rec. historical	–10.80	–11.30	–9.10	11.3	7.9	Hydro wheat rec. historical	–7.5	–8.1	–5.6	11.9	7.3
–20% historical	–5.9	–6.4	–3.6	11.4	9.47	–20% historical	–11.20	–11.70	–9.50	11.3	9.6	–20% historical	–8.0	–8.6	–6.1	11.9	6.5
–60% historical	–13.2	–13.7	–11.7	10.7	10.04	–60% historical	–16.80	–17.20	–15.70	10.8	10.6	–60% historical	–16.7	–17.3	–15.8	11.2	4 9
Hydro rotation nil fertiliser historical	–21.8	–22.2	–21.2	10.2	0.00	Rotation nil fertiliser historical	–23.60	–24.00	–23.10	10.2	0	Hydro wheat nil fertiliser historical	–23.5	–23.9	–23.0	10.2	4.3

Note. Modelling was undertaken for historical and predicted lower and upper-bound climate change. The results for the climate change simulations are consistent these results and have been omitted for conciseness. Rec. = recommended.

Table 6.33

Crop Rotation (1960–2015) With Hydro-Primed Wheat Using Predicted Climate Change and Fertiliser Input Variation in $2020

Fertiliser input quantity and climate scenario	Net present value			Soil change (%)			Average crop yield (t/ha)	Gross margin *SD* ($/ha)
	2%	5%	7%	Carbon	Nitrogen	Productivity		
+60% high	164,811	547,942	1,294,636	1.2%	–0.4%	3.0%	6.0	742
+60% low	167,788	554,703	1,306,554	2.7%	1.2%	4.8%	6.0	769
+20% high	131,464	434,201	1,022,913	–1.6%	–2.8%	0.3%	5.0	635
+20% low	165,957	546,359	1,285,674	–0.2%	–1.3%	2.0%	5.0	749
Recommended high	111,788	368,333	866,760	–4.1%	–5.2%	–2.3%	4.4	535
Recommended low	111,524	365,620	857,880	–2.6%	–3.6%	–0.5%	4.4	538
–20% high	109,076	359,716	847,079	–4.9%	–5.9%	–3.1%	4.3	512
–20% low	89,854	295,047	693,034	–5.7%	–6.7%	–4.0%	3.8	413
–60% high	45,367	154,222	368,245	–15.4%	–16.4%	–14.7%	2.5	199
–60% low	44,313	149,680	356,495	–14.5%	–15.4%	–13.6%	2.4	203
Nil fertiliser high	-269	9,148	33,545	–22.7%	–23.3%	–22.4%	1.0	84
Nil fertiliser low	-1,535	4,723	22,767	–22.3%	–22.9%	–21.9%	1.0	83

6.9 SUMMARY

The stability of the farming system has been a critical research area recently, with biophysical studies focusing on reducing the environmental effect of land management practices, including fertiliser input quantities. When fertiliser inputs increase, the soil carbon, nitrogen, and productivity increase. This study supports Hunt’s (2021) biophysical findings that higher fertiliser application quantities increase soil nitrogen content, crop yields, and farmers’ NPV returns from crop production land use. Furthermore, maintaining a consistent fertiliser application regime regardless of climatic conditions reduces crop exposure to climatic shocks.

Adverse soil productivity shocks decrease significantly with higher fertiliser application quantities.

The potential effect of a carbon price on fertiliser emissions was found to be ineffective. The effect on NPV returns from wheat production with a carbon price on emissions was marginal. As fertiliser emissions significantly contribute to greenhouse gas emissions, identifying methods to reduce fertiliser emissions from crop production is a key research theme globally. Placing a carbon price on fertiliser emissions is ineffective; further investigation of alternative methods to improve fertiliser efficiency is required.

A method of evaluating the effect of agricultural land management practices on soil quality and land value was developed in this study, with the results robust across a range of climatic conditions. The soil productivity index developed using soil carbon and nitrogen variation identified periods in which adverse soil productivity shocks occurred. The soil productivity index is an important contribution to agricultural land use analysis and enables the incorporation of biophysical data within an economic model.

The soil productivity index applied to periodic land value to evaluate the effect of land management practices can be utilised with empirical or simulated data and is a robust new alternative method to valuing the effect of management processes on land value. Land value has used empirical or survey data to elicit agricultural land values (Berazneva et al., 2019; Goodwin et al., 2003). An important outcome of this study was the development of an alternative method that farmers can utilise to evaluate management decisions’ short- or long-run effect on soil productivity, crop yields, and subsequent land value.

The land value developed in this study is time-invariant. It can be utilised with simulation data or field study soil carbon and nitrogen data, bridging the gap between economic and biophysical agricultural research. The soil productivity land value variable was robust across all management treatments and simulated climatic conditions, demonstrating why soil carbon is critical for crop productivity. This development addressed a fundamental gap in the literature.

The results generated with APSIM simulations across climate simulations using existing management practices are consistent with those derived by Kandulu et al. (2012). These researchers simulated the effect of climate change to evaluate its effect on crop production in South Australia, calibrating climate modelling using statistical downscaling to determine the range of land uses to diversify climate change risks to dryland crop producers. This study ignored alternative land uses and focused on methods to reduce climate risk within wheat production and a crop rotation system. Dryland crop production in Australia is currently exposed to climate risk, with variable precipitation and temperature adversely effecting land use returns. Climate change is predicted to exacerbate this. Therefore, investigating methods to mitigate the effect of climate change and maintain crop yields is a key research area. The hydro-priming management technique is a novel process that adds to the literature by providing a method to improve wheat yields and reduces climate risk within current production system processes. Whilst hydro-priming increases NPV returns it exacerbates gross margin variance with favourable seasonal climatic conditions strongly increasing gross margins.

The novel, low-technology management technique of hydro-priming improves crop yields in low-rainfall dryland crop-producing regions. This study adds to a vast body of literature by identifying and evaluating a simple management practice that farmers can implement regardless of capital endowments. This contribution is a significant development as crop producers on dryland, low-rainfall soils are heavily exposed to production risks (Kingwell, 2011). Hydro-priming improves farmers' technical efficiency and is more profitable than current wheat production processes when implemented in a continuous wheat land use system. However, when implemented within a crop rotation system, capital expenditure on hydro-priming equipment outweighs any increase in the wheat production land use profits.

Hydro-priming can mitigate some of the climatic production risks farmers face. Climate production risk is one of the biggest challenges facing low-rainfall dryland crop producers; hydro-priming seeds increases crop yields when below- and above-average rainfall is experienced in the crop-producing period. Although climate change is predicted to increase the quantity and severity of climate shocks on crop production, hydro-priming seeds with higher fertiliser inputs reduce wheat exposure to climate change and adverse soil carbon and nitrogen content shocks. A crop rotation with hydro-primed wheat and field peas maximises farmer NPV returns, increases soil productivity, and reduces farmer climate risk exposure.

Chapter 7: Analysis

This chapter discusses the results presented in Chapter 6 using the economic model developed in Chapter 5, and how these address the critical research questions posed in the Introduction. The simulation results are compared to existing literature and identify how the results address any research gaps that were identified in Chapter 2. The practical implications for wheat farmers are explored and future research directions identified.

A summary of the research objectives is provided in Section 7.1. The impact of the results derived in Chapter 6 is investigated by analysing the impact of climate risk and climate change on wheat production and the NPV returns from land use. These results are compared with existing literature on crop production and climate risk mitigation in Section 7.2. Section 7.3 explores the effectiveness of hydro-priming wheat seeds to mitigate climate risks, evaluates the soil productivity index developed in Chapter 4 and discusses the effectiveness of a carbon price on fertiliser emissions. A sensitivity analysis to test the robustness of the modelling approach is undertaken in Section 7.4. The theoretical and practical implications of the results are explored in Section 7.5. The chapter concludes with a summary and potential future research directions in Section 7.6.

7.1 SUMMARY OF RESEARCH OBJECTIVES

This study investigates the impact of climate shocks on dryland wheat yields and NPV returns using current management processes for a representative study site in south-eastern Australia. The predicted increase in climate shocks will increase yield variance, impacting the land’s productive capacity and farmers’ NPV returns from wheat production. This study identifies the climate shocks that significantly impact the soil’s productive capacity and future wheat yields. Further, it investigates the best profit-maximising quantity of fertiliser to mitigate climate shocks and maintain soil productivity and land value.

Hydro-priming, an alternative fertilising method, was presented in Chapter 3 and evaluated in Chapter 6, with the findings that hydro-priming reduces the impact of climate shocks and decreases the required fertiliser inputs to maintain wheat yields and gross margins from land use. Higher gross margins increase yield variance with the improvement with favourable climatic conditions exceeding the net improvement with drought or climate shock events. A simulation of a crop rotation using double wheat and field pea showed that hydro-priming increased farmer gross margin and NPV returns across all discount rates and fertiliser input quantities, with historical climate data and predicted climate change. Therefore, hydro-priming is an effective technique to mitigate drought, heat stress and excessive rainfall climate shock impacts on wheat production and farmer income.

The development of a soil productivity index enabled the evaluation of interactions between soil carbon and nitrogen, identifying how climate shocks impact wheat yields and the land’s productive capacity in future years. Applying the soil productivity index developed in this study to land value provides an alternative method of valuing agricultural land, utilises the wealth of data available to farmers and is a valuable tool for strategic land use planning.

Finally, climate change is exacerbated by fertiliser emissions. The impact on farmer management decisions of a policy shift to reduce fertiliser emissions is explored, finding that a carbon price on fertiliser emissions does not reduce agricultural greenhouse gas emissions.

7.2 COMPARISON WITH EXISTING LITERATURE

7.2.1 Climate Risk

Many studies have explored management methods that reduce climate risk exposure for dryland farmers. Regional studies of methods to mitigate the risks of dryland crop production in south-eastern Australia have investigated technology to apply fertiliser strategically using the methods discussed in Chapter 2 (van Rees et al., 2014). Variation in wheat sowing times is another risk management tool explored in various studies (Monjardino et al., 2019; Wang et al., 2019; Zeleke & Nendel, 2016). This study adds to the literature by investing in a novel method of fertiliser application that reduces wheat production risk exposure in south-eastern Australia.

Previous works have assumed farmers are risk-averse (Ball et al., 2010; Pope & Chavas, 1994); however, recent research has found that most Australian farmers consider themselves risk-neutral (Aither, 2020). Therefore, increasing risk exposure by varying management practices may not be undertaken if significant capital investment is required or if there are potential production losses compared to existing management practices. Hydro-priming represents a new management process that requires capital investment. This is important because risk-averse and risk-neutral farmers are likelier to implement low-cost management practices (Antle & Stoorvogel, 2006). The yield and economic benefits of hydro-priming under various climatic conditions must be demonstrated before farmers will consider implementing them in their production process.

An alternative method to reduce the risk of negative returns from land use is to diversify farming area land use. Browne et al. (2013) found that combining land uses with negatively correlated profits across the farming land area supports farmer mitigation and adaptation to climate risks. This finding was supported by Kandulu et al. (2012, p. 110), who showed that diversification of land use in the Lower Murray region reduces climate risks to farmers by 52%. The benefits of incorporating hydro-primed crops within a diversified crop rotation production process include increased profits and further reduces farmer climate risk exposure.

A financial risk management method to reduce farmer climate risk exposure is to purchase crop insurance, which can mitigate the financial impact of seasonal droughts on periodic wheat production returns (LaFrance et al., 2002). However, only a few hundred Australian farmers have agricultural weather insurance because the agricultural risk insurance market is not well developed in Australia (Aither, 2020; Mase et al., 2017). In part, this is because such insurance markets depend on extensive and ongoing government subsidies that are not provided in Australia. This is despite the fact that there has been research interest in Australian agricultural weather insurance for decades. Nonetheless, attempts by insurers to develop an Australian market, including recent discussions in the NSW state parliament, have been largely unsuccessful (Aither, 2020). Given the underdeveloped crop insurance market in Australia, investigating on-farm climate risk mitigation methods is an important research area this study contributes to.

The vast literature on climate risk mitigation and adaptation for dryland farming covers several strands. Climate risk mitigation can involve land use diversification and financial risk management through insurance. Management techniques such as wheat cultivar selection, variation in planting times and strategic fertiliser application have all been investigated. Hydro-priming seeds is an alternative fertiliser application method that has not been considered previously by crop producers in Australia and therefore, this study adds a novel method to reduce the effect of climate risk on cereal production in Australia.

7.2.2 Soil Productivity

The soil productivity index links previous biophysical research identifying the importance of maintaining soil carbon to retain soil nitrogen and crop productivity (Aguilera et al., 2013; Turmel et al., 2015). The development of the soil productivity index has not previously been undertaken within an economic land use analysis. The results presented in Chapter 6 demonstrate that the soil productivity index consistently reflects the soil carbon and nitrogen variation across the climate scenarios, management treatments and fertiliser input quantities modelled. The soil productivity index is concordant with results in biophysical studies measuring the impact of soil nitrogen or carbon losses on soil productivity (Dai et al., 1993; Lassaletta, 2014).

The study evaluated the soil productivity index under a range of climatic conditions, management practices and fertiliser rates, producing soil carbon and nitrogen variations that are consistent with soil carbon or nitrogen field studies that did not apply soil carbon or nitrogen variation to land value (Gray & Bishop, 2018; Liu et al., 2021). When applied to land value, the variable provides a realistic estimation of the impact of land management practices on the value of the land.

Gretton and Salma (1996, p. 52) analysed the impact of land degradation in NSW using an econometric analysis of field trials and found that a loss of 1% in soil structure resulted in a 0.12% loss in returns from crop production. The soil productivity index presented in Chapter 4, which uses an exponential function of soil carbon and nitrogen content, provides a more flexible valuation method to calculate the impact of soil productivity losses than Gretton and Salma (1996) who use a fixed relationship between soil productivity losses and land returns. Overall however, the results presented in this study using the existing management practices treatment with soil productivity losses are consistent with the findings of Gretton and Salma (1996).

Biophysical studies investigating the impact of changed soil structure (e.g. Oldfield et al., 2019), loss of soil carbon or nutrients (e.g. Hunt et al., 2019) do not consider the economic impact of changes to the future productive capacity of the soil. This study provides an alternative method of evaluating the impacts of land management practices by incorporating land value within an economic analysis. The soil productivity index provides an alternative to traditional *ex-post* empirical land price data analysis, which uses historical land values capturing the land quality and market conditions at the time the land was sold and may not be reflective of current land quality (Ervin & Mill, 1985; Pope et al., 1983).

Agricultural land value has been estimated by Goodwin et al. (2003) using a cost–benefit analysis model that incorporates the discounted value of government payments, market returns, and urban pressures on agricultural land to determine a land value per hectare. This study builds on that concept, integrating periodic variations in land value taken from APSIM simulation results to create a dynamic soil productivity index. Further, by including soil nitrogen in the dynamic soil productivity index the study here builds on the work of Berazneva et al. (2019) and provides insight into the relationship between soil carbon and nitrogen for maintaining soil and crop productivity.

This study takes a similar approach to that of Choumert and Phélinas (2015), who adjusted empirical land values to site and tenure conditions. However, this study uses dynamic variation in soil carbon and nitrogen from APSIM simulation results to measure the dynamic changes in soil quality. In contrast, Choumert and Phélinas (2015) used a hedonic price function derived from empirical statistical data. The use of dynamic biophysical data in land valuation is not a foreign concept, numerous studies have used soil carbon or soil losses to evaluate the impact of soil carbon losses and erosion on land value (Ervin & Mill, 1985; Goetz, 1997). Nevertheless, the periodic variation is a new method of valuing agricultural land.

7.2.3 NPV Returns from Land Use

The use of NPV economic analysis with crop software simulation results to evaluate crop production and management techniques has been undertaken for a range of studies across dryland crop production in Australia. For instance, using software simulation results, Bell et al. (2008) used NPV analysis to evaluate perennial wheat land use in the Western Australian wheatbelt. The crop sequencing in Bell et al. (2008) was investigated using APSIM software simulations and the results were incorporated into an NPV analysis by Cann et al. (2020).

Crossman et al. (2011) investigated soil carbon benefits by using APSIM simulation results to compare permanent plantings with wheat production in a South Australian temperate grain-producing region. Additionally, Smith et al. (2019) investigated the optimal fertiliser input quantity to maintain soil nitrogen in Southern Australian grain production using APSIM. Previous studies have utilised crop software simulation results to investigate the economic impact of soil carbon or nitrogen variation. This study adds to this by exploring how predicted climate change impacts farmer income with current and alternative management practices and hydro-primed wheat seeds.

The impact and adoption rates of alternative agricultural research questions and land management practices have been investigated using NPV economic analysis. A NPV economic analysis of alternative land use can be conducted to assess the environmental impacts of alternative land uses. Bryan et al. (2008) investigated the value of perennial timber plantations incorporating soil erosion and salinity reduction in an NPV analysis of South Australian farmlands. Pannell et al. (2014) analysed the farm-level economic impacts of zero-tillage, mulching, and crop rotation for small landholders in developing economies using NPV analysis. This study adds to the literature by investigating a conservation agricultural technique to mitigate productivity losses that have not been previously considered and extends the literature by developing and incorporating the change in land value into the NPV analysis.

Studies exploring capital investment costs and land use decisions for Australian farmers have also used NPV analysis. Sanderson et al. (2016) studied the impact of climate change on South Australian farmers’ land use management decisions and they found that the transformational change required to adapt to climate change may leave some assets stranded, with farmers potentially exposed to costly mistakes as part of climate change adaptation. Marsh et al. (2004) incorporated the results of a multivariate regression in an NPV analysis of investments required by both the private and public sectors to support the development of new crops in the Western Australian wheatbelt. Developing a partial budget for hydro-priming seeds and including this in the NPV analysis adds to studies investigating how farmers’ capital investments mitigate climate risks.

7.2.4 Fertiliser Input Variation

A rich array of literature explores fertiliser usage in Australian dryland crop production. Australian grain producers are some of the most efficient users of fertiliser globally (van Rees et al., 2014). The literature has considered fertiliser placement, application time, frequency, and varied field application volumes (Angus & Grace, 2017; Harries et al., 2021; Robertson et al., 2008). What has not been considered in fertiliser application efficiency is how hydro-priming may decrease fertiliser usage while maintaining crop yields. This study adds to the literature on dryland Australian crop producers' fertiliser efficiency techniques.

The environmental impact of fertiliser application has been investigated using crop simulation software. The APSIM software was used by Hunt (2021), who found that maintaining soil nitrogen content increased wheat yields with little environmental impact and was a more profitable strategy than targeted fertiliser application throughout the growing season. Using crop simulation software with varied fertiliser inputs for a study site in South Australia, found increased nitrogen leaching and economic risks to farmers when soils with low water holding capacity were exposed to variable rainfall and higher fertiliser application rates (Sadras, 2002). Thorburn et al. (2001) used APSIM crop simulations to investigate fertiliser usage with sugarcane, finding that higher fertiliser application quantities increased nitrous oxide emissions.

Using APSIM to investigate fertiliser application has a rich history and this study adds to this literature by investigating fertiliser application and predicted climate change. Many studies have considered predicted climate change and fertiliser input quantities in Australian dryland crop production. Ludwig and Asseng (2006) investigated the impact of climate change on wheat production in Western Australia with varied fertiliser inputs using APSIM simulations. A literature review by Pannell (2017) found that farm management decisions are impacted by climate risks, farmer risk profiles, and the marginal benefit of increasing fertiliser application. This study adds to the literature by investigating how hydro-priming fertiliser application can reduce the climate risks that dryland crop farmers are exposed to.

7.2.5 Hydro-priming

After significant research and investment in improvements to wheat production processes, production technology, land management and wheat cultivars in the preceding decades, wheat production efficiency in South-eastern Australia is at 70–80% of crop water limited yield potential (van Rees et al., 2014, p. 5). Further increases in crop productivity will require innovative marginal improvements. Recent research has focussed on the marginal crop productivity benefits of integrating mobile phone technology into crop management and precision agriculture using capital-intensive management techniques (Mendes et al., 2020; Shafi et al., 2019). Hydro-priming represents a new pathway to explore potential wheat production efficiencies. Hydro-priming can potentially increase crop and soil productivity across irrigated and dryland crop production worldwide.

The hydro-priming management technique contributes to the body of research investigating fertiliser practices. It is a method of increasing crop yield and returns from land use that can improve wheat yields, soil productivity, and the stability of the farming system. This study adds to the research on the environmental impacts of crop production and fertiliser usage. The long-run simulations completed in this study add to the literature by determining the effectiveness of alternative management techniques to reduce land degradation by applying the soil productivity index to evaluate the long-run impact on land quality and value.

Despite hydro-priming reducing climatic risk, there is increased gross margin variance which has the most significant impact on wheat production income. Climate risk increases soil productivity losses, with rainfall shocks increasing fertiliser nutrient flows through soils and higher soil temperatures increasing the rate of soil carbon loss. This is consistent with studies on soil carbon content and the impact on farmer returns with climate change, which did not consider links between soil productivity shocks and seasonal climatic conditions (John et al., 2005; Ludwig et al., 2009; Nelson et al., 2014). Improving soil productivity increases soil water and nutrient retention, mitigating the impacts of climatic variation on crop production, and increasing farmer profits (Arora, 2019).

7.2.6 Carbon Pricing Agricultural Emissions

Pannell (2006) identified that a farmer’s risk profile might have little influence on fertiliser application decisions, with a range of fertiliser application rates around the optimal quantity, which are similarly profitable. A flat pay-off function for fertiliser application is found to increase fertiliser application rates. Existing research on the externalities associated with fertiliser application has considered policies to reduce fertiliser emissions using an implicit water quality variable to evaluate the impact of fertiliser runoff using a hedonic property values model (Poor et al., 2007). Other studies have investigated using a nitrogen input quota (Moxey & White, 1994). Studies on the economic impact of fertiliser emissions have focussed on the impact of over-fertilisation on water quality.

Agricultural emissions from crop production consider the interrelationships between land use and greenhouse gas emissions. Fertiliser usage and food production are linked. Global food demand and fertiliser emissions are increasing (Tilman et al., 2002). The farm-level impacts of fertiliser emissions have been quantified in previous studies on global and local scales (Goglio et al., 2014; Snyder et al., 2009; Wu et al., 2021). The relationship between crop residue soil amendments and subsequent nitrous oxide emissions has also been explored (Chen et al., 2013). Solutions to increase Australian crop producers' fertiliser input efficiency and reduce nitrous oxide emissions have been explored by Chen et al. (2008). However, the economic impact of agricultural fertiliser emissions using a carbon price has not previously been considered.

7.3 INTERPRETATION OF FINDINGS

The results presented in Chapter 6 uncovered some key trends across the wheat production simulations using historical data and predicted climate change, identifying key climate drivers of wheat yield variation. Climate shocks impact wheat yields, farmers' incomes, and the productive capacity of the soil. Varying fertiliser inputs can mitigate the impact of climate shocks. Hydro-priming further reduces the effect of drought, heat stress and excessive rainfall climate shocks and is an alternative method to increase wheat yields and NPV returns from land use across a range of fertiliser inputs. Applying a carbon price to fertiliser emissions was ineffective in reducing fertiliser inputs for wheat production. The key trends identified in the results are discussed in more detail below.

7.3.1 Climate Risk

Wheat production in south-eastern Australia is exposed to climate risk, resulting in variable annual wheat yields. Identifying the key drivers of wheat yield variance is crucial for the development of mitigation strategies. As identified in Chapter 6, rainfall variance, when combined with warmer temperatures, has the most significant impact on wheat yields and farmer income.

Maximising soil productivity reduces farmer exposure to climatic risks. Climate production risk is one of the most significant production risks facing wheat producers in Australia (John et al., 2005). Soil carbon has a demonstrated positive relationship, up to a threshold, with soil temperature, oxygen, and water content (Probert et al., 1998). Increasing soil carbon increases the soil's ability to retain water, which enhances the resilience of crops to varied climatic conditions, ultimately boosting wheat yield and land use returns (Campbell, 1974; Leirós et al., 1999).

Above-average rainfall over the production period can increase wheat yields, with timing being the critical factor in determining the yield impacts. In some periods with significantly higher than average rainfall, the wheat yield was lower than the average for the modelling period. In the 1974 and 1984 production periods, there was a 1% decline in soil carbon and a 1.6% decline in soil nitrogen, consistent with research by Bouwman et al. (2005), which found above-average rainfall denitrifies soil nutrients through topsoil into the subsoil.

The upper-bound climate change simulation investigated the impact of increased temperatures and rainfall predicted to occur with climate change. The simulation results suggest that an increase in rainfall will, on average, increase wheat yields but, extreme weather rainfall during biomass production (from June to August) is associated with a reduction in wheat yields and income. Waterlogged soils reduce nutrient uptake and, therefore, biomass production. The simulation results align with biophysical research by Browne et al. (2013) that finds a positive relationship between wheat biomass and yields.

Higher temperatures impact wheat development because hotter temperatures during key growth stages generate different responses from wheat crops. Temperature spikes above 30 °C during germination and early growth periods have less impact on wheat yields than temperature spikes that occur during grain filling before harvest (Koetz et. al., 2016). Heat stress can be combined with rainfall deficits, increasing crop stress response, and decreasing wheat yields. When the study site was exposed to recurring droughts, wheat yields declined by 18–32%, and the gross margin reduced by 22% during the millennial drought period (1997–2009) compared to the average gross margin over the modelling period in the historical climate scenario. The simulation results using lower-bound climate change suggest that if another millennial drought occurred, wheat yields at the study site could decline to between 0–2 t/ha, with gross margins decreasing by 28% for the drought period compared with average gross margins for the modelling period.

A crop rotation of double wheat and field pea increases yield and gross margin variance more than continuous wheat cropping. Rotating crops of field pea and wheat reduces climate risk exposure, with crop rotations generating an average gross margin of $801/ha each year over the millennial drought period, compared with an average return of $663/ha each year for continuous wheat over the same period. When wheat is hydro-primed within a crop rotation sequence, the interannual variance in gross margins and farmer NPV returns increase. The increased interannual variance from hydro-priming is associated with positive increases in wheat yields and gross margins with favourable climatic conditions compared with returns generated with non-primed continuous wheat cropping. Crop rotations reduce the potential of negative gross margins, decreasing drought related climate risk exposure however, increasing annual income variance.

7.3.2 Soil Productivity

The soil productivity index combines soil nitrogen and carbon variation with simulated nitrogen and carbon variation results. The carbon and nitrogen variation simulated with APSIM is consistent with Gray and Bishop (2018), who used NARCliM simulations to estimate the effect of climate change of on NSW soil carbon and nutrient content. Previous economic studies identified soil carbon as critical to crop productivity (Berazneva et al., 2019) but did not determine why soil carbon content was necessary. The soil productivity index developed in Chapter 4 incorporates biophysical research to demonstrate the exponential relationship between soil carbon and nitrogen in economic analysis, utilising a new method of evaluating soil productivity.

The soil productivity index provides insight into why higher soil nitrogen is insufficient to increase soil productivity. The exponential relationship between soil and soil carbon becomes most evident when soil productivity losses or gains increase. The soil productivity index does not provide a great deal of insight with minor variations in soil carbon and nitrogen; however, with climate shocks, more significant variations in soil carbon and nitrogen occur and the soil productivity land value provides a good explanatory insight into changes in the productive capacity of the soil.

Extending the soil productivity index to vary land value creates a method of evaluating the impact of management processes on soil quality. Using the soil productivity index to vary land value in Wagga Wagga generated a variation in land value consistent with the NSW Government's land valuation variation for the region between 2010 and 2014 (New South Wales Department of Finance and Services , 2014). Consistent with stock market theory of Chen et al. (1986) changes in soil productivity represent unrealised returns to land assets that must be allocated to the asset. Incorporating biophysical changes in the productive capacity of land into an economic land value analysis represents a new approach utilising the wealth of soil data available to farmers and enabling evaluation of alternative management processes.

7.3.3 Soil Productivity and NPV Returns with Hydro-priming

Simulations modelling crop production using climate data can provide insight into how farmers can adapt to climate change. Identifying the impact of climate shocks can support the development of methods to mitigate its effect on dryland wheat production. General global circulation modelling with predicted climate change has found that cereal crop yields will decline by 10–38% with current management processes (Müller & Robertson, 2014, p. 43). The results of this study consistent with Oldfield et al. (2019) suggest that climatic conditions and fertiliser management decisions impact wheat yields, farmer income and soil productivity.

Australian farmers are among the most productive dryland crop producers globally (Sadras et al., 2016). As noted in Chapter 6, the yield and NPV returns from land use with the alternative management technique of hydro-priming increases farmer profits and crop productivity regardless of climatic and soil conditions. Improving global low-rainfall crop productivity is a crucial research goal. The short-run difference in soil productivity and crop returns between non-primed and hydro-primed seeds is marginal. However, over the longer term, soil productivity losses with non-primed seeds are compounded, affecting crop production returns in the latter half of the period modelled. Hydro-priming increases Australian dryland wheat production efficiency across various fertiliser input quantities and climate scenarios.

Across all climatic scenarios, it was found that with hydro-priming, farmers can reduce fertiliser inputs by 20% while maintaining crop yields, soil productivity, and income from wheat production. This study also found that hydro-priming boosts soil productivity and carbon and nitrogen content across all climate scenarios within continuous wheat and crop rotation scenarios. Further productivity increases may be realised by varying crop sowing times. Hydro-priming across all climatic conditions and discount rates increases crop production returns, land value and the expected NPV of farmer profits per hectare, building on the field studies of hydro-priming efficacy conducted by Foy (1992) and Imran et al. (2013).

While this research demonstrates the effectiveness of hydro-priming in improving land quality and crop production returns, the uptake and implementation depend on individual farmer attitudes and risk profiles. For instance, Australian wheat farmers’ most significant production risks are variation in market prices and adverse weather (Monjardino et al., 2015). Consequently, farmers can be reluctant to vary management techniques from traditional methods and, as noted by Ahnström et al. (2009), may require a demonstration of the effectiveness of alternative management processes for successful uptake and implementation of these approaches. In addition as suggested by Kuhene et al. (2017) the upfront investment costs in hydro-priming equipment may reduce uptake and implementation, requiring government support to demonstrate efficacy and increase uptake and implementation.

7.3.4 Net Present Value Profits from Land Use

Hydro-primed continuous wheat production simulations showed increased gross margins and NPV returns. This finding was robust across fertiliser inputs and climate scenarios. Despite increased production costs, hydro-priming wheat seeds increased NPV returns from land use. However, the impact of hydro-primed seeds on the NPV of land value is inconsequential compared to returns from wheat production. Hydro-priming increases wheat production returns while increasing the soil's productive capacity compared with non-primed wheat.

NPV results suggest hydro-primed continuous wheat cropping is the most profitable across all climatic simulations for continuous wheat production. However, compared to crop rotation, including double wheat and field pea, across all climate scenarios and fertiliser input quantities, the gross margin and NPV returns for crop rotation exceed those for continuous hydro-primed wheat. Consistent with the results of Armstrong et al. (2012) crop rotations with a double rotation of hydro-primed wheat and field pea generate higher gross margins, crop yields, and NPV returns across all climate scenarios and fertiliser inputs than continuous wheat production. The best strategy to maximise farmer income is to undertake a crop rotation with hydro-primed wheat however, the gross margin variance increases in this scenario because of the increased income from wheat yields with hydro-primed seeds in favourable seasons and compared to field pea gross margins. Soil productivity and land values increase compared to non-primed rotations, while climate risks are mitigated.

7.3.5 Fertiliser Input Variation

Fertiliser is used to overcome low nutrient content in Australian soils but, it is one of the most expensive inputs in the crop production process (Koch et al., 2015). Therefore, the application and timing of fertiliser inputs to maximise efficiency is a crucial research focus (Bell et al., 2020). Maintaining a fixed fertiliser application rate over the modelling period smooths soil productivity variation across production periods, increases the farming system’s long-run soil productivity and stability and mitigates the impacts of climate risk on soil productivity and wheat yields.

By combining hydro-priming seeds with fertiliser input variation, soil productivity, wheat yields and income from land use can be maintained with a 20% reduction in fertiliser across climate simulations investigated. Hydro-priming can increase fertiliser input efficiency and overcome low rainfall during the early growth phase of wheat. Hydro-priming is a successful technique to increase fertiliser application efficiency in low-nutrient dryland agricultural production.

Increasing soil nitrogen and soil carbon with the alternative management practices and the fixed, profit-maximising fertiliser quantities investigated in this study increases soil nitrogen and carbon balances, thus increasing farmer NPV income from land use. It is more productive than targeted fertiliser applications over the crop growing season, maintaining higher soil nitrogen content through higher fertiliser applications increases farmer profits and is consistent with the biophysical results of Smith et al. (2019). This study adds to Smith et al. (2019) simulating increased fertiliser application with predicted climate change and integrates land value within an economic analysis.

7.3.6 Carbon Pricing Fertiliser Emissions

A carbon price on fertiliser emissions caused an insignificant increase in production costs across the simulations investigated and did not affect farmer fertiliser input decisions. Therefore, introducing a carbon price is an ineffective method for decreasing fertiliser demand and emissions. Further, implementing and regulating a fertiliser emissions policy would potentially be more costly to the government than any income raised. Instead, the Grains Research Development Corporation (GRDC) has developed a range of growing guides for different grains, including recommended fertiliser application rates, methods, and timing (Matthews et al., 2020). The growing guides are a more cost-effective method for the government to reduce fertiliser input usage through farmer behavioural change. The GRDC continues to research, develop, and present growers with new information on efficient fertiliser usage, which is less costly and potentially more effective than implementing and regulating a price on fertiliser emissions.

7.4 SENSITIVITY ANALYSIS

Throughout the modelling process, sensitivity analyses was undertaken to test the robustness of the modelling process. The impact of prices used in the wheat and field pea economic models was tested by varying input prices by 20% to investigate the impact on gross margins. When the varied gross margins were integrated into an NPV analysis, the results were robust across discount rates of 2, 5 and 7%. Using a range of discount rates in the NPV returns enabled the robustness of the results to be evaluated while applying the economic model to a range of fertiliser input quantities tested the sensitivity of wheat production to fertiliser inputs.

The hydro-priming process was evaluated using a range of root and shoot growth rates derived from previous field studies and used to vary the APSIM wheat file. Simulations were then performed using a range of fertiliser input quantities across historical data and predicted climate change scenarios with the yield, gross margin and NPV income evaluated across discount rates of 2, 5 and 7%. As discussed in Chapter 6, the results did not vary significantly between the lower- and upper-bounds of the root and shoot growth rates derived from field trials, providing some robustness.

A range of carbon prices was used in the fertiliser emissions economic analysis, taken from carbon markets. The carbon prices were selected from 2020 to reflect current market conditions and converted into AUD using the average annual exchange rate for each currency. Carbon markets are relatively new and were subject to significant variation in earlier years as they matured. The range of carbon prices ensured a robust analysis of the impact of a price on carbon emissions and was integrated into the economic analysis using the discount rates identified previously.

7.5 THEORETICAL AND PRACTICAL IMPLICATIONS

Studies have predicted that climate change will impact the global wheat supply. In 2022, Australia produced 13.7% of global wheat exports (ABARES, 2023). This study contributes to the literature by investigating methods to mitigate climate change risk on wheat yields in dryland crop production in south-eastern Australia to help Australia maintain its share of global wheat exports and wheat supply. Maintaining Australia’s wheat productive capacity through the utilisation of hydro-primed seeds will not only support global wheat supply but also, at the farm level, support ongoing profitability for farmers. Increasing climate risks are expected to increase variability in returns, impacting farmers’ abilities to service capital investment loans. Maintaining productive capacity through increased resilience to climate shocks will help farmers remain profitable.

Farmers in south-eastern Australia are currently exposed to significant variations in climatic conditions and this variability is expected to increase with climate change. Developing methods to support farmers in mitigating the impact of variable climatic conditions on wheat production is a critical research area. The Australian Government has identified drought resilience as a key research objective.[39] Hydro-priming seeds reduces negative climate shocks across historical data and predicted climate change, both with reduced and increased rainfall. The method is robust across climatic conditions when used for a farm sowing 500 ha of wheat. Hydro-priming can also be applied to other cereals such as barley, canola, sorghum and potentially leguminous crops. This study providing a first attempt at evaluating a new technique that can be widely used by grain producers across Australia. This study contributes to this research objective by developing a hydro-priming method that can be applied to cereal production.

Technological developments in the past 20 years have provided farmers with ready access to climate and soil data at a fine scale that can be utilised in strategic farm management. The soil productivity index developed here provides an alternative method of utilising the available data to evaluate the impact of land management practices on the productivity capacity of the soil and the variation in land value. Farmland is generally the most significant asset a farmer controls. Using the available technology to determine its value provides a more robust method than

---

[39] More information on the Australian Government's *Future Drought Fund* initiative, being implemented by the Department of Agriculture, Fisheries and Forestry, is available at https://www.agriculture.gov.au/agriculture-land/farm-food-drought/drought/future-drought-fund.

current practices using hedonic pricing or regression analysis of historical land sales data to estimate land value.

7.6 CONCLUSION

The analysis provided here demonstrated that, when applied to a continuous monoculture rotation or within a crop rotation, hydro-priming wheat seeds increases farmers’ gross margins and NPV returns while increasing soil productive capacity and land value. Hydro-priming reduces farmer exposure to climate risks, including heat stress, drought and above-average precipitation. Climate risk can be further mitigated by increasing fertiliser inputs, with a positive relationship identified between fertiliser inputs, soil productivity and wheat yields. The results are robust across various fertiliser input quantities and for historical climate data and predicted climate change.

The soil productivity index developed in Chapter 4 and applied in Chapter 6 reflects changes in the land’s productive capacity and is consistent with the NSW Land Valuers Office change in land value for the region between 2010 and 2014 (D.F&S, 2014). Applying the soil productivity index to land value is a novel method of valuing agricultural land that utilises site-specific soil characteristics.

Chapter 8: Conclusions

This work has evaluated the effectiveness of the soil productivity variable and its application to land value together with the efficacy of the hydro-priming process to mitigate climate shocks and increase farmers' NPV returns. The impact of predicted climate change on soil productivity and the effectiveness of the hydro-priming technique to mitigate the impact of climate shocks on soil productivity, crop yield, and farmer profitability are discussed. The effectiveness of a policy shift implementing a carbon price to reduce agricultural contributions to greenhouse gas emissions is analysed. Future applications and extensions of the land value and management treatments developed in this work are suggested. The main contributions of the work to the body of knowledge are summarised and evaluated, concluding this chapter and the thesis.

Section 8.1 provides an overview of the key findings and how they address the research questions posed in Chapter 1.. Section 8.2 evaluates and reflects on the work presented in the previous chapters. The limitations of the study and the modelling process are discussed in Section 8.3. The contributions of this study to agricultural research and the broader community are presented in Section 8.4. In Section 8.5, suggestions are made on future research directions for dryland crop production and crop management using the outcomes of this study. Section 8.6 comprises concluding remarks on the process and the study outcomes.

8.1 SUMMARY OF FINDINGS

Dryland crop production in Australia is exposed to climate risks with significant interannual yield and income variance. The work here contributes to the wider body of research investigating the link between climatic conditions and wheat yield variance, farmer income, and the future productive capacity of the land in south-eastern Australia using a representative study site in Wagga Wagga, New South Wales, Australia, from 1960 to 2015. The climate shocks with the most significant adverse effect on wheat yield and the future productive capacity of the land are when above-average rainfall and temperature shocks occur in the same calendar month. Higher-than-average rainfall climate shocks significantly decrease soil carbon stocks, with subsequent crop yields lower than the long-run average for several seasons. Climate shocks with higher rainfall and warmer temperatures are the most significant drivers of interannual yield and income variance for wheat farmers in the region.

South-eastern Australia is exposed to recurring droughts, which minimise wheat yield when they occur but have a minor impact on the land’s productive capacity compared to climate shocks with higher rainfall and temperature. Heat stress is another climate shock impacting wheat yields but not the land’s productive capacity. The most significant heat stress effect occurred with temperature spikes during wheat flower production. Heat stress does not impact the future productive capacity of the land but can result in negative gross margins in the season it occurs. Predicted climate change will increase the frequency of droughts and heat stress events so developing methods to reduce climate shocks is critical to supporting farmers to mitigate the impacts.

Hydro-priming seeds before planting is a method to reduce the impact of heat stress and droughts. Hydro-priming minimises the effects of drought and heat stress, increasing wheat yields and farmer income compared to non-primed wheat. It is a novel method for increasing early crop growth rates. Wheat profitability is maximised by combining higher fertiliser inputs with hydro-primed seeds. Hydro-priming increases the profitability of wheat land and crop production with historical and forecast climate change. Simulations show higher soil productivity was generated in the Millennium Drought years (1997-2009) with hydro-primed seeds and profit-maximising fertiliser inputs, increasing crop productivity compared to existing management practices. The higher soil productivity increased crop yields in the drought compared to the existing management treatment. Hydro-priming increases soil carbon and nitrogen content and reduces farmers climate risk.

The most effective strategy to maximise farmer income and reduce climate shocks is to undertake a crop rotation with a double hydro-primed wheat and field pea rotation with increased fertiliser inputs. Crop yields, farmer gross margins, and NPV returns are improved for all climate scenarios and increased fertiliser input quantities compared to crop rotations with non-primed wheat and field pea or continuous hydro-primed or non-primed wheat land use. Crop rotation systems, including hydro-primed wheat, increase soil productive capacity and land value, generating the largest reduction in climate shocks on dryland wheat production.

One of the critical features of this study was the development and application of a soil productivity index to measure the impact of periodic soil carbon and nitrogen fluctuation on land quality and subsequent land use. The soil productivity index captures the effects of management practices on soil carbon and nutrient content and is a valuable tool to inform land use decision-making. The index provides a method to investigate the impact of seasonal climate shocks on soil quality and crop yield. Understanding how climate shocks impact soil productivity can improve land management techniques.

Improving soil productivity reduces the impact of climate shocks on soil and increases long-run profitability for crop producers. Using a soil productivity index in strategic management decisions is a valuable way of incorporating the impact of management decisions on farmers’ most significant and crucial asset farmers—their land. The soil productivity index is consistent across fertiliser input quantities, discount rates, and climatic conditions. The soil productivity index captures the impact of soil carbon variation on the capacity of the soil to retain nitrogen, which is essential in crop growth processes (see Berazneva et al., 2019; Turmel et al., 2015). The soil productivity index can be used in simulations investigating various land use research questions, including forestry, livestock, and horticultural land uses. The index can be used in biophysical data taken from field trials used within an economic analysis to evaluate the economic impact of biophysical land use outcomes.

The soil productivity index applied to land value is a new method of determining land value using site-specific soil characteristics. Agricultural land value variation with soil carbon, soil erosion and land degradation has previously been estimated using empirical land data (Choumert & Phélinas, 2015; Goetz, 1997; Goodwin et al., 2003). A soil productivity index provides an alternative to empirical analysis and can utilise the wealth of site-specific data created with recent technological innovations. Applying the soil productivity index to land value provides a mechanism for valuing land management practices across land use simulations and biophysical field trials, providing a flexible method to investigate soil productivity and land use impacts.

The impact of climate change on dryland crop production has been a critical research area as researchers try to understand how predicted increases in climate shocks will impact dryland crop production across Australia (Asseng & Pannell, 2012; Nelson et al., 2014; van Rees et al., 2014). This study found that hydro-priming wheat seeds reduces the impact of climate change and increases farmer NPV returns compared to non-primed seeds. Hydro-priming seeds increases soil productivity, with a positive relationship identified between fertiliser inputs, soil productivity, wheat yields and farmer income for all climatic conditions simulated. The results from climate change simulations support the findings derived from historical climate data: rainfall is the critical driver of soil productivity variation. Climate change increases the climate risks dryland crops are exposed to; however, hydro-priming is a beneficial strategy to mitigate the impact of climate risks on wheat yields and soil productivity.

Farmers can increase the expected NPV returns from wheat production by increasing fertiliser inputs beyond the DPI-recommended rates. Wheat yields and land productivity increase with higher fertiliser input quantities. This finding is consistent with recent biophysical research showing that maintaining higher soil nitrogen levels increases wheat productivity (Hunt, 2021; C. J. Smith et al., 2019). Using the APSIM production function, fertiliser was applied annually at sowing regardless of the forecast climatic conditions, in contrast to current management practices. Despite lower crop yields during drought, with the set fertiliser application regime, APSIM soil productivity improved over the Millennium Drought, resulting in strong yields and profits in the production periods after the drought broke. Fertilisers are critical production inputs in low-rainfall, nutrient-poor soils in Australia to increase long-run profitability and reduce the impact of climate shocks on land use. Fertiliser application regimes should be calibrated to soil conditions to maintain soil productivity.

While fertiliser inputs are critical to wheat production, they contribute to climate change through nitrous oxide emissions. The effect of nitrous oxide emissions on greenhouse gases is 298 times that of carbon dioxide (Pachuri et al., 2014). However, a policy shift that puts a price on fertiliser emissions within an emissions trading scheme is ineffective in reducing fertiliser usage. The profit-maximising strategy is to maintain higher fertiliser application rates, as the carbon price per tonne of carbon equivalent nitrous oxide emissions is smaller than the marginal revenue realised with higher fertiliser inputs. Therefore, a carbon price policy to reduce fertiliser emissions is not recommended.

8.2 EVALUATION

The soil productivity index can be applied across agricultural and environmental research topics. There is scope for its application in various issues, promoting sustainable land management decision-making. Applying the soil productivity index to vary land value is a new method of simulating illiquid asset price variation and capturing the impacts of management processes on asset value, providing a robust alternative to empirical regression analysis.

The hydro-priming method investigated in this study could revolutionise how dryland farmers sow their crops and increase dryland grain resilience to climate shocks. A critical research objective is the development of processes to support farmers in Australia to mitigate the impact of drought on their production processes. This study contributes to that objective and can be incorporated into field studies to generate yield data supporting the study’s findings.

This study utilises the wealth of data available to farmers to develop a new method of valuing changes in agricultural land value, providing an alternative to previous economic approaches reliant on historical data. While the soil productivity index applied to land value does not capture all the market factors impacting land value, it provides farmers with a tool to support short-term and strategic land management decisions.

While this study focused on dryland grain production in south-eastern Australia, the hydro-priming technique and soil productivity index can be utilised by farmers and researchers globally. Potentially, farmers in African nations similarly exposed to climatic risks can use the seed hydro-priming technique. Evaluating the benefits of hydro-priming in different locations globally with different grain crops is a crucial research theme to mitigate the predicted impact of climate change on wheat supply variance with increasing global populations and demand. A further application for hydro-primed seeds is in irrigated crop-producing around the globe, some of which are highly inefficient fertiliser users. Hydro-priming can support improved fertiliser input efficiency and potentially reduce the volume of agricultural nitrous oxide emissions by supporting early crop germination and growth in irrigated grain producing regions.

Applying a carbon price to fertiliser inputs with the alternative management processes did not decrease the impact of farmers’ fertiliser input management decisions as expected. Developing a policy to include fertiliser emissions will generate regulatory paperwork; however, the marginal cost of emissions is insignificant, and a carbon price does not impact farmers’ fertiliser input management decisions. With a profit maximisation objective, farmers do not care about the externality fertiliser application causes, capturing current farmer behaviours globally. Further work is required to develop policies or management processes to reduce fertiliser emissions.

8.3 LIMITATIONS AND CAVEATS

The simulation's production function is fixed with the crop planting period, management processes, harvest and fertiliser input quantities fixed across the modelling period. This somewhat unrealistic assumption facilitates a comparison of hydro-priming with current management practices and across historical climate data and with predicted climate change. Wheat prices, production costs, technology and carbon prices are fixed to simplify the modelling process and focus analysis on the relationship between management treatments, soil productivity and climate shocks.

Variations in input and output prices were considered. However, including price risk, without the ability for farmers to adjust the production function in response to price risk was inconsistent with the fixed production function approach. Farmers adjust to risk by varying land use or management processes, the stylised approach with a fixed production process was used to investigate how hydro-primed wheat crops respond to different climate shocks. Price variation may skew the results, however, to ensure the clarity and robustness of the findings, the fixed input and output prices were retained.

Evaluating climate shocks with predicted climate change required statistical downscaling of historical daily climate data using NARCliM modelling of expected climate change impacts on rainfall and temperature throughout the year (Evans et al., 2014). Statistical downscaling of predicted future temperature and rainfall variations for the region, and application to historical data might not accurately reflect future climate. Climate change has occurred in the region from 1960 to 2015 using stepped linear increases in temperature and the severity of rainfall variation of predicted climate change is not realistic.

The simulations used the region’s upper and lower bounds of predicted climate change to present a future worst-case scenario for low and high rainfall conditions. It is recognised that the lower and upper bounds may be outliers and occur less than 5% of the time in the future. However, rainfall variation’s lower and upper bounds provide a range of expected wheat production returns and soil productivity impacts with future climate change. It facilitated testing the robustness of the alternative management treatments to ensure that the alternative management treatments with the worst-case scenario predicted climate change.

Limited wheat data was available for hydro-priming hence, reliance was placed on field study results for wheat hydro-primed in India. While the root and shoot growth rates used to modify the APSIM wheat crop cultivar were checked with other hydro-priming results using vegetable crops, there was limited peer-reviewed cereal crop data available. Sensitivity testing was undertaken to mitigate this using the upper and lower bounds of wheat hydro-priming field studies, with the results not generating significant yield or gross margin differences.

A partial budget was constructed to evaluate hydro-priming’s economic cost, utilising numerous personal communications between agricultural equipment suppliers. Economic analysis of hydro-priming has had limited attention in academic literature and therefore input costs used were obtained from supplier communications. The partial budget represents a first attempt at quantifying the cost of hydro-priming. Three alternative methods were investigated to mitigate constraints around hydro-priming production cost data.

8.4 CONTRIBUTION TO RESEARCH LITERATURE

This study found that climate shocks on dryland wheat yields and NPV returns using current management processes for a representative study site in south-eastern Australia can be mitigated through increased fertiliser application and hydro-primed wheat seeds. The predicted increase in climate shocks is mitigated when soil nitrogen and carbon content is increased—an increase in fertiliser inputs increases soil productive capacity and wheat resilience to climate shocks.

This study investigated the efficient profit-maximising quantity of fertiliser to mitigate climate shocks and maintain soil productivity and land value. Using historical and predicted climate data to increase fertiliser inputs beyond what the NSW DPI (2013) recommended will increase crop yields and farmer income and reduce climate risks for continuous wheat and wheat, wheat, and field pea crop rotations. The research extends the work of Smith et al. (2019), who found that increasing soil nitrogen increases wheat yields with little environmental cost.

Developing the soil productivity index utilising periodic soil carbon or nitrogen variation is an important development in economic analysis. It provides the link between research identifying soil carbon as crucial to crop productivity and an alternative strand of research that finds nitrogen critical to maximising crop yield (e.g. Berazneva et al., 2019; Halvorson et al., 2002; Knops & Tilman, 2000; Petersen & Hoyle, 2016). Both carbon and nitrogen are critical to maximising crop productivity, with carbon instrumental in retaining nitrogen within the soil. The soil productivity index links soil carbon and nitrogen and is robust in application across different crops, climatic conditions, and management treatments.

Using the soil productivity index to measure the impact of fertiliser input variation provides a new robust method for estimating the effects of production processes on land quality and value across different climatic conditions and management treatments. The soil productivity-adjusted land value provides an alternative land value evaluation method. The soil productivity index can be applied to simulation data, improving economic and land use analysis. The soil productivity index can be used for various land uses where soil productivity impacts returns derived from land use. Other potential soil productivity index land value applications include evaluating state forest reserves, plantation timber, agricultural livestock production and horticultural land use sequestration. The application of the soil productivity index to land value is consistent across management treatments and fertiliser input quantities.

Finally, climate change is exacerbated by fertiliser emissions. The impact on farmer management decisions of a policy shift to reduce fertiliser emissions was explored to provide insight into potential solutions to improve fertiliser input efficiency usage and reduce agricultural greenhouse gas emissions. A carbon price on fertiliser emissions is ineffective in changing farmer behaviour and reducing fertiliser inputs. Interest in agricultural emissions and ways to reduce emissions continues to grow. Agricultural emissions are a complex field; the need to balance food demand and supply with emissions reductions creates a complex framework for policy development and implementation. Evaluating the impact of a carbon price on fertiliser emissions in an emissions trading scheme presents essential information for policy analysts’ consideration when developing methods to reduce agricultural emissions.

8.5 FUTURE RESEARCH DIRECTIONS

Future research can undertake field studies utilising the hydro-priming of seeds to verify modelling and determine the effectiveness of hydro-priming with various crops. The work completed in this study is based on horticultural practices and field studies used to measure crop growth in the early stages. However, no field study has been undertaken in Australia evaluating hydro-priming's effectiveness in increasing crop yield. A further consideration for future field studies is alternative planting times to determine whether hydro-primed seeds are more productive with later sowing times than the traditional planting period used in modelling.

This study represents a first attempt at investigating the potential benefits of hydro-priming on cereal production in Australia. Field trials are required to validate the effectiveness of hydro-priming and can be investigated with a range of dryland and irrigated crops produced in Australia. Future work can analyse the results from field trials and validate this study's findings. As part of the field trials, an economic analysis of hydro-priming cost should be undertaken to refine and validate the partial budget constructed in this study. The outcomes of this study can be utilised to develop field trials and may be a stepping-stone towards the reform of industry practices.

The simple economic model developed here, including soil productivity and land value, can be modified and utilised to investigate several biophysical research questions. Modification of crop growth processes can be undertaken to evaluate the economic impact of new biophysical research to improve cultivar water or nutrient uptake. The profitability model, including crop production returns and land value, can be easily adapted to numerous land use research questions. The model can be extended to include soil carbon sequestration payments and the impact on farmers' profitability and management decisions. The burgeoning field of soil carbon sequestration and the development of saleable soil carbon credits represent a newly developing asset class; including the soil productivity index in assessing land value and participation in soil carbon markets is a potential future application and research area.

Field trials utilising measurements of soil carbon and nitrogen change over a period for use in the soil productivity index and applied to land value can be undertaken to validate the soil productivity index and its application to land value. A crucial future area is determining if the soil productivity index can be applied to field data. It can be applied to further innovations in crop management processes across various climatic conditions. Additional work is required to determine its impact on crop productivity in alternative crop-producing regions and with irrigated crop production.

The impact of climate risks on cereal production is a critical research area, with future global food demand predicted to increase and global food supply impacted by climate change. While a carbon price on fertiliser emissions was found to be ineffective, developing a carbon price applied to all emissions produced on a farm may be more effective in reducing global agricultural emissions. Continuing research into methods to reduce fertiliser usage and increase efficiency requires further attention.

8.6 CONCLUSION

This study investigated the biophysical and economic impacts of climate risks on dryland wheat production in south-eastern Australia. Increased temperature and rainfall climate shocks had the greatest impact on wheat yields and income, with the timing of these climate shocks having a significant long-run impact on future yields and income. The study contributes to the literature by exploring a new method to mitigate the effects of these shocks: hydro-priming wheat before planting significantly reduced the impacts of drought, heat stress and rainfall climate shocks. This method can contribute to supporting Australian dryland crop producers in mitigating the effects of climate shocks on crop yields and income variance.

The soil productivity index utilises the wealth of site-specific soil data available to farmers generated through recent technological advances. The soil productivity index provides insight into the interlinkages between soil carbon and nitrogen. Applying the soil productivity index to vary land value is a new method of valuing agricultural land. Although it does not incorporate market factors, it provides a way of evaluating the impact of farmers' management practices on the value of their agricultural land by incorporating the wealth of biophysical data available.

This research contributes to the literature investigating methods to mitigate climate risks and reduce wheat yield and income variance for dryland wheat producers in Australia. It simulated predicted climate change and identified the key climate shocks that must be addressed to maintain the productive capacity of soils. The hydro-priming method effectively reduces climate risks; it is hoped that field trials can be undertaken to investigate this thoroughly.

Bibliography

1. ABARES. (2019). Agsurf Data (Broadacre Crop Production, Issue. http://apps.agriculture.gov.au/agsurf/
2. ABARES. (2020a). About My Region - Riverina, New South Wales. Department of Agriculture, Water and the Environment Retrieved 29/10/2020 from https://www.agriculture.gov.au/abares/research-topics/aboutmyregion/nsw-riverina#regional-overview
3. ABARES. (2020b). Broadacre crop production. Department of Water, Agriculture and the Environment. https://www.agriculture.gov.au/abares/data#agsurf--data-on-agricultural-industries
4. ABARES. (2023). Australian crop report overview. Retrieved 31/05/2023 from https://www.agriculture.gov.au/abares/research-topics/agricultural-outlook/australian-crop-report/overview
5. Abid, M., Hakeem, A., Shao, Y., Liu, Y., Zahoor, R., Fan, Y., Suyu, J., Ata-Ul-Karim, S. T., Tian, Z., Jiang, D., Snider, J. L., & Dai, T. (2018). Seed osmopriming invokes stress memory against post-germinative drought stress in wheat (Triticum aestivum L.). Environmental and Experimental Botany, 145, 12-20. https://doi.org/https://doi.org/10.1016/j.envexpbot.2017.10.002
6. AEGIC. (n.d.). Australian wheat Quality, versatility, and reliability. https://www.aegic.org.au/wp-content/uploads/2021/03/AEGIC-Grain-Note-wheat_LR.pdf
7. Agegnehu, G., Nelson, P. N., & Bird, M. I. (2016). Crop yield, plant nutrient uptake and soil physicochemical properties under organic soil amendments and nitrogen fertilization on Nitisols. Soil and Tillage Research, 160, 1-13. https://doi.org/https://doi.org/10.1016/j.still.2016.02.003
8. AgGrow. (2018). WHEAT & BARLEY VARIETY TRIALS Beelbangera & Hillston (AgGrow Agronomy and Research, Issue. https://www.aggrowagronomy.com.au/wp-content/uploads/2019/03/HBS-Trial-Report-2018.pdf
9. Aguilera, J., Motavalli, P., Valdivia, C., & Gonzales, M. A. (2013). Impacts of Cultivation and Fallow Length on Soil Carbon and Nitrogen Availability in the Bolivian Andean Highland Region. Mountain Research and Development, 33(4), 391-403, 313. https://doi.org/10.1659/MRD-JOURNAL-D-12-00077.1
10. Aither. (2020). Sub-Project 1: Insurance in the agricultural sector, On-farm Financial Risk Management Project.
11. Ali, N., Farooq, M., Hassan, M. A., Arshad, M. S., Saleem, M. K., & Faran, M. (2018). Micronutrient seed priming improves stand establishment, grain yield and biofortification of bread wheat. Crop and Pasture Science, 69(5), 479-487.
12. Amthor, J. S. (1989). Respiration and Crop Productivity (1st ed. 1989.. ed.). New York, NY : Springer New York : Imprint: Springer.
13. Andrén, O., Kihara, J., Bationo, A., Vanlauwe, B., & Kätterer, T. (2007). Soil climate and decomposer activity in sub-Saharan Africa estimated from standard weather station data: A simple climate index for soil carbon balance calculations. AMBIO: A Journal of the Human Environment, 36(5), 379-386.

14. Angus, J. F., & Grace, P. R. (2017). Nitrogen balance in Australia and nitrogen use efficiency on Australian farms. Soil research (Collingwood, Vic.), 55(5-6), 435. https://doi.org/10.1071/SR16325
15. Anon. (2023). History of floods in Wagga Wagga. City of Wagga Wagga. Retrieved 7/05/2023 from https://wagga.nsw.gov.au/services/emergencies/floods/history-of-floods-in-wagga-wagga
16. Antle, J. M., & Capalbo, S. M. (2001). Econometric-Process Models for Integrated Assessment of Agricultural Production Systems. American Journal of Agricultural Economics, 83(2), 389-401. https://doi.org/10.1111/0002-9092.00164
17. Antle, J. M., & Stoorvogel, J. J. (2006). Predicting the Supply of Ecosystem Services from Agriculture. American Journal of Agricultural Economics, 88(5), 1174-1180. https://doi.org/10.1111/j.1467-8276.2006.00929.x
18. APSIM. (2019). APSIM Model Information. Retrieved 23/11/2019 from https://www.apsim.info/
19. Armstrong, R. D., Perris, R., Munn, M., Dunsford, K., Robertson, F., Hollaway, G. J., & Leary, G. J. O. (2019). Effects of long-term rotation and tillage practice on grain yield and protein of wheat and soil fertility on a Vertosol in a medium-rainfall temperate environment. Crop and Pasture Science, 70(1), 1-15. https://doi.org/https://doi.org/10.1071/CP17437
20. Arora, N. K. (2019). Impact of climate change on agriculture production and its sustainable solutions. Environmental Sustainability, 2(2), 95-96. https://doi.org/10.1007/s42398-019-00078-w
21. Assaeed, A. M., McGowan, M., Hebblethwaite, P. D., & Brereton, J. C. (1990). Effect of soil compaction on growth, yield and light interception of selected crops. Annals of Applied Biology, 117(3), 653-666. https://doi.org/10.1111/j.1744-7348.1990.tb04831.x
22. Asseng, S., & Pannell, D. J. (2012). Adapting dryland agriculture to climate change: Farming implications and research and development needs in Western Australia. Climatic change, 118(2), 167-181. https://doi.org/10.1007/s10584-012-0623-1
23. Asseng, S., Foster, I., & Turner, N. C. (2011). The impact of temperature variability on wheat yields. Global Change Biology, 17(2), 997-1012.
24. Asseng, S., McIntosh, P. C., Wang, G., & Khimashia, N. (2012). Optimal N fertiliser management based on a seasonal forecast. European journal of agronomy, 38, 66-73
25. Asseng, S., van Keulen, H., & Stol, W. (2000). Performance and application of the APSIM Nwheat model in the Netherlands. European journal of agronomy, 12(1), 37-54. https://doi.org/10.1016/S1161-0301(99)00044-1
26. ATO. (2022). TR 2022/1 Income tax: effective life of depreciating assets. https://www.ato.gov.au/law/view/document?DocID=TXR%2FTR20221%2FNAT%2FATO%2F00001
27. Baldrock, J., & Farrell, M. (2013). Analysis of soils for carbon (Land and Water sustainable agriculture flagship, Issue. https://cdn.csu.edu.au/__data/assets/pdf_file/0005/918005/Stubble-Forum-2013-02-12-Wagga-soil-carbon-Baldock.pdf
28. Ball, V. E., Cavazos, R., LaFrance, J., Pope, R., & Tack, J. (2010). Aggregation and Arbitrage in Joint Production (Vol. 7). New York, NY: Springer New York. https://doi.org/10.1007/978-1-4419-6385-7_16
29. Barlow, K., Christy, B., O’leary, G., Riffkin, P., & Nuttall, J. (2015). Simulating the impact of extreme heat and frost events on wheat crop production: A review. Field Crops Research, 171, 109-119.

30. Basra, S. M. A., Afzal, I., Anwar, S., Anwar-ul-Haq, M., Shafiq, M., & Majeed, K. (2006). Alleviation of salinity stress by seed invigoration techniques in wheat (Triticum aestivum). Seed Technology, 28(1), 36-46.
31. Basso, B., Ritchie, J. T., Cammarano, D., & Sartori, L. (2011). A strategic and tactical management approach to select optimal N fertilizer rates for wheat in a spatially variable field. European journal of agronomy, 35(4), 215-222. https://doi.org/10.1016/j.eja.2011.06.004
32. Bauer, A., & Black, A. L. (1992). Organic Carbon Effects on Available Water Capacity of Three Soil Textural Groups. Soil Science Society of America journal, 56(1), 248-254. https://doi.org/10.2136/sssaj1992.03615995005600010038x
33. Bell, M., Lester, D., & Sands, D. (2020). Strategies to improve efficiency of use of applied N, P and K fertiliser in Central Queensland (Groundcover, Issue. https://qaafi.uq.edu.au/article/2020/03/nutritional-strategies-support-productive-farming-systems
34. Bellotti, B., & Rochecouste, J. F. (2014). The development of Conservation Agriculture in Australia—Farmers as innovators. International Soil and Water Conservation Research, 2(1), 21-34. https://doi.org/https://doi.org/10.1016/S2095-6339(15)30011-3
35. Benhin, J. K. (2008). South African crop farming and climate change: An economic assessment of impacts. Global Environmental Change, 18(4), 666-678.
36. Berazneva, J., Conrad, J. M., Güereña, D. T., Lehmann, J., & Woolf, D. (2019). Agricultural Productivity and Soil Carbon Dynamics: A Bioeconomic Model. American Journal of Agricultural Economics. https://doi.org/10.1093/ajae/aaz014
37. Binkley, D., & Hart, S. C. (1989). The components of nitrogen availability assessments in forest soils. Advances in Soil Science: Volume 10, 57-112.
38. BOM. (2020). Climate data online. Retrieved 11/02/2020 from http://www.bom.gov.au/climate/data/
39. BOM. (2023). Previous Droughts. Commonwelath fo Australia. Retrieved 01/05/2023 from http://www.bom.gov.au/climate/drought/knowledge-centre/previous-droughts.shtml
40. Borrelli, P., Paustian, K., Panagos, P., Jones, A., Schütt, B., & Lugato, E. (2016). Effect of good agricultural and environmental conditions on erosion and soil organic carbon balance: a national case study. Land Use Policy, 50, 408-421.
41. Bouwman, A. F., Van Drecht, G., Knoop, J. M., Beusen, A. H. W., & Meinardi, C. R. (2005). Exploring changes in river nitrogen export to the world's oceans. Global Biogeochemical Cycles, 19(1). https://doi.org/10.1029/2004gb002314
42. Boylan, S., Beyer, K., Schlosberg, D., Mortimer, A., Hime, N., Scalley, B., Alders, R., Corvalan, C., & Capon, A. (2018). A conceptual framework for climate change, health and wellbeing in NSW, Australia. Public Health Research & Practice, 28(4).
43. Brennan, R. (2017). Monitoring Plant Nurition Levels. Retrieved 19/05/2020 from https://www.agric.wa.gov.au/mycrop/monitoring-plant-nutrition-levels
44. Brown, D. F., McCool, D. K., Papendick, R. L., & McDonough, L. M. (1985). Herbicide residues from winter wheat plots: effect of tillage and crop management. Journal of environmental quality, 14(4), 521-532. https://doi.org/10.2134/jeq1985.00472425001400040012x
45. Brown, P. R., Bridle, K. L., & Crimp, S. J. (2016). Assessing the capacity of Australian broadacre mixed farmers to adapt to climate change: Identifying constraints and opportunities. Agricultural Systems, 146, 129-141. https://doi.org/https://doi.org/10.1016/j.agsy.2016.05.002

46. Browne, N., Kingwell, R., Behrendt, R., & Eckard, R. (2013). The relative profitability of dairy, sheep, beef and grain farm enterprises in southeast Australia under selected rainfall and price scenarios. Agricultural Systems, 117, 35-44.
47. Bryan, B. A., Ward, J., & Hobbs, T. (2008). An assessment of the economic and environmental potential of biomass production in an agricultural region. Land use policy, 25(4), 533-549. https://doi.org/https://doi.org/10.1016/j.landusepol.2007.11.003
48. Burt, O. R. (1981). Farm Level Economics of Soil Conservation in the Palouse Area of the Northwest. American Journal of Agricultural Economics, 63(1), 83-92. https://doi.org/10.2307/1239814
49. Cai, R., Mullen, J. D., Wetzstein, M. E., & Bergstrom, J. C. (2013). The impacts of crop yield and price volatility on producers' cropping patterns: A dynamic optimal crop rotation model. Agricultural Systems, 116, 52-59.
50. Cai, Y., Guan, K., Lobell, D., Potgieter, A. B., Wang, S., Peng, J., Xu, T., Asseng, S., Zhang, Y., & You, L. (2019). Integrating satellite and climate data to predict wheat yield in Australia using machine learning approaches. Agricultural and forest meteorology, 274, 144-159.
51. Campbell, S. G. (1974). A SIMPLE METHOD FOR DETERMINING UNSATURATED CONDUCTIVITY FROM MOISTURE RETENTION DATA. Soil Science, 117(6), 311-314. https://doi.org/10.1097/00010694-197406000-00001
52. Cann, D. J., Hunt, J. R., & Malcolm, B. (2020). Long fallows can maintain whole-farm profit and reduce risk in semi-arid south-eastern Australia. Agricultural Systems, 178, 102721. https://doi.org/https://doi.org/10.1016/j.agsy.2019.102721
53. Carberry, P., Bruce, S., Walcott, J., & Keating, B. (2011). Innovation and productivity in dryland agriculture: a return-risk analysis for Australia. The Journal of Agricultural Science, 149(S1), 77-89.
54. Celestina, C., Hunt, J., Kuchel, H., Harris, F., Porker, K., Biddulph, B., Bloomfield, M., McCallum, M., Graham, R., Matthews, P., Aisthorpe, D., Al-Yaseri, G., Hyles, J., Trevaskis, B., Wang, E., Zhao, Z., Zheng, B., Huth, N., & Brown, H. (2023). A cultivar phenology classification scheme for wheat and barley. European journal of agronomy, 143, 126732. https://doi.org/https://doi.org/10.1016/j.eja.2022.126732
55. CER. (2022). Australian carbon credit units (ACCUs) 2022 Quarter 1 Update. Retrieved 21/03/2023 from https://www.cleanenergyregulator.gov.au/Infohub/Markets/Pages/qcmr/march-quarter-2022/Australian-carbon-credit-units-(ACCUs).aspx
56. Chan, K. Y., & Heenan, D. P. (1999). Microbial-induced soil aggregate stability under different crop rotations. Biology and fertility of soils, 30(1-2), 29-32. https://doi.org/10.1007/s003740050583
57. Charles-Edwards, D. A. (1982). Physiological determinants of crop growth (Vol. 1). Academic Press London
58. Chaudhary, M. I., Adu-Gyamfi, J. J., Saneoka, H., Nguyen, N. T., Suwa, R., Kanai, S., El-Shemy, H. A., Lightfoot, D. A., & Fujita, K. (2008). The effect of phosphorus deficiency on nutrient uptake, nitrogen fixation and photosynthetic rate in mashbean, mungbean and soybean. Acta Physiologiae Plantarum, 30(4), 537-544. https://doi.org/10.1007/s11738-008-0152-8
59. Chen, B., Liu, E., Tian, Q., Yan, C., & Zhang, Y. (2014). Soil nitrogen dynamics and crop residues. A review. Agronomy for sustainable development, 34, 429-442.
60. Chen, C., Wang, E., & Yu, Q. (2010). Modelling the effects of climate variability and water management on crop water productivity and water balance in the North

China Plain. Agricultural Water Management, 97(8), 1175-1184. https://doi.org/10.1016/j.agwat.2008.11.012

61. Chen, D., Suter, H., Islam, A., Edis, R., Freney, J. R., & Walker, C. N. (2008). Prospects of improving efficiency of fertiliser nitrogen in Australian agriculture: a review of enhanced efficiency fertilisers. Soil Research, 46(4), 289-301. https://doi.org/https://doi.org/10.1071/SR07197
62. Chen, H., Li, X., Hu, F., & Shi, W. (2013). Soil nitrous oxide emissions following crop residue addition: a meta-analysis. Global Change Biology, 19(10), 2956-2964. https://doi.org/https://doi.org/10.1111/gcb.12274
63. Chen, N.-F., Roll, R., & Ross, S. A. (1986). Economic forces and the stock market. Journal of business, 383-403.
64. Choumert, J., & Phélinas, P. (2015). Determinants of agricultural land values in Argentina. Ecological Economics, 110, 134-140. https://doi.org/https://doi.org/10.1016/j.ecolecon.2014.12.024
65. CROSSMAN, N. D., BRYAN, B. A., & SUMMERS, D. M. (2011). Carbon Payments and Low-Cost Conservation. Conservation Biology, 25(4), 835-845. https://doi.org/https://doi.org/10.1111/j.1523-1739.2011.01649.x
66. D.F&S. (2014). Land Values Issued for Wagga Wagga https://www.valuergeneral.nsw.gov.au/__data/assets/pdf_file/0003/194826/Wagga_Wagga.pdf
67. Dai, Q., Fletcher, J. J., & Lee, J. G. (1993). Incorporating stochastic variables in crop response models: implications for fertilization decisions. American Journal of Agricultural Economics, 75(2), 377-386. https://doi.org/10.2307/1242922
68. Dalal, R. C., & Chan, K. Y. (2001). Soil organic matter in rainfed cropping systems of the Australian cereal belt. Australian journal of soil research, 39(3), 435-464. https://doi.org/10.1071/SR99042
69. Davidson, E. A., & Janssens, I. A. (2006). Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. Nature, 440(7081), 165-173.
70. DCCEEW. (2022). National Inventory Report Volume 1. https://www.dcceew.gov.au/sites/default/files/documents/national-inventory-report-2020-volume-1.pdf
71. De Neve, S., & Hofman, G. (2000). Influence of soil compaction on carbon and nitrogen mineralization of soil organic matter and crop residues. Biology and fertility of soils, 30, 544-549.
72. Debonne, N. (2019). Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems: Chapter 1: Framing and Context.
73. Deihimfard, R., Eyni-Nargeseh, H., & Mokhtassi-Bidgoli, A. (2018). Effect of Future Climate Change on Wheat Yield and Water Use Efficiency Under Semi-arid Conditions as Predicted by APSIM-Wheat Model. International Journal of Plant Production, 12(2), 115-125. https://doi.org/10.1007/s42106-018-0012-4
74. Di Girolamo, G., & Barbanti, L. (2012). Treatment conditions and biochemical processes influencing seed priming effectiveness. Italian journal of agronomy, 7(2), 25-e25. https://doi.org/10.4081/ija.2012.e25
75. Doole, G., & Hertzler, G. (2011). Optimal Dynamic Management of Agricultural Land-Uses: An Application of Regime Switching. Journal of Agricultural and Applied Economics, 43(1), 43-56. https://doi.org/10.1017/S1074070800004041
76. DPI, N. (2018). Riverina Murray Region – Agricultural Profile (Important Agricultural Land Mapping, Issue.

https://www.dpi.nsw.gov.au/__data/assets/pdf_file/0009/843363/Draft-ial-mapping-riverina-murray-agricultural-profile.pdf

77. DPI, NSW. (n.d.-a). Cation Exchange Capacity. Retrieved 28/02/2023 from https://www.dpi.nsw.gov.au/agriculture/soils/guides/soil-nutrients-and-fertilisers/cec#:~:text=The%20five%20most%20abundant%20exchangeable,clay%20and%20humus%20called%20colloids.
78. DPI, NSW. (n.d.-b). Plant Nutrients in the Soil. Retrieved 28/02/2023 from https://www.dpi.nsw.gov.au/agriculture/soils/soil-testing-and-analysis/plant-nutrients
79. DPI. (2013). All Southern East Winter Crop Dryland Budgets 2012. https://www.dpi.nsw.gov.au/__data/assets/pdf_file/0006/176073/winter-dryland-south-east-full.pdf
80. DPI. (2022). Our History, New South Wales Department of Primary Industries. Retrieved 01/06/2023 from https://www.dpi.nsw.gov.au/about-us/research-development/centres/wagga/our-history#:~:text=Agricultural%20research%20commenced%20at%20Wagga,most%20famous%20wheat%20variety%2C%20Federation.
81. Droge, S., & Goss, K.-U. (2013). Development and Evaluation of a New Sorption Model for Organic Cations in Soil: Contributions from Organic Matter and Clay Minerals. Environmental Science & Technology, 47(24), 14233. https://doi.org/10.1021/es4031886
82. Dumortier, J., & Elobeid, A. (2021). Effects of a carbon tax in the United States on agricultural markets and carbon emissions from land-use change. Land use policy, 103, 105320.
83. Equip2go. (2023). 1000L plastic poly tank. Retrieved 7/03/2023 from https://www.equip2go.com.au/_mycart?ts=1678130097096899
84. Ervin, D. E., & Mill, J. W. (1985). Agricultural Land Markets and Soil Erosion: Policy Relevance and Conceptual Issues. American Journal of Agricultural Economics, 67(5), 938-942. https://doi.org/https://doi.org/10.2307/1241350
85. Evans, J. P., Ji, F., Lee, C., Smith, P., Argüeso, D., & Fita, L. (2014). Design of a regional climate modelling projection ensemble experiment – NARCliM. Geoscientific model development, 7(2), 621-629. https://doi.org/10.5194/gmd-7-621-2014
86. FAO, E. (2006). World agriculture: towards 2030/2050. Interim report, Rome.
87. FAO. (n.d.). Soil Structure. United Nations Food and Agriculture Organisation Retrieved 01/06/2023 from https://www.fao.org/fishery/docs/CDrom/FAO_Training/FAO_Training/General/x6706e/x6706e07.htm
88. Farooq, M., Basra, S. M. A., Afzal, I., & Khaliq, A. (2006). Optimization of hydropriming techniques for rice seed invigoration. Seed Science and Technology, 34(2), 507-512. https://doi.org/10.15258/sst.2006.34.2.25
89. Farooq, M., Hussain, M., Habib, M. M., Khan, M. S., Ahmad, I., Farooq, S., & Siddique, K. H. M. (2020). Influence of seed priming techniques on grain yield and economic returns of bread wheat planted at different spacings. Crop and Pasture Science, 71(8), 725. https://doi.org/10.1071/CP20065
90. Farooq, M., Irfan, M., Aziz, T., Ahmad, I., & Cheema, S. (2013). Seed priming with ascorbic acid improves drought resistance of wheat. Journal of Agronomy and Crop Science, 199(1), 12-22.
91. Farooq, M., Usman, M., Nadeem, F., Rehman, H. u., Wahid, A., Basra, S. M. A., & Siddique, K. H. M. (2019). Seed priming in field crops: potential benefits, adoption

and challenges. Crop and Pasture Science, 70(9), 731-771. https://doi.org/10.1071/CP18604

92. Farrell, M., Gupta, V., & Macdonald, L. M. (2021). Addressing the rundown of nitrogen and soil organic carbon. Proceedings GRDC Grains Research Update, Bendigo, 51-60.
93. Featherstone, A. M., Taylor, M. R., & Gibson, H. (2017). Forecasting Kansas land values using net farm income. Agricultural finance review, 77(1), 137-152. https://doi.org/10.1108/AFR-03-2016-0025
94. Feng, P., Wang, B., Li Liu, D., Waters, C., Xiao, D., Shi, L., & Yu, Q. (2020). Dynamic wheat yield forecasts are improved by a hybrid approach using a biophysical model and machine learning technique. Agricultural and forest meteorology, 285, 107922.
95. Feng, P., Wang, B., Liu, D. L., Xing, H., Ji, F., Macadam, I., Ruan, H., & Yu, Q. (2018). Impacts of rainfall extremes on wheat yield in semi-arid cropping systems in eastern Australia. Climatic change, 147(3-4), 555-569. https://doi.org/10.1007/s10584-018-2170-x
96. Fertilizer Australia. (2018). *Fertilizer Handling Code of Practice.* Fertilizer Australia Incorporated. https://fertilizer.org.au/Portals/0/Documents/COPs/Fertilizer%20Handling%20Code%20of%20Practice.pdf?ver=2018-01-10-153851-487
97. Fita, L., Evans, J., Argüeso, D., King, A., & Liu, Y. (2017). Evaluation of the regional climate response in Australia to large-scale climate modes in the historical NARCliM simulations. Climate dynamics, 49(7), 2815-2829.
98. Flohr, B. M., Hunt, J. R., Kirkegaard, J. A., & Evans, J. R. (2017). Water and temperature stress define the optimal flowering period for wheat in south-eastern Australia. Field Crops Research, 209, 108-119. https://doi.org/https://doi.org/10.1016/j.fcr.2017.04.012
99. Fortin, J., Bolinder, M., Anctil, F., Kätterer, T., Andrén, O., & Parent, L. (2011). Effects of climatic data low-pass filtering on the ICBM temperature-and moisture-based soil biological activity factors in a cool and humid climate. Ecological Modelling, 222(17), 3050-3060.
100. Foy, C. D. (1992). Soil Chemical Factors Limiting Plant Root Growth. In J. L. Hatfield & B. A. Stewart (Eds.), Limitations to Plant Root Growth (pp. 97-149). Springer New York. https://doi.org/10.1007/978-1-4612-2894-3_5
101. Gaffin, S. R., Rosenzweig, C., Xing, X., & Yetman, G. (2004). Downscaling and geo-spatial gridding of socio-economic projections from the IPCC Special Report on Emissions Scenarios (SRES). Global Environmental Change, 14(2), 105-123.
102. Ghaley, B. B., Wösten, H., Olesen, J. E., Schelde, K., Baby, S., Karki, Y. K., Børgesen, C. D., Smith, P., Yeluripati, J., Ferrise, R., Bindi, M., Kuikman, P., Lesschen, J. P., & Porter, J. R. (2018). Simulation of soil organic carbon effects on long-term winter wheat (Triticum aestivum) production under varying fertilizer inputs. Frontiers in plant science, 9, 1158. https://doi.org/10.3389/fpls.2018.01158
103. Godde, C. M., Thorburn, P. J., Biggs, J. S., & Meier, E. A. (2016). Understanding the Impacts of Soil, Climate, and Farming Practices on Soil Organic Carbon Sequestration: A Simulation Study in Australia.(Report). Frontiers in plant science, 7(2016). https://doi.org/10.3389/fpls.2016.00661
104. Goetz, R. U. (1997). Diversification in agricultural production: a dynamic model of optimal cropping to manage soil erosion. American Journal of Agricultural Economics, 79(2), 341-356.

105. Goglio, P., Grant, B. B., Smith, W. N., Desjardins, R. L., Worth, D. E., Zentner, R., & Malhi, S. S. (2014). Impact of management strategies on the global warming potential at the cropping system level. Science of The Total Environment, 490, 921-933. https://doi.org/https://doi.org/10.1016/j.scitotenv.2014.05.070
106. Gomez-Macpherson, H., & Richards, R. A. (1995). Effect of sowing time on yield and agronomic characteristics of wheat in south-eastern Australia. Australian Journal of Agricultural Research, 46(7), 1381-1399. https://doi.org/10.1071/AR9951381
107. Goodwin, B. K., Mishra, A. K., & Ortalo-Magné, F. N. (2003). What's Wrong with Our Models of Agricultural Land Values? American Journal of Agricultural Economics, 85(3), 744-752. http://www.jstor.org/stable/1245006
108. Görlach, B., Landgrebe-Trinkunaite, R., Interwies, E., Bouzit, M., Darmendrail, D., & Rinaudo, J.-D. (2004). Assessing the economic impacts of soil degradation. Volume IV: Executive Summary. Study commissioned by the European Commission, DG Environment, Berlin.
109. Grace, P., Post, W., Godwin, D., Bryceson, K., Truscott, M., & Hennessy, K. J. (2019). Soil carbon dynamics in relation to soil surface management and cropping systems in Australian agroecosystems. Management of carbon sequestration in soil, 175-193.
110. Grafton, R. Q., Williams, J., & Jiang, Q. (2015). Food and water gaps to 2050: preliminary results from the global food and water system (GFWS) platform [journal article]. Food Security, 7(2), 209-220. https://doi.org/10.1007/s12571-015-0439-8
111. GrainTrade. (2020). GTA Location Differentials 2020/2021 - NSW. Retrieved 13/03/2023 from https://www.graintrade.org.au/sites/default/files/Final%202020_21%20GTA%20Location%20Differentials%20NSW.pdf
112. GrainTrade. (2021). 2021/22 Bulk Wheat and Non-Wheat Port Terminal Services Fee Summary. Retrieved 13/03/2023 from https://grains.graincorp.com.au/wp-content/uploads/2021/02/2021-2022-Pricing-Schedules-PTSA.pdf
113. Gray, J., & Bishop, T. (2018). Climate Change Impacts on Three Key Soil Properties in New South Wales.
114. GRDC. (2018). Grow Notes Section 5, Plant Growth and Physiology. Southern Section. https://grdc.com.au/__data/assets/pdf_file/0019/366211/GrowNote-Peas-South-5-Plant-Growth-Physiology.pdf
115. Gretton, P., & Salma, U. (1996). Land degradation and the Australian agricultural industry. Industry Commission Canberra.
116. Grosjean, G., Fuss, S., Koch, N., Bodirsky, B. L., De Cara, S., & Acworth, W. (2018). Options to overcome the barriers to pricing European agricultural emissions. Climate Policy, 18(2), 151-169.
117. Guenther, M., Saunders, J. T., & Driver, T. (2022). Emissions targets of New Zealand’s agricultural export competitors–.
118. Halvorson, A. D., Wienhold, B. J., & Black, A. L. (2002). Tillage, nitrogen, and cropping system effects on soil carbon sequestration.
119. Hamza, M., & Anderson, W. K. (2005). Soil compaction in cropping systems: A review of the nature, causes and possible solutions. Soil and Tillage Research, 82(2), 121-145.
120. Harries, M., Flower, K. C., & Scanlan, C. A. (2021). Sustainability of nutrient management in grain production systems of south-west Australia. Crop and Pasture Science, 72(3), 197-212. https://doi.org/10.1071/CP20403
121. Harris, F., Graham, R., Matthews, P., Burch, D., Koetz, E., Menz, I., McMaster, C., & Mumford, M. (2019). Yield responses to sowing date in southern NSW: one

cultivar doesn’t fit all. http://agronomyaustraliaproceedings.org/images/sampledata/2019/2019ASA_Harris_Felicity_262.pdf

122. Heenan, D. P. (1995). Effects of broad-leaf crops and their sowing time on subsequent wheat production. Field Crops Research, 43(1), 19-29. https://doi.org/https://doi.org/10.1016/0378-4290(95)00033-M
123. Hemmings, B., & Hill, D. (2003). A promising strategy for service delivery in rural Australia. Society for the Provision of Education in Rural Australia Conference,
124. Hertzler, G. (2007). Adapting to climate change and managing climate risks by using real options. Australian Journal of Agricultural Research, 58(10), 985-992. https://doi.org/https://doi.org/10.1071/AR06192
125. Hobbs, P. R., Sayre, K., & Gupta, R. (2008). The role of conservation agriculture in sustainable agriculture. Philosophical Transactions of the Royal Society B: Biological Sciences, 363(1491), 543-555.
126. Hochman, Z., Gobbett, D. L., & Horan, H. (2017). Climate trends account for stalled wheat yields in Australia since 1990. Global Change Biology, 23(5), 2071-2081. https://doi.org/https://doi.org/10.1111/gcb.13604
127. Hofman, G. v. C., Oswald. (2004). Soil and Plant Nitrogen. (International Fertiliser Association)
128. Holzworth, D. P., Huth, N. I., deVoil, P. G., Zurcher, E. J., Herrmann, N. I., McLean, G., Chenu, K., van Oosterom, E. J., Snow, V., Murphy, C., Moore, A. D., Brown, H., Whish, J. P. M., Verrall, S., Fainges, J., Bell, L. W., Peake, A. S., Poulton, P. L., Hochman, Z., Thorburn, P. J., Gaydon, D. S., Dalgliesh, N. P., Rodriguez, D., Cox, H., Chapman, S., Doherty, A., Teixeira, E., Sharp, J., Cichota, R., Vogeler, I., Li, F. Y., Wang, E., Hammer, G. L., Robertson, M. J., Dimes, J. P., Whitbread, A. M., Hunt, J., van Rees, H., McClelland, T., Carberry, P. S., Hargreaves, J. N. G., MacLeod, N., McDonald, C., Harsdorf, J., Wedgwood, S., & Keating, B. A. (2014). APSIM – Evolution towards a new generation of agricultural systems simulation. Environmental Modelling & Software, 62, 327-350. https://doi.org/https://doi.org/10.1016/j.envsoft.2014.07.009
129. Howitt, R. E., Medellín-Azuara, J., MacEwan, D., & Lund, J. R. (2012). Calibrating disaggregate economic models of agricultural production and water management. Environmental Modelling & Software, 38, 244-258.
130. http://primo-direct-apac.hosted.exlibrisgroup.com/openurl/61LATROBE/LATROBE_SERVICES_PAGE?url_ver=Z39.88-2004&rft_val_fmt=info:ofi/fmt:kev:mtx:journal&genre=article&sid=ProQ:ProQ%3Aabiglobal&atitle=Measuring+the+contributions+of+site+characteristics+to+the+value+of+agricultural+land&title=Land+Economics&issn=00237639&date=1993-11-01&volume=69&issue=4&spage=356&au=Xu%2C+Feng%3BMittelhammer%2C+Ron+C%3BBarkley%2C+Paul+W&isbn=&jtitle=Land+Economics&btitle=&rft_id=info:eric/00771677&rft_id=info:doi/
131. https://doi.org/https://doi.org/10.1016/j.agsy.2013.01.002
132. Hughes, L., Steffen, W., Rice, M., & Pearce, A. (2015). Feeding a hungry nation: Climate change, food and farming in Australia.
133. Hunt, J. (2021). Managing nitrogen for high crop yields and sustainable farming systems (Grains Research Update, Wagga Wagga, NSW, Issue. https://grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2020/07/managing-nitrogen-for-high-crop-yields-and-sustainable-farming-systems

134. Hunt, J. R., Lilley, J. M., Trevaskis, B., Flohr, B. M., Peake, A., Fletcher, A., Zwart, A. B., Gobbett, D., & Kirkegaard, J. A. (2019). Early sowing systems can boost Australian wheat yields despite recent climate change. Nature Climate Change, 9(3), 244-247.
135. Ignaciuk, A., & Mason-D'Croz, D. (2014). Modelling adaptation to climate change in agriculture.
136. Imran, M., Mahmood, A., Römheld, V., & Neumann, G. (2013). Nutrient seed priming improves seedling development of maize exposed to low root zone temperatures during early growth. European journal of agronomy, 49, 141-148. https://doi.org/https://doi.org/10.1016/j.eja.2013.04.001
137. IPNI. (2019). IPNI Estimates of Plant Nutrient Uptake and Removal. Retrieved 19/05/2020 from http://www.ipni.net/article/IPNI-3296
138. Irving, D. E., & Silsbury, J. H. (1987). A Comparison of the Rate of Maintenance Respiration in Some Crop Legumes and Tobacco Determined by Three Methods. Annals of Botany, 59(3), 257-264. www.jstor.org/stable/42757768
139. Jacks, D. S., O'Rourke, K. H., & Williamson, J. G. (2011). Commodity Price Volatility and World Market Integration since 1700. The Review of Economics and Statistics, 93(3), 800-813. https://doi.org/10.1162/REST_a_00091
140. Jeffrey, S. J., Carter, J. O., Moodie, K. B., & Beswick, A. R. (2001). Using spatial interpolation to construct a comprehensive archive of Australian climate data. Environmental Modelling & Software, 16(4), 309-330. https://doi.org/https://doi.org/10.1016/S1364-8152(01)00008-1
141. Jisha, K. C., Jisha, K. C., Vijayakumari, K., Vijayakumari, K., Puthur, J. T., & Puthur, J. T. (2013). Seed priming for abiotic stress tolerance: an overview. Acta Physiologiae Plantarum, 35(5), 1381-1396. https://doi.org/10.1007/s11738-012-1186-5
142. John, M., Pannell, D., & Kingwell, R. (2005). Climate Change and the Economics of Farm Management in the Face of Land Degradation: Dryland Salinity in Western Australia. Canadian Journal of Agricultural Economics/Revue canadienne d'agroeconomie, 53(4), 443-459. https://doi.org/https://doi.org/10.1111/j.1744-7976.2005.00029.x
143. Jones, J. W., Hoogenboom, G., Porter, C. H., Boote, K. J., Batchelor, W. D., Hunt, L., Wilkens, P. W., Singh, U., Gijsman, A. J., & Ritchie, J. T. (2003). The DSSAT cropping system model. European journal of agronomy, 18(3-4), 235-265.
144. Kandulu, J. M., Bryan, B. A., King, D., & Connor, J. D. (2012). Mitigating economic risk from climate variability in rain-fed agriculture through enterprise mix diversification. Ecological Economics, 79, 105-112. https://doi.org/https://doi.org/10.1016/j.ecolecon.2012.04.025
145. Kariuki, L., Masinde, P., Onyango, A., Githiri, M., & Ogila, K. (2014). The growth and seed yield of five linseed (Linum usitatissimum L.) varieties as influenced by nitrogen application. Journal of animal and Plant Sciences, 22, 3493-3509.
146. Kaur, S., Gupta, A. K., & Kaur, N. (2002). Effect of osmo- and hydropriming of chickpea seeds on seedling growth and carbohydrate metabolism under water deficit stress. Plant growth regulation, 37(1), 17-22. https://doi.org/10.1023/A:1020310008830
147. Keating, B. A., Carberry, P. S., Hammer, G. L., Probert, M. E., Robertson, M. J., Holzworth, D., Huth, N. I., Hargreaves, J. N. G., Meinke, H., Hochman, Z., McLean, G., Verburg, K., Snow, V., Dimes, J. P., Silburn, M., Wang, E., Brown, S., Bristow, K. L., Asseng, S., Chapman, S., McCown, R. L., Freebairn, D. M., & Smith, C. J. (2003). An overview of APSIM, a model designed for farming systems simulation.

European Journal of Agronomy, 18(3), 267-288. https://doi.org/https://doi.org/10.1016/S1161-0301(02)00108-9

148. Kerridge, E. (1969). The Agricultural Revolution Reconsidered. Agricultural History, 43(4), 463-476. http://www.jstor.org/stable/4617724
149. Khazaei, F., Hamzi, S., & Heidari-Sharifabad, H. (2009). Improvement of seed germination traits in canola (Brassica napus L.) as affected by saline and drought stresses. Plant Ecophysiol., 3.
150. Kik, M. C., Claassen, G. D. H., Meuwissen, M. P. M., Smit, A. B., & Saatkamp, H. W. (2021). The economic value of sustainable soil management in arable farming systems – A conceptual framework. European journal of agronomy, 129, 126334. https://doi.org/10.1016/j.eja.2021.126334
151. King, D. A., & Sinden, J. (1988). Influence of soil conservation on farm land values. Land economics, 64(3), 242-255.
152. King, D. A., & Sinden, J. A. (1994). Price Formation in Farm Land Markets. Land economics, 70(1), 38-52. https://doi.org/10.2307/3146439
153. Kingwell, R. S. (2011). Revenue volatility faced by Australian wheat farmers.
154. Kingwell, R. S., Morrison, D. A., & Bathgate, A. D. (1992). The effect of climatic risk on dryland farm management. Agricultural Systems, 39(2), 153-175. https://doi.org/https://doi.org/10.1016/0308-521X(92)90106-X
155. Kingwell, R., Anderton, L., Islam, N., Xayavong, V., Wardell-Johnson, A., Feldman, D., & Speijers, J. (2014). Broadacre farmers adapting to a changing climate. Applied Studies in Climate Adaptation, 130-138.
156. Kleemann, S., & Gill, G. (2010). Variation in the response of canola cultivars to changes in row spacing. " Food Security from Sustainable Agriculture", Proceedings of the 15th Australian Agronomy Conference, 15-18 November 2010, Lincoln, New Zealand,
157. Knops, J. M. H., & Tilman, D. (2000). DYNAMICS OF SOIL NITROGEN AND CARBON ACCUMULATION FOR 61 YEARS AFTER AGRICULTURAL ABANDONMENT. Ecology, 81(1), 88-98. https://doi.org/https://doi.org/10.1890/0012-9658(2000)081[0088:DOSNAC]2.0.CO;2
158. Koch, A., Chappell, A., Eyres, M., & Scott, E. (2015). Monitor Soil Degradation or Triage for Soil Security? An Australian Challenge. Sustainability, 7(5), 4870-4892. https://www.mdpi.com/2071-1050/7/5/4870
159. Koetz., E., Kanaley, H. & Harris., F. (2016). Wheat cultivar and sowing date getting it right to maximize grain yield in Southern NSW. Grains Research Development Corporation. https://grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2016/02/wheat-cultivar-and-sowing-date-getting-it-right
160. Koo, J. (2016). DSSAT listed as one of the greatest accomplishments of the UF-IFAS. https://dssat.net/2164
161. Kragt, M. E., Pannell, D. J., Robertson, M. J., & Thamo, T. (2012). Assessing costs of soil carbon sequestration by crop-livestock farmers in Western Australia. Agricultural Systems, 112, 27-37. https://doi.org/https://doi.org/10.1016/j.agsy.2012.06.005
162. LaFrance, J. T., Shimshack, J. P., & Wu, S. (2002). Crop Insurance & the Extensive Margin.
163. LaFrance, J., Pope, R., & Tack, J. (2011). Risk response in agriculture (0898-2937).
164. Lal, R. (2004). Soil carbon sequestration to mitigate climate change. Geoderma, 123(1), 1-22. https://doi.org/https://doi.org/10.1016/j.geoderma.2004.01.032

165. Lange, M., Eisenhauer, N., Sierra, C. A., Bessler, H., Engels, C., Griffiths, R. I., Mellado-Vázquez, P. G., Malik, A. A., Roy, J., & Scheu, S. (2015). Plant diversity increases soil microbial activity and soil carbon storage. Nature Communications, 6(1), 1-8.
166. Lassaletta, L. (2014). 50 year trends in nitrogen use efficiency of world cropping systems: the relationship between yield and nitrogen input to cropland. Environmental Resource Letters, 9. https://doi.org/doi: `10.1088/1748-9326/9/10/1050011
167. Lee, K. C., Cunningham, B. A., Paulsen, G. M., Liang, G. H., & Moore, R. B. (1976). Effects of Cadmium on Respiration Rate and Activities of Several Enzymes in Soybean Seedlings. Physiologia Plantarum, 36(1), 4-6. https://doi.org/10.1111/j.1399-3054.1976.tb05017.x
168. Leirós, M. C., Trasar-Cepeda, C., Seoane, S., & Gil-Sotres, F. (1999). Dependence of mineralization of soil organic matter on temperature and moisture. Soil Biology and Biochemistry, 31(3), 327-335. https://doi.org/10.1016/S0038-0717(98)00129-1
169. Li, G. D., Conyers, M. K., Schwenke, G. D., Hayes, R. C., Li Liu, D., Lowrie, A. J., Poile, G. J., Oates, A. A., & Lowrie, R. J. (2016). Tillage does not increase nitrous oxide emissions under dryland canola (Brassica napus L.) in a semiarid environment of south-eastern Australia.(Report). Soil Research, 54(5), 512. https://doi.org/10.1071/SR15289
170. Li, S., Wang, B., Feng, P., Liu, D. L., Li, L., Shi, L., & Yu, Q. (2022). Assessing climate vulnerability of historical wheat yield in south-eastern Australia's wheat belt. Agricultural Systems, 196, 103340. https://doi.org/https://doi.org/10.1016/j.agsy.2021.103340
171. Liu, B., Wang, X., Ma, L., Chadwick, D., & Chen, X. (2021). Combined applications of organic and synthetic nitrogen fertilizers for improving crop yield and reducing reactive nitrogen losses from China’s vegetable systems: A meta-analysis. Environmental Pollution, 269, 116143. https://doi.org/https://doi.org/10.1016/j.envpol.2020.116143
172. Ludwig, F., & Asseng, S. (2006). Climate change impacts on wheat production in a Mediterranean environment in Western Australia. Agricultural Systems, 90(1), 159-179. https://doi.org/https://doi.org/10.1016/j.agsy.2005.12.002
173. Ludwig, F., Milroy, S. P., & Asseng, S. (2009). Impacts of recent climate change on wheat production systems in Western Australia. Climatic change, 92(3), 495-517.
174. Luo, Z., Wang, E., Fillery, I. R. P., Macdonald, L. M., Huth, N., & Baldock, J. (2014). Modelling soil carbon and nitrogen dynamics using measurable and conceptual soil organic matter pools in APSIM. Agriculture, Ecosystems & Environment, 186, 94-104. https://doi.org/https://doi.org/10.1016/j.agee.2014.01.019
175. Lynch, J. P. (2007). Roots of the second green revolution. Australian Journal of Botany, 55(5), 493-512.
176. Magdoff, F., & Weil, R. R. (2004). Soil organic matter in sustainable agriculture. CRC press.
177. Magnani, F., Mencuccini, M., Borghetti, M., Berbigier, P., Berninger, F., Delzon, S., Grelle, A., Hari, P., Jarvis, P. G., & Kolari, P. (2007). The human footprint in the carbon cycle of temperate and boreal forests. Nature, 447(7146), 849-851.
178. Mahawar, M. K., Samuel, D. V. K., Sinha, J. P., & Jalgaonkar, K. (2016). Optimization of pea (Pisum sativum) seeds hydropriming by application of response surface methodology. Acta Physiologiae Plantarum, 38(9), 1-13. https://doi.org/10.1007/s11738-016-2234-3

179. Mahawar, M. K., Samuel, D. V. K., Sinha, J. P., & Jalgaonkar, K. (2016). Optimization of pea (Pisum sativum) seeds hydropriming by application of response surface methodology. Acta physiologiae plantarum, 38(9), 1-13. https://doi.org/10.1007/s11738-016-2234-3
180. Mahjourimajd, S., Taylor, J., Rengel, Z., Khabaz-Saberi, H., Kuchel, H., Okamoto, M., & Langridge, P. (2016). The Genetic Control of Grain Protein Content under Variable Nitrogen Supply in an Australian Wheat Mapping Population. PLoS One, 11(7), e0159371-e0159371. https://doi.org/10.1371/journal.pone.0159371
181. Major, D. J. (1980). PHOTOPERIOD RESPONSE CHARACTERISTICS CONTROLLING FLOWERING OF NINE CROP SPECIES. Canadian Journal of Plant Science, 60(3), 777-784. https://doi.org/10.4141/cjps80-115
182. Mallawaarachchi, T., Nauges, C., Sanders, O., & Quiggin, J. (2017). State-contingent analysis of farmers' response to weather variability: irrigated dairy farming in the Murray Valley, Australia. The Australian journal of agricultural and resource economics, 61(1), 36-55. https://doi.org/10.1111/1467-8489.12193
183. Mann, L., Tolbert, V., & Cushman, J. (2002). Potential environmental effects of corn (Zea mays L.) stover removal with emphasis on soil organic matter and erosion. Agriculture, ecosystems & environment, 89(3), 149-166. https://doi.org/https://doi.org/10.1016/S0167-8809(01)00166-9
184. Mannaf, M., Zuo, A., & Wheeler, S. A. (2022). The spatial influences of organic farming and environmental heterogeneity on biodiversity in South Australian landscapes. Journal of Environmental Management, 324, 116414.
185. Maphosa, L., Langridge, P., Taylor, H., Emebiri, L. C., & Mather, D. E. (2015). Genetic control of grain protein, dough rheology traits and loaf traits in a bread wheat population grown in three environments. Journal of cereal science, 64, 147-152. https://doi.org/10.1016/j.jcs.2015.05.010
186. Marcos-Martinez, R., Bryan, B. A., Connor, J. D., & King, D. (2017). Agricultural land-use dynamics: Assessing the relative importance of socioeconomic and biophysical drivers for more targeted policy. Land use policy, 63, 53-66.
187. Marsh, S. P., Pannell, D. J., & Lindner, R. K. (2004). Does agricultural extension pay? Agricultural Economics, 30(1), 17-30. https://doi.org/https://doi.org/10.1111/j.1574-0862.2004.tb00173.x
188. Mary, B., Recous, S., Darwis, D., & Robin, D. (1996). Interactions between decomposition of plant residues and nitrogen cycling in soil. Plant and soil, 181, 71-82.
189. Mase, A. S., Gramig, B. M., & Prokopy, L. S. (2017). Climate change beliefs, risk perceptions, and adaptation behavior among Midwestern U.S. crop farmers. Climate Risk Management, 15, 8-17. https://doi.org/https://doi.org/10.1016/j.crm.2016.11.004
190. Matthews, P., McCaffery, D., & Jenkins, L. (2020). Winter crop variety sowing guide 2020. NSW DPI. https://grdc.com.au/resources-and-publications/all-publications/nvt-crop-sowing-guides/2020/nsw-winter-crop-variety-sowing-guide-2020.pdf
191. Mavi, K., Ermis, S., & Demir, I. (2006). The effect of priming on tomato rootstock seeds in relation to seedling growth. Asian Journal of Plant Sciences, 5(6), 940-947.
192. McConnell, K. (1983). An economic model of soil conservation. American Journal of Agricultural Economics, 65(1), 83-89. https://doi.org/10.2307/1240340
193. McCown, R. L., Hammer, G. L., Hargreaves, J. N. G., Holzworth, D. P., & Freebairn, D. M. (1996). APSIM: a novel software system for model development,

model testing and simulation in agricultural systems research. Agricultural Systems, 50(3), 255-271. https://doi.org/10.1016/0308-521X(94)00055-V

194. McDonald, G., & O'Leary, R. (2016). Drought tolerance of wheat varieties (GRDC Update Papers, Issue. https://grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2016/02/drought-tolerance-fo-wheat-varieties

195. McKenzie, D. C. (2013). Visual soil examination techniques as part of a soil appraisal framework for farm evaluation in Australia. Soil & tillage research, 127, 26-33. https://doi.org/10.1016/j.still.2012.05.004

196. McKenzie, N. (2004). Australian Soils and Landscapes An Illustrated Compendium. Melbourne : CSIRO Publishing.

197. McKenzie, N., Jacquier, D., Maschmedt, D., Griffin, E., & Brough, D. (2012). The Australian soil resource information system (ASRIS) technical specifications. Revised Version, 1(6).

198. McNunn, G., Heaton, E., Archontoulis, S., Licht, M., & VanLoocke, A. (2019). Using a crop modeling framework for precision cost-benefit analysis of variable seeding and nitrogen application rates. Frontiers in sustainable food systems, 108.

199. Meier, E. A., Thorburn, P. J., Kragt, M. E., Dumbrell, N. P., Biggs, J. S., Hoyle, F. C., & van Rees, H. (2017). Greenhouse gas abatement on southern Australian grains farms: Biophysical potential and financial impacts. Agricultural Systems, 155, 147-157. https://doi.org/https://doi.org/10.1016/j.agsy.2017.04.012

200. Mendelsohn, R., & Dinar, A. (2003). Climate, Water, and Agriculture. Land economics, 79(3), 328-341. https://EconPapers.repec.org/RePEc:uwp:landec:v:79:y:2003:i:3:p:328-341

201. Mendes, J., Pinho, T. M., Neves dos Santos, F., Sousa, J. J., Peres, E., Boaventura-Cunha, J., Cunha, M., & Morais, R. (2020). Smartphone applications targeting precision agriculture practices—A systematic review. Agronomy, 10(6), 855.

202. Menegat, S., Ledo, A., & Tirado, R. (2022). Greenhouse gas emissions from global production and use of nitrogen synthetic fertilisers in agriculture. Scientific Reports, 12(1). https://doi.org/10.1038/s41598-022-18773-w

203. Meppem, G. (2020). GRDC Grains Research Update (GRDC Grains Research Update, Issue.

204. Mielenz, H., Thorburn, P. J., Harris, R. H., Officer, S. J., Li, G., Schwenke, G. D., & Grace, P. R. (2016). Nitrous oxide emissions from grain production systems across a wide range of environmental conditions in eastern Australia. Soil Research, 54(5), 659-674.

205. Ministry for the Environment. (2023). *National Policy Statement for Freshwater Management 2020.* Ministry for the Environment, New Zealand. https://environment.govt.nz/assets/publications/National-Policy-Statement-for-Freshwater-Management-2020.pdf

206. Miranowski, J. (1984). Impacts of productivity loss on crop production and management in a dynamic economic model. American Journal of Agricultural Economics, 66(1), 61-71. https://doi.org/10.2307/1240616

207. Mjelde, J. W., Sonka, S. T., Dixon, B. L., & Lamb, P. J. (1988). Valuing Forecast Characteristics in a Dynamic Agricultural Production System. American Journal of Agricultural Economics, 70(3), 674-684. https://doi.org/10.2307/1241506

208. Moll, R. H., Kamprath, E. J., & Jackson, W. A. (1982). Analysis and Interpretation of Factors Which Contribute to Efficiency of Nitrogen Utilization1. Agronomy Journal, 74(3), 562-564. https://doi.org/https://doi.org/10.2134/agronj1982.00021962007400030037x

209. Monjardino, M., Hochman, Z., & Horan, H. (2019). Yield potential determines Australian wheat growers' capacity to close yield gaps while mitigating economic risk. Agronomy for sustainable development, 39(6), 49. https://doi.org/10.1007/s13593-019-0595-x
210. Monjardino, M., McBeath, T., Ouzman, J., Llewellyn, R., & Jones, B. (2015). Farmer risk-aversion limits closure of yield and profit gaps: A study of nitrogen management in the southern Australian wheatbelt. Agricultural Systems, 137, 108-118. https://doi.org/https://doi.org/10.1016/j.agsy.2015.04.006
211. Movahhedy-Dehnavy, M., Modarres-Sanavy, S. A. M., & Mokhtassi-Bidgoli, A. (2009). Foliar application of zinc and manganese improves seed yield and quality of safflower (Carthamus tinctorius L.) grown under water deficit stress. Industrial Crops and Products, 30(1), 82-92. https://doi.org/https://doi.org/10.1016/j.indcrop.2009.02.004
212. MoverDB. (2023). 2023 Sea Freight Container Shipping Rates To & From Australia. MoverDB. Retrieved 6/03/2023 from https://moverdb.com/container-shipping/australia/
213. Moxey, A., & White, B. (1994). Efficient compliance with agricultural nitrate pollution standards. Journal of Agricultural Economics, 45(1), 27-37.
214. Müller, C., & Robertson, R. D. (2014). Projecting future crop productivity for global economic modeling. Agricultural Economics, 45(1), 37-50. https://doi.org/10.1111/agec.12088
215. Mulvaney, R., Khan, S., & Ellsworth, T. (2009). Synthetic nitrogen fertilizers deplete soil nitrogen: a global dilemma for sustainable cereal production. Journal of environmental quality, 38(6), 2295-2314.
216. Murray, G. M., & Brennan, J. P. (2009). Estimating disease losses to the Australian wheat industry. Australasian Plant Pathology, 38(6), 558-570. https://doi.org/10.1071/AP09053
217. Nelson, D. R., & Mele, P. M. (2006). The impact of crop residue amendments and lime on microbial community structure and nitrogen-fixing bacteria in the wheat rhizosphere. Australian journal of soil research, 44(7), 319.
218. Nelson, G. C., Valin, H., Sands, R. D., Havlík, P., Ahammad, H., Deryng, D., Elliott, J., Fujimori, S., Hasegawa, T., Heyhoe, E., Kyle, P., Von Lampe, M., Lotze-Campen, H., Mason d'Croz, D., van Meijl, H., van der Mensbrugghe, D., Müller, C., Popp, A., Robertson, R., Robinson, S., Schmid, E., Schmitz, C., Tabeau, A., & Willenbockel, D. (2014). Climate change effects on agriculture: Economic responses to biophysical shocks. Proceedings of the National Academy of Sciences, 111(9), 3274-3279. https://doi.org/10.1073/pnas.1222465110
219. Nordblom, T. L., Hutchings, T. R., Godfrey, S. S., & Schefe, C. R. (2021). Precision variable rate nitrogen for dryland farming on waterlogging Riverine Plains of Southeast Australia?. Agricultural Systems, 186, 102962.
220. O'Keeffe, P. (2018). Maximising efficiency, marginalising equity: a genealogy of Australian wheat export market deregulation and 'the good farmer'. Australian Geographer, 49(4), 497-515. https://doi.org/10.1080/00049182.2017.1353585
221. Oldfield, E. E., Bradford, M. A., & Wood, S. A. (2019). Global meta-analysis of the relationship between soil organic matter and crop yields. SOIL, 5(1), 15-32. https://doi.org/10.5194/soil-5-15-2019
222. Olof, A., & Thomas, K. (1997). ICBM: The Introductory Carbon Balance Model for Exploration of Soil Carbon Balances. Ecological applications, 7(4), 1226-1236. https://doi.org/10.1890/1051-0761(1997)007[1226:ITICBM]2.0.CO

223. Pachauri, R. K., & Meyer, L. A. (2014). IPCC Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.
224. Pal, R. N., Rai, V. K., & Laloraya, M. M. (1973). Calcium in Relation to Respiratory Activity of Peanut and Linseed Plants. Biochemie und Physiologie der Pflanzen, 164(3), 258-265. https://doi.org/10.1016/S0015-3796(17)30694-7
225. Palmquist, R. B., & Danielson, L. E. (1989). A Hedonic Study of the Effects of Erosion Control and Drainage on Farmland Values. American Journal of Agricultural Economics, 71(1), 55-62. https://doi.org/10.2307/1241774
226. Pannell, D. J. (2017). Economic perspectives on nitrogen in farming systems: managing trade-offs between production, risk and the environment. Soil research (Collingwood, Vic.), 55(5-6), 473. https://doi.org/10.1071/SR16284
227. Pannell, D. J., Llewellyn, R. S., & Corbeels, M. (2014). The farm-level economics of conservation agriculture for resource-poor farmers. Agriculture, ecosystems & environment, 187, 52-64. https://doi.org/https://doi.org/10.1016/j.agee.2013.10.014
228. Parton, W., Stewart, J., & Cole, C. (1988). Dynamics of C, N, P and S in grassland soils: a model. Biogeochemistry, 5(1), 109-131. https://doi.org/10.1007/BF02180320
229. Patanè, C., Cavallaro, V., Avola, G., & D'Agosta, G. (2006). Seed respiration of sorghum [Sorghum bicolor (L.) Moench] during germination as affected by temperature and osmoconditioning. Seed Sci. Res., 16(4), 251-260. https://doi.org/10.1017/SSR2006259
230. Patra, S., Mehera, B., Rout, S., Tomar, S., Singh, M., & Kumar, R. (2016). Effect of hydropriming and different sowing dates on growth and yield attributes of Wheat (Triticum aestivum L.). Journal of Applied and Natural Science, 8, 971-980. https://doi.org/10.31018/jans.v8i2.907
231. Pedersen, S. M., & Lind, K. M. (2017). Precision agriculture: Technology and economic perspectives. Springer.
232. Pedrini, S., Balestrazzi, A., Madsen, M. D., Bhalsing, K., Hardegree, S. P., Dixon, K. W., & Kildisheva, O. A. (2020). Seed enhancement: getting seeds restoration-ready. Restoration Ecology, 28, S266-S275.
233. Petersen, E., & Hoyle, F. C. (2016). Estimating the economic value of soil organic carbon for grains cropping systems in Western Australia. Soil Research, 54(4), 383-396.
234. Phipps, T. T. (1984). Land Prices and Farm-Based Returns. American Journal of Agricultural Economics, 66(4), 422-429. https://doi.org/10.2307/1240920
235. Pill, W. G., Collins, C. M., Goldberger, B., & Gregory, N. (2009). Responses of non-primed or primed seeds of ‘Marketmore 76’ cucumber (Cucumis sativus L.) slurry coated with Trichoderma species to planting in growth media infested with Pythium aphanidermatum. Scientia horticulturae, 121(1), 54-62. https://doi.org/10.1016/j.scienta.2009.01.004
236. Plantinga, A. J., Lubowski, R. N., & Stavins, R. N. (2002). The effects of potential land development on agricultural land prices. Journal of urban economics, 52(3), 561-581. https://doi.org/https://doi.org/10.1016/S0094-1190(02)00503-X
237. Pluske, W., Murphy, D., & Sheppard, J. (2023). Facts sheets: Total organic carbon soilquality.org.au. Retrieved 28/02/2023 from https://www.soilquality.org.au/factsheets/organic-carbon
238. Poor, P. J., Pessagno, K. L., & Paul, R. W. (2007). Exploring the hedonic value of ambient water quality: a local watershed-based study. Ecological Economics, 60(4), 797-806.

239. Pope, C. A., Bhide, S., & Heady, E. O. (1983). The Economics of Soil Conservation: An Optimal Control Theory Approach. North Central Journal of Agricultural Economics, 5(2), 83-89. https://doi.org/10.2307/1349143
240. Pope, R. D., & Chavas, J. P. (1994). Cost Functions Under Production Uncertainty. American Journal of Agricultural Economics, 76(2), 196-204. https://doi.org/10.2307/1243621
241. Potgieter, A., Meinke, H., Doherty, A., Sadras, V., Hammer, G., Crimp, S., & Rodriguez, D. (2013). Spatial impact of projected changes in rainfall and temperature on wheat yields in Australia. Climatic change, 117, 163-179.
242. Price, P. (2009). Preface: Nutrient management by the Australian grains industry. Soil Research, 47(1), i-iii.
243. Probert, M. E., Dimes, J. P., Keating, B. A., Dalal, R. C., & Strong, W. M. (1998). APSIM's water and nitrogen modules and simulation of the dynamics of water and nitrogen in fallow systems. Agricultural Systems, 56(1), 1-28. https://doi.org/https://doi.org/10.1016/S0308-521X(97)00028-0
244. R.B.A. (2020). Historical Data. Reserve Bank of Australia. Retrieved 21/10/2020 from https://www.rba.gov.au/statistics/historical-data.html#interest-rates
245. Rötter, R.P., Fichtler, M.A.E., Kersebaum, K.C., Trnka, M., & Hoffmann, M.P. (2018). Linking modelling and experimentation to better capture crop impacts of agroclimatic extremes—A review, . Field Crops Research, 221, 142-156. https://doi.org/https://doi.org/10.1016/j.fcr.2018.02.023.
246. Rabbi, S. M. F., Tighe, M., Cowie, A., Wilson, B. R., Schwenke, G., McLeod, M., Badgery, W., & Baldock, J. (2014). The relationships between land uses, soil management practices, and soil carbon fractions in South Eastern Australia. Agriculture, ecosystems & environment, 197, 41-52. https://doi.org/10.1016/j.agee.2014.06.020
247. RBA. (2023). Inflation calculator. Reserve Bank of Australia. Retrieved 15/3/2023 from https://www.rba.gov.au/calculator/
248. Reader, M. A., Revoredo-Giha, C., Lawrence, R. J., Hodge, I. D., & LANG, B. G. (2018). Farmers’ spending on variable inputs tends to maximise crop yields, not profit. International Journal of Agricultural Management, 7(1), 1-11.
249. Reay, D. S., Davidson, E. A., Smith, K. A., Smith, P., Melillo, J. M., Dentener, F., & Crutzen, P. J. (2012). Global agriculture and nitrous oxide emissions. Nature Climate Change, 2(6), 410-416.
250. Reichstein, M., Bednorz, F., Broll, G., & Kätterer, T. (2000). Temperature dependence of carbon mineralisation: conclusions from a long-term incubation of subalpine soil samples. Soil Biology and Biochemistry, 32(7), 947-958.
251. Ritchie, J.T. (1998). Soil water balance and plant water stress. Understanding options for agricultural production, 41-54.
252. Robertson, M. J., Lyle, G., & Bowden, J. W. (2008). Within-field variability of wheat yield and economic implications for spatially variable nutrient management. Field Crops Research, 105(3), 211-220. https://doi.org/10.1016/j.fcr.2007.10.005
253. Robertson, M., & Lilley, J. (2016). Simulation of growth, development and yield of canola (Brassica napus) in APSIM. Crop & Pasture Science, 67(3 & 4), 332-344. https://doi.org/10.1071/CP15267
254. Rochecouste, J.-F., Dargusch, P., Cameron, D., & Smith, C. (2015). An analysis of the socio-economic factors influencing the adoption of conservation agriculture as a climate change mitigation activity in Australian dryland grain production. Agricultural Systems, 135, 20-30. https://doi.org/https://doi.org/10.1016/j.agsy.2014.12.002

255. Rochette, P., Angers, D. A., Chantigny, M. H., Gasser, M. O., MacDonald, J. D., Pelster, D. E., & Bertrand, N. (2013). Ammonia volatilization and nitrogen retention: how deep to incorporate urea? Journal of Environmental Quality, 42(6), 1635-1642.
256. Rosenzweig, C., & Hillel, D. (2013). Handbook of Climate Change and Agroecosystems (Vol. 2). World Scientific. https://doi.org/10.1142/p970
257. RuralBank. (2020). Australian Farmland Values, New South Wales. https://www.ruralbank.com.au/siteassets/knowledgeandinsights/publications/farmlandvalues/newsouthwales/afv-nsw-2020.pdf
258. Sadras, V. c. (2002). Interaction between rainfall and nitrogen fertilisation of wheat in environments prone to terminal drought: economic and environmental risk analysis. Field Crops Research, 77(2), 201-215. https://doi.org/https://doi.org/10.1016/S0378-4290(02)00083-7
259. Sadras, V. c., Roget, D., & Krause, M. (2003). Dynamic cropping strategies for risk management in dry-land farming systems. Agricultural Systems, 76(3), 929-948.
260. Sadras, V. O., Hayman, P. T., Rodriguez, D., Monjardino, M., Bielich, M., Unkovich, M., Mudge, B., & Wang, E. (2016). Interactions between water and nitrogen in Australian cropping systems: physiological, agronomic, economic, breeding and modelling perspectives. Crop and Pasture Science, 67(10), 1019-1053. https://doi.org/https://doi.org/10.1071/CP16027
261. Samarah, N., Wang, H., & Welbaum, G. (2016). Pepper (Capsicum annuum) seed germination and vigour following nanochitin, chitosan or hydropriming treatments. Seed Science and Technology, 44(3), 609-623.
262. Sanderson, T., Hertzler, G., Capon, T., & Hayman, P. (2016). A real options analysis of Australian wheat production under climate change. Australian Journal of Agricultural and Resource Economics, 60(1), 79-96. https://doi.org/https://doi.org/10.1111/1467-8489.12104
263. Schwember, A. R., & Bradford, K. J. (2010). Quantitative trait loci associated with longevity of lettuce seeds under conventional and controlled deterioration storage conditions. J Exp Bot, 61(15), 4423-4436. https://doi.org/10.1093/jxb/erq248
264. Schwenke, G., Peoples, M., Turner, G., & Herridge, D. (1998). Does nitrogen fixation of commercial, dryland chickpea and faba bean crops in north-west New South Wales maintain or enhance soil nitrogen? Australian journal of experimental agriculture, 38(1), 61. https://doi.org/10.1071/EA97078
265. Sewell, T., Stephens, R. E., Dominey-Howes, D., Bruce, E., & Perkins-Kirkpatrick, S. (2016). Disaster declarations associated with bushfires, floods and storms in New South Wales, Australia between 2004 and 2014. Scientific Reports, 6(1), 36369. https://doi.org/10.1038/srep36369
266. Shafi, U., Mumtaz, R., García-Nieto, J., Hassan, S. A., Zaidi, S. A. R., & Iqbal, N. (2019). Precision agriculture techniques and practices: From considerations to applications. Sensors, 19(17), 3796.
267. Sinclair, T., & Muchow, R. (1999). Radiation Use Efficiency. Advances in agronomy, 65(C), 215-265. https://doi.org/10.1016/S0065-2113(08)60914-1
268. Sisodia, A., Padhi, M., Pal, A., Barman, K., & Singh, A. K. (2018). Seed priming on germination, growth and flowering in flowers and ornamental trees. Advances in Seed Priming, 263-288.
269. Smil, V. (2011). Harvesting the biosphere: The human impact. Population and development review, 37(4), 613-636.
270. Smith, C. J., Hunt, J. R., Wang, E., Macdonald, B. C. T., Xing, H., Denmead, O. T., Zeglin, S., & Zhao, Z. (2019). Using fertiliser to maintain soil inorganic nitrogen can increase dryland wheat yield with little environmental cost. Agriculture, Ecosystems

& Environment, 286, 106644. https://doi.org/https://doi.org/10.1016/j.agee.2019.106644

271. Smith, C. J., Hunt, J. R., Wang, E., Macdonald, B. C., Xing, H., Denmead, O., Zeglin, S., & Zhao, Z. (2019). Using fertiliser to maintain soil inorganic nitrogen can increase dryland wheat yield with little environmental cost. Agriculture, ecosystems & environment, 286, 106644.
272. Snyder, C. S., Bruulsema, T. W., Jensen, T. L., & Fixen, P. E. (2009). Review of greenhouse gas emissions from crop production systems and fertilizer management effects. Agriculture, ecosystems & environment, 133(3), 247-266. https://doi.org/https://doi.org/10.1016/j.agee.2009.04.021
273. Södergård, C. (2021). Big Data in Bioeconomy Results from the European DataBio Project. Cham : Springer International Publishing AG.
274. Speer, M. S., Leslie, L. M., MacNamara, S., & Hartigan, J. (2021). From the 1990s climate change has decreased cool season catchment precipitation reducing river heights in Australia's southern Murray-Darling Basin. Sci Rep, 11(1), 16136. https://doi.org/10.1038/s41598-021-95531-4
275. Stanford, G., & Smith, S. (1972). Nitrogen mineralization potentials of soils. Soil Science Society of America Journal, 36(3), 465-472.
276. Stevens, A. W. (2022). The economics of land tenure and soil health. Soil Security, 100047.
277. Stoorvogel, J. J., Antle, J. M., Crissman, C. C., & Bowen, W. (2004). The tradeoff analysis model: integrated bio-physical and economic modeling of agricultural production systems. Agricultural Systems, 80(1), 43-66. https://doi.org/https://doi.org/10.1016/j.agsy.2003.06.002
278. Tack, J. B., Pope, R. D., LaFrance, J. T., & Cavazos, R. H. (2015). Modelling an aggregate agricultural panel with application to US farm input demands. European Review of Agricultural Economics, 42(3), 371-396. https://doi.org/10.1093/erae/jbu026
279. Talan, D. (2014). Murray Murrumbidgee Climate change snapshot.
280. Taylor, A., Prusinski, J., Hill, H., & Dickson, M. (1992). Influence of seed hydration on seedling performance. HortTechnology, 2(3), 336-344.
281. Tejada, M., Gonzalez, J., García-Martínez, A., & Parrado, J. (2008). Effects of different green manures on soil biological properties and maize yield. Bioresource technology, 99(6), 1758-1767.
282. Thorburn, P. J., Biggs, J. S., Collins, K., & Probert, M. E. (2010). Using the APSIM model to estimate nitrous oxide emissions from diverse Australian sugarcane production systems. Agriculture, ecosystems & environment, 136(3), 343-350. https://doi.org/10.1016/j.agee.2009.12.014
283. Thorburn, P. J., Probert, M. E., & Robertson, F. A. (2001). Modelling decomposition of sugar cane surface residues with APSIM–Residue. Field Crops Research, 70(3), 223-232. https://doi.org/10.1016/S0378-4290(01)00141-1
284. Tilman, D., Cassman, K. G., Matson, P. A., Naylor, R., & Polasky, S. (2002). Agricultural sustainability and intensive production practices. Nature, 418(6898), 671-677. https://doi.org/10.1038/nature01014
285. Tsoodle, L. J., Golden, B. B., & Featherstone, A. M. (2006). Factors Influencing Kansas Agricultural Farm Land Values. Land economics, 82(1), 124-139. https://doi.org/10.3368/le.82.1.124
286. Turmel, M.-S., Speratti, A., Baudron, F., Verhulst, N., & Govaerts, B. (2015). Crop residue management and soil health: A systems analysis. Agricultural Systems, 134, 6-16. https://doi.org/https://doi.org/10.1016/j.agsy.2014.05.009

287. Uhart, S. A., & Andrade, F. H. (1995). Nitrogen Defeciency in Maize: I. Effects on Crop Growth, Development, Dry Matter Partitioning, and Kernel Set. Crop Science, 35(5), 1376-1383. https://doi.org/10.2135/cropsci1995.0011183X003500050020x
288. Umina, P. A., McDonald, G., Maino, J., Edwards, O., & Hoffmann, A. A. (2019). Escalating insecticide resistance in Australian grain pests: contributing factors, industry trends and management opportunities. Pest Management Science, 75(6), 1494-1506. https://doi.org/10.1002/ps.5285
289. Van Grinsven, H. J., Holland, M., Jacobsen, B. H., Klimont, Z., Sutton, M. A., & Jaap Willems, W. (2013). Costs and benefits of nitrogen for Europe and implications for mitigation. Environmental Science & Technology, 47(8), 3571-3579.
290. van Groenigen, K.-J., Six, J., Hungate, B. A., de Graaff, M.-A., Van Breemen, N., & Van Kessel, C. (2006). Element interactions limit soil carbon storage. Proceedings of the National Academy of Sciences, 103(17), 6571-6574.
291. Van Keulen, H. (1986). Crop yield and nutrient requirements. In Modelling of agricultural production: weather, soils and crops (pp. 155-181). Pudoc.
292. van Rees, H., McClelland, T., Hochman, Z., Carberry, P., Hunt, J., Huth, N., & Holzworth, D. (2014). Leading farmers in South East Australia have closed the exploitable wheat yield gap: Prospects for further improvement. Field Crops Research, 164, 1-11. https://doi.org/https://doi.org/10.1016/j.fcr.2014.04.018
293. Venkateswarlu, B., & Shanker, A. K. (2012). Dryland agriculture: bringing resilience to crop production under changing climate. Crop stress and its management: Perspectives and strategies, 19-44.
294. Viscarra Rossel, R. A., Webster, R., Bui, E. N., & Baldock, J. A. (2014). Baseline map of organic carbon in Australian soil to support national carbon accounting and monitoring under climate change. Glob Chang Biol, 20(9), 2953-2970. https://doi.org/10.1111/gcb.12569
295. von Lampe, M., Willenbockel, D., Ahammad, H., Blanc, E., Cai, Y., Calvin, K., Fujimori, S., Hasegawa, T. v. L., 2014 #48}, Havlik, P., Heyhoe, E., Kyle, P., Lotze-Campen, H., Mason d'Croz, D., Nelson, G. C., Sands, R. D., Schmitz, C., Tabeau, A., Valin, H., van der Mensbrugghe, D., & van Meijl, H. (2014). Why do global long-term scenarios for agriculture differ? An overview of the AgMIP Global Economic Model Intercomparison. Agricultural Economics, 45(1), 3-20. https://doi.org/10.1111/agec.12086
296. Waisman, H., Bataille, C., Winkler, H., Jotzo, F., Shukla, P., Colombier, M., Buira, D., Criqui, P., Fischedick, M., & Kainuma, M. (2019). A pathway design framework for national low greenhouse gas emission development strategies. Nature Climate Change, 9(4), 261-268.
297. Wang, B., Feng, P., Chen, C., Liu, D. L., Waters, C., & Yu, Q. (2019). Designing wheat ideotypes to cope with future changing climate in South-Eastern Australia. Agricultural Systems, 170(C), 9-18. https://doi.org/10.1016/j.agsy.2018.12.005
298. Wheeler, S. A., Nauges, C., & Zuo, A. (2021). How stable are Australian farmers' climate change risk perceptions? New evidence of the feedback loop between risk perceptions and behaviour. Global Environmental Change, 68, 102274.
299. White, J., & Edwards, J. (2007). Procrop wheat growth and development (Grow Note, Durum West Plant Growth, Issue. https://www.dpi.nsw.gov.au/__data/assets/pdf_file/0008/516185/Procrop-wheat-growth-and-development.pdf
300. Whitehead, V. B. (1977). Agricultural history : an index, 1927-1976. Davis : Agricultural History Center, University of California, Davis.

301. Williams, J., Jones, C., Kiniry, J., & Spanel, D. A. (1989). The EPIC crop growth model. Transactions of the ASAE, 32(2), 497-0511.
302. Wolman, M. G. (1985). Soil Erosion and Crop Productivity: A Worldwide Perspective. In Soil Erosion and Crop Productivity (pp. 9-21). https://doi.org/https://doi.org/10.2134/1985.soilerosionandcrop.c2
303. WorldBank, T. (2020). Commodity Markets The World Bank. https://www.worldbank.org/en/research/commodity-markets
304. WorldBank. (2022). Carbon Pricing Dashboard Version 21/03/2023). https://carbonpricingdashboard.worldbank.org/map_data
305. Wu, H., MacDonald, G. K., Galloway, J. N., Zhang, L., Gao, L., Yang, L., Yang, J., Li, X., Li, H., & Yang, T. (2021). The influence of crop and chemical fertilizer combinations on greenhouse gas emissions: A partial life-cycle assessment of fertilizer production and use in China. Resources, Conservation and Recycling, 168, 105303.
306. Xiao, D., Bai, H., & Liu, D. L. (2018). Impact of Future Climate Change on Wheat Production: A Simulated Case for China’s Wheat System. Sustainability, 10(4), 1277. https://www.mdpi.com/2071-1050/10/4/1277
307. Xing, H., Liu, D. L., Li, G., Wang, B., Anwar, M. R., Crean, J., Lines-Kelly, R., & Yu, Q. (2017). Incorporating grain legumes in cereal-based cropping systems to improve profitability in southern New South Wales, Australia. Agricultural Systems, 154, 112-123. https://doi.org/https://doi.org/10.1016/j.agsy.2017.03.010
308. Xu, F., Mittelhammer, R. C., & Barkley, P. W. (1993). Measuring the contributions of site characteristics to the value of agricultural land. Land economics, 69(4), 356.
309. YAN, W., & WALLACE, D. H. (1998). Simulation and Prediction of Plant Phenology for Five Crops Based on Photoperiod×Temperature Interaction. Annals of Botany, 81(6), 705-716. https://doi.org/10.1006/anbo.1998.0625
310. Yang, Y., Liu, D. L., Anwar, M. R., Zuo, H., & Yang, Y. (2014). Impact of future climate change on wheat production about plant-available water capacity in a semiaridenvironment. Theoretical and applied climatology, 115(3-4), 391-410. https://doi.org/10.1007/s00704-013-0895-z
311. Yang, Y., Liu, D. L., Anwar, M. R., Zuo, H., & Yang, Y. (2014). Impact of future climate change on wheat production in relation to plant-available water capacity in a semiaridenvironment. Theoretical and applied climatology, 115(3-4), 391-410. https://doi.org/10.1007/s00704-013-0895-z
312. Ye, L., & Van Ranst, E. (2009). Production scenarios and the effect of soil degradation on long-term food security in China. Global Environmental Change, 19(4), 464-481. https://doi.org/https://doi.org/10.1016/j.gloenvcha.2009.06.002
313. Zeleke, K. T., & Nendel, C. (2016). Analysis of options for increasing wheat (Triticum aestivum L.) yield in south-eastern Australia: The role of irrigation, cultivar choice and time of sowing. Agricultural Water Management, 166, 139-148. https://doi.org/https://doi.org/10.1016/j.agwat.2015.12.016
314. Zeleke, K. T., & Nendel, C. (2016). Analysis of options for increasing wheat (Triticum aestivum L.) yield in south-eastern Australia: The role of irrigation, cultivar choice and time of sowing. Agricultural Water Management, 166, 139-148. https://doi.org/https://doi.org/10.1016/j.agwat.2015.12.016
315. Zhao, G., Bryan, B. A., King, D., Luo, Z., Wang, E., & Yu, Q. (2015). Sustainable limits to crop residue harvest for bioenergy: maintaining soil carbon in Australia's agricultural lands. Global change biology. Bioenergy, 7(3), 479-487. https://doi.org/10.1111/gcbb.12145

316. Zheng, B., Chenu, K., Doherty, A., & Chapman, S. (2014). The APSIM-wheat module (7.5 R3008). Agricultural Production Systems Simulator (APSIM) Initiative, 615.
317. Zheng, T., Liang, Y., Ye, S., & He, Z. (2009). Superabsorbent hydrogels as carriers for the controlled-release of urea: Experiments and a mathematical model describing the release rate. Biosystems engineering, 102(1), 44-50. https://doi.org/10.1016/j.biosystemseng.2008.09.027

Appendices

Appendix A: Economic Modelling Process

1. Source and collate data inputs for crop simulation and economic modelling including:
    - Download daily temperature minimum, maximum, rainfall and solar radiation for 1960-2015 from The Bureau of Meteorology (BOM) (B.O.M, 2020).
    - Identify wheat cultivar suitable for winter production in the region from currently used cultivars which are available in crop modelling software **(Matthews & Maccaffery, 2019)**, including optimal time for sowing the cultivar in the Wagga Wagga region
    - Obtain recommended wheat planting density per hectare, planting depth, planting times, soil preparation and recommended fertiliser inputs **(DPI, 2013; Meppem, 2020)**
    - Obtain site soil characteristics including soil nitrogen, soil carbon and soil clay content **(Li et al., 2016; McKenzie, 2004)**
    - Source recommended input quantities and prices including: herbicide, labour, fertiliser, tractor maintenance and repairs, tractor depreciation, harvest contract, seed. **(DPI, 2013; The World Bank, 2021)**
    - Select global average annual wheat price (output price), modelling used 2018 global average wheat price **(DPI, 2013; WorldBank, 2020)**
    - Harmonise cost and price data to 2020 prices using relevant inflation rates from The Reserve Bank of Australia (R.B.A, 2020)
    - Extract livestock crop grazing herd size, minimum crop above ground biomass to retain triggering herd removal and grazing times from **S. J. Sprague et al. (2015); Susan J Sprague et al. (2014)**
    - Source sheep manure nitrogen and carbon content **(Ogejo et al., 2010; Sani & Jokhtan, 2016)**

2. From BOM climate data sourced in Step 1, extract the daily climate data for the period 1/1/1960-31/12/2015 inclusive. Create a Microsoft Excel table with days of the year ascending numerically, with corresponding minimum and maximum daily temperatures, daily rainfall, and solar radiation in columns adjacent. Save as "Historical Climate Data".

3. Download and install The Agricultural Production Systems sIMulator (APSIM) Next Gen version from https://www.apsim.info/ **(McCown et al., 1996)**. Installation will require Microsoft Visual Studio which can be obtained from https://visualstudio.microsoft.com/downloads/. Run the APSIM software and select a new file.

4. From the data collated in Step 1calibrate the APSIM software site soil characteristics, wheat cultivar, wheat production function including fertiliser inputs, soil preparation, seed sowing time, depth, and density in the 1-hectare field. Set the sowing time to a minimum 15mm of required rainfall in 7 days prior to sowing, with forced sowing at the end of the crop sowing period if insufficient rainfall has occurred during the crop sowing period defined.

5. Set the wheat production simulation period to 1/1/1960- 1/1/2015.

6. Upload the climate data using the "Historical Climate Data" Microsoft Excel file created in Step 2.

7. Simulation wheat production, export annual production wheat yield, soil nitrogen and soil carbon content using function in APSIM creating a Microsoft Excel results data table.

8. Aggregate soil nitrogen and carbon, using wheat price data calculate wheat revenue, using assumption wheat is sold in the period following production. Calculate input costs using DPI input quantities and cost data sourced in Step 1. Costs are incurred at the start of the production period, prior to sowing the

crop, therefore a discount rate (2,5 or 7%) must be applied to harmonise cost and revenue.

9. Use the soil nitrogen and carbon content to calculate the soil productivity at the end of the annual production period. Using the prior annual production period soil productivity, calculate the percentage change in soil productivity over the period. To ensure the nominal value of land is consistent, multiply land value by (1 + discount rate + % change in soil productivity) at the end of each annual production period. This closing value becomes the opening value of land in the next production period.

10. At the end of the modelling period discount the terminal land value and annual profits realised from wheat production using the discount rate to determine the NPV value of land and wheat production returns generated from land use over the modelling period.

11. Repeat Step 3 and create a copy of APSIM, label this "Hydropriming APSIM". Run the code in Microsoft Visual, in the wheat cultivar that was selected for simulations, find the crop growth code and vary the root and shoot growth rates for the period of germination to emergence using hydropriming growth rate variation taken from **Muhammad Farooq et al. (2020); Muhammad Farooq et al. (2019); Jisha et al. (2013); Patra et al. (2016)**.

12. Calibrate the Hydropriming APSIM following Step 4 and repeat Steps 5 -10, save results as "Hydropriming with historical climate data".

13. Analyse impacts of fixed climate conditions on soil productivity, land degradation, wheat yield and NPV returns from land use on the 4 alternative management treatments simulated:
    - **i.** Existing management practices
    - **ii.** Hydropriming seeds prior to planting

14. Using the BOM historical climate data and default APSIM calibrated according to Step 4, with modelling period set to 1/1/1960-31/12/2015, vary APSIM fertiliser applied at sowing. Undertake simulations following Steps 7-10 starting at 100kg/ha of DAP fertiliser applied at sowing and 85kg/ha of urea applied in July. Vary fertiliser inputs by +/- 60% as per Chapter 5 and repeat the simulation process.

15. Using Hydropriming APSIM software created in Step11 repeat Step 14 and save results as "Hydropriming with varied fertiliser inputs".

16. Analysis impacts of using actual climate data on soil productivity, wheat yields, and land use returns for the current and hydro-priming wheat management practices simulated.
    - **a.** Identify the profit maximising quantity of fertiliser inputs for each alternative management treatment
    - **b.** Identify fertiliser quantity minimising land degradation for each alternative management practice
    - **c.** Compare alternative treatments soil productivity and land use returns with the profit maximising fertiliser input quantity

17. Using the results generated in Steps 7 – 15 apply carbon prices set out in Chapter 5 to fertiliser inputs. Name results including "Carbon price" at the end.

18. Undertake analysis following Step 17, to identify the imapct of a carbon price on gross margin, fertiliser input quantitites and NPV returns with a carbon price compared to the profit maximising quantity of fertilsier, returns and without a carbon price.

19. Using the Global Circulation Modelling Climate data and downscaling methods described by **Jeffrey et al. (2001)** calibrate historical daily climate

data using the information in Table 3.4. Use 1960-79 as a proxy for 2020-39, 1980-99 for 2040-59 and 2000-15 as a proxy weather data for 2060-75.

- **a.** Use the average temperature increase and upper and lower bounds of predicted rainfall varation to creat upper and lower bound of predicted climate change for the study site.
- **b.** Create 2 copies of the BOM daily historical climate data.
- **c.** Save one as "Lower bound climate change", vary daily rainfall using the minimum bound in Table 3.4 and average temperature increase for daily rainfall, minimum and maximum temperatures in the Microsoft Excel daily climate data tables, consistent with the method undertaken in Step 2.
- **d.** Repeat the process from Step 19(c) using the upper bound of predicted rainfall variation with the average temperature increase, save the data as "Upper bound climate change".

Table 8.4 Wagga Wagga, NSW, Australia, Regional Predicted Climate Variation

Period	Temperature increases (°C)	Rainfall variation summer (%)	Rainfall variation autumn (%)	Rainfall variation winter (%)	Rainfall variation spring (%)
1960–1979 (2020–2039)	0.6–0.7	-16 to +27	-13 to +57	-9 to +4	-26 to -1
1980–1999 (2040–2059)	1.3–1.4	-12 to +27.5	-9 to +63	-13 to +10	-23 to -4
2000–2015 (2060–2075)	1.9–2.0	-7 to +28	-5 to +69	-18 to +16	-19 to -8

Source: Evans et al. (2014); Fita et al. (2017); Talan (2014)

20. Using low rainfall climate change daily climate data instead of historical cliamte data in APSIM repeat Steps 1-15.

21. Using high rainfall climate change climate data instead of historical climate data in APSIM repeat Steps 1-15.

22. Analysis impacts of climate change on soil productivity, wheat yields, and land use returns for the currnet and hydro-priming wheat management practices simulated.

  - **a.** Identify the profit maximising quantity of fertiliser inputs for each alternative management treatment under each climate simulation
  - **b.** Identify period with low yields and / or soil productivity losses
  - **c.** Compare alternative treatments soil productivity and land use returns with the profit maximising fertiliser input quantity within each climate simulation and compare to analysis undertaken in Step 16

23. Using the results generated in Steps 20 and 21 apply a carbon price to fertilsier emissions as outlined in Step 17.

24. Undertake analysis following Step 22, with the additional comparison of profit maximising quantity, NPV returns and identify climate shocks with a carbon prive compared to the profit maximising quantity of fertilsier, returns without a carbon price.

25. Compile results, create tables and graphs to incorporate into results presented in Chapter 6.

Appendix B: Annual wheat yield, soil productivity and gross margin using historical climate data

Year	Current yield (kg/ha)	Hydro yield (kg/ha)	Rotation yield (kg/ha)	Hydro rotate yield (kg/ha)	Current soil product (kg/ha)	Hydro soil product (kg/ha)	Rotation soil product (kg/ha)	Hydro rotate soil product (kg/ha)	Current GM ($/ha)	Hydro GM ($/ha)	Rotation GM ($/ha)	Hydro rotate GM ($/ha)
1960	5,367	5,124	4,789	5,124	0.00263	0.00263	0.00263	0.00263	1,104	835	1,032	1,064
1961	2,636	2,545	1,726	2,545	0.00276	0.00277	0.00275	0.00277	436	382	250	489
1962	2,693	3,462	4,612	3,462	0.00274	0.00277	0.00273	0.00277	784	635	984	606
1963	3,519	4,095	4,569	4,095	0.00273	0.00275	0.00272	0.00275	777	809	972	781
1964	4,533	5,955	2,396	5,956	0.00270	0.00273	0.00272	0.00273	1,263	1,322	495	1,736
1965	3,366	3,832	4,942	3,832	0.00271	0.00276	0.00270	0.00276	727	736	1,075	708
1966	3,043	5,694	5,070	5,694	0.00269	0.00274	0.00269	0.00274	1,221	1,250	1,110	1,221
1967	3,641	4,122	2,436	4,121	0.00270	0.00277	0.00270	0.00277	862	816	509	1,065
1968	1,669	4,149	6,451	4,149	0.00269	0.00276	0.00266	0.00276	706	824	1,490	796
1969	2,730	3,244	2,730	3,243	0.00272	0.00281	0.00270	0.00281	604	574	465	546
1970	4,565	4,058	3,085	4,058	0.00271	0.00280	0.00269	0.00280	852	799	746	1,042
1971	6,076	7,075	6,147	7,076	0.00266	0.00273	0.00265	0.00273	1,420	1,630	1,407	1,602
1972	3,467	4,013	3,778	4,013	0.00266	0.00275	0.00265	0.00275	850	786	754	758
1973	4,916	6,304	4,058	6,304	0.00264	0.00272	0.00261	0.00272	1,237	1,418	1,102	1,863
1974	3,154	1,167	4,882	1,167	0.00267	0.00277	0.00261	0.00277	89	2	1,058	-26
1975	5,076	7,143	3,553	7,144	0.00262	0.00271	0.00261	0.00271	1,358	1,649	692	1,621
1976	6,154	5,448	3,904	5,448	0.00260	0.00270	0.00257	0.00270	1,132	1,182	1,046	1,550
1977	3,666	4,959	5,775	4,959	0.00261	0.00271	0.00256	0.00271	979	1,047	1,304	1,019
1978	2,510	2,493	2,158	2,493	0.00263	0.00274	0.00259	0.00274	395	367	307	339

1979	4,390	6,842	3,815	6,842	0.00259	0.00269	0.00255	0.00269	1,268	1,566	1,013	2,060
1980	1,116	1,572	6,109	1,572	0.00261	0.00273	0.00254	0.00273	218	114	1,396	85
1981	5,489	7,672	2,431	7,672	0.00257	0.00268	0.00257	0.00268	1,655	1,795	383	1,767
1982	3,195	3,654	4,438	3,654	0.00258	0.00270	0.00252	0.00270	629	430	1,241	894
1983	2,905	5,841	4,668	5,841	0.00256	0.00267	0.00252	0.00267	1,185	1,290	999	1,262
1984	4,099	1,446	2,490	1,446	0.00260	0.00274	0.00256	0.00274	102	79	399	51
1985	5,755	7,444	3,961	7,444	0.00255	0.00267	0.00251	0.00267	1,504	1,732	1,067	2,280
1986	3,540	3,221	5,175	3,221	0.00257	0.00275	0.00250	0.00275	649	568	1,139	540
1987	3,498	5,098	4,418	5,098	0.00255	0.00272	0.00250	0.00272	1,081	1,085	930	1,057
1988	2,718	4,342	3,058	4,342	0.00255	0.00271	0.00250	0.00271	780	877	737	1,146
1989	3,128	3,110	5,609	3,110	0.00258	0.00277	0.00248	0.00277	508	538	1,258	509
1990	5,135	4,713	3,437	4,712	0.00254	0.00271	0.00248	0.00271	967	979	660	951
1991	6,249	6,426	3,910	6,426	0.00251	0.00267	0.00245	0.00267	1,157	1,451	1,048	1,908
1992	3,241	4,966	4,733	4,966	0.00252	0.00270	0.00245	0.00270	955	1,049	1,017	1,021
1993	3,723	3,348	3,052	3,348	0.00254	0.00275	0.00248	0.00275	596	603	554	575
1994	6,523	6,080	3,532	6,080	0.00251	0.00269	0.00244	0.00269	1,220	1,356	910	1,781
1995	2,922	4,601	5,499	4,600	0.00251	0.00270	0.00243	0.00270	882	948	1,228	920
1996	4,222	4,037	3,034	4,037	0.00252	0.00271	0.00245	0.00271	743	793	549	765
1997	5,157	5,777	3,600	5,776	0.00249	0.00267	0.00241	0.00267	1,088	1,272	935	1,670
1998	2,426	4,281	5,459	4,281	0.00250	0.00269	0.00241	0.00269	909	860	1,217	832
1999	2,997	3,010	2,603	3,010	0.00252	0.00272	0.00244	0.00272	504	510	430	482
2000	4,061	5,806	3,501	5,806	0.00248	0.00268	0.00240	0.00268	836	1,281	898	1,681
2001	6,295	5,969	4,986	5,970	0.00246	0.00265	0.00240	0.00265	1,259	1,326	1,087	1,297
2002	3,736	5,456	4,824	5,456	0.00245	0.00265	0.00239	0.00265	1,075	1,184	1,042	1,156
2003	2,889	3,173	2,734	3,173	0.00247	0.00267	0.00240	0.00267	474	298	618	718
2004	2,308	2,874	4,559	2,874	0.00250	0.00272	0.00239	0.00272	414	472	969	444
2005	2,553	3,036	2,755	3,037	0.00252	0.00275	0.00242	0.00275	510	517	472	489

2006	2,124	4,414	3,328	4,413	0.00249	0.00270	0.00239	0.00270	708	897	835	1,172
2007	1,570	2,533	4,341	2,533	0.00247	0.00269	0.00238	0.00269	366	379	909	350
2008	1,707	2,565	2,609	2,565	0.00250	0.00274	0.00242	0.00274	397	387	431	359
2009	2,343	3,756	4,106	3,756	0.00247	0.00268	0.00237	0.00268	760	715	1,120	931
2010	357	1,392	4,839	1,392	0.00249	0.00271	0.00237	0.00271	81	64	1,046	36
2011	7,136	8,090	3,471	8,091	0.00246	0.00267	0.00238	0.00267	1,426	1,910	669	1,882
2012	5,446	5,692	3,500	5,691	0.00246	0.00269	0.00236	0.00269	1,199	1,249	898	1,639
2013	5,417	6,130	5,555	6,129	0.00244	0.00266	0.00234	0.00266	1,197	1,370	1,244	1,341
2014	3,014	3,375	2,755	3,375	0.00247	0.00270	0.00238	0.00270	615	611	472	582
2015	2,039	2,167	2,134	2,167	0.00248	0.00272	0.00239	0.00272	229	277	399	350

Appendix C: Annual wheat yield, soil productivity and gross margin with lower-bound climate change

Year	Current yield (kg/ha)	Hydro yield (kg/ha)	Rotation yield (kg/ha)	Hydro rotate yield (kg/ha)	Current soil product (kg/ha)	Hydro soil product (kg/ha)	Rotation soil product (kg/ha)	Hydro rotate soil product (kg/ha)	Current GM ($/ha)	Hydro GM ($/ha)	Rotation GM ($/ha)	Hydro rotate GM ($/ha)
1960	5,367	5,467	5,517	5,001	0.00263	0.00263	0.00263	0.00263	1,069	930	1,233	1,030
1961	2,636	2,535	1,584	2,522	0.00276	0.00277	0.00276	0.00277	350	379	198	461
1962	2,693	2,758	4,465	4,104	0.00277	0.00278	0.00273	0.00275	365	440	943	783
1963	3,519	3,436	3,648	3,946	0.00275	0.00277	0.00273	0.00274	582	627	718	740
1964	4,533	5,654	2,550	5,709	0.00275	0.00275	0.00273	0.00272	849	1,239	551	1,626
1965	3,366	3,166	5,148	3,627	0.00275	0.00278	0.00270	0.00275	542	553	1,131	652
1966	3,043	5,296	5,118	5,514	0.00276	0.00278	0.00270	0.00273	457	1,140	1,123	1,172
1967	3,641	4,102	2,600	4,243	0.00275	0.00281	0.00270	0.00276	614	811	569	1,090
1968	1,669	2,353	4,782	4,120	0.00275	0.00282	0.00267	0.00274	95	329	1,030	788
1969	2,730	3,159	3,018	2,862	0.00275	0.00285	0.00271	0.00278	374	551	544	441
1970	4,565	4,432	3,126	7,039	0.00274	0.00284	0.00271	0.00271	858	902	762	2,112
1971	6,076	7,725	5,911	4,569	0.00272	0.00277	0.00266	0.00271	1,256	1,809	1,342	911
1972	3,467	3,748	3,910	5,237	0.00271	0.00278	0.00266	0.00269	569	713	790	1,095
1973	4,916	5,458	3,690	5,267	0.00269	0.00276	0.00263	0.00268	951	1,185	968	1,464
1974	3,154	1,002	5,225	1,858	0.00272	0.00280	0.00262	0.00271	486	-43	1,153	164
1975	5,076	8,197	3,706	6,425	0.00269	0.00273	0.00262	0.00266	993	1,939	734	1,423
1976	6,154	5,719	4,481	5,420	0.00265	0.00272	0.00257	0.00265	1,277	1,256	1,257	1,520
1977	3,666	4,000	5,561	4,600	0.00267	0.00274	0.00258	0.00268	621	783	1,245	920
1978	2,510	2,524	2,084	2,540	0.00269	0.00277	0.00260	0.00270	316	376	287	352
1979	4,390	5,017	3,380	6,366	0.00268	0.00276	0.00258	0.00265	812	1,063	854	1,866
1980	1,116	1,054	6,262	1,607	0.00269	0.00278	0.00256	0.00270	-51	-29	1,438	95
1981	5,489	5,731	2,181	7,735	0.00265	0.00272	0.00258	0.00263	1,102	1,260	314	1,784

1982	3,195	3,955	4,414	3,641	0.00265	0.00274	0.00254	0.00266	497	513	1,232	870
1983	2,905	2,920	4,849	6,303	0.00265	0.00276	0.00253	0.00262	420	485	1,049	1,389
1984	4,099	4,279	2,732	1,614	0.00266	0.00278	0.00257	0.00270	735	860	465	97
1985	5,755	6,678	4,458	7,107	0.00262	0.00273	0.00252	0.00262	1,172	1,521	1,249	2,137
1986	3,540	3,320	5,255	3,617	0.00266	0.00281	0.00251	0.00268	588	595	1,161	649
1987	3,498	4,430	4,159	4,772	0.00265	0.00279	0.00252	0.00265	577	901	859	967
1988	2,718	2,820	2,448	5,363	0.00266	0.00280	0.00252	0.00263	371	458	514	1,499
1989	3,128	3,149	4,314	2,302	0.00269	0.00284	0.00253	0.00269	479	548	901	286
1990	5,135	5,569	4,610	5,453	0.00263	0.00275	0.00250	0.00262	1,008	1,215	983	1,155
1991	6,249	7,130	4,578	5,482	0.00259	0.00271	0.00247	0.00260	1,302	1,645	1,292	1,543
1992	3,241	3,437	5,442	4,671	0.00264	0.00280	0.00247	0.00261	509	628	1,212	939
1993	3,723	3,657	3,050	3,358	0.00264	0.00281	0.00249	0.00265	636	688	553	578
1994	6,523	7,624	4,078	6,253	0.00259	0.00274	0.00245	0.00260	1,374	1,782	1,109	1,825
1995	2,922	3,105	5,590	4,505	0.00261	0.00276	0.00244	0.00262	425	536	1,253	894
1996	4,222	4,353	2,964	4,052	0.00260	0.00276	0.00246	0.00262	768	880	529	769
1997	5,157	6,144	4,068	5,848	0.00258	0.00273	0.00242	0.00259	1,014	1,374	1,106	1,677
1998	2,426	2,469	5,551	4,117	0.00262	0.00279	0.00242	0.00262	294	361	1,242	787
1999	2,997	2,898	2,166	2,885	0.00262	0.00281	0.00245	0.00264	445	479	309	447
2000	4,061	5,713	4,284	5,801	0.00258	0.00274	0.00240	0.00259	725	1,255	1,185	1,659
2001	6,295	6,732	5,048	5,846	0.00254	0.00271	0.00240	0.00257	1,314	1,536	1,104	1,263
2002	3,736	3,976	5,296	5,121	0.00254	0.00271	0.00238	0.00256	639	776	1,172	1,064
2003	2,889	2,984	3,121	4,057	0.00255	0.00272	0.00240	0.00258	416	246	759	1,022
2004	2,308	2,325	3,069	3,059	0.00256	0.00274	0.00239	0.00262	263	321	558	495
2005	2,553	2,528	2,556	3,199	0.00258	0.00277	0.00241	0.00265	328	377	417	534
2006	2,124	2,204	2,884	3,732	0.00257	0.00276	0.00240	0.00262	215	288	673	903
2007	1,570	1,613	2,508	2,336	0.00255	0.00273	0.00238	0.00259	69	125	404	296

2008	1,707	1,762	1,876	2,946	0.00256	0.00274	0.00239	0.00261	105	166	229	464
2009	2,343	2,329	5,664	4,010	0.00253	0.00270	0.00236	0.00258	272	322	1,689	1,005
2010	357	401	2,381	1,505	0.00255	0.00273	0.00239	0.00261	-251	-209	369	67
2011	7,136	7,221	5,060	7,882	0.00252	0.00269	0.00237	0.00257	1,535	1,671	1,107	1,825
2012	5,446	5,694	4,108	5,583	0.00251	0.00268	0.00236	0.00259	1,090	1,250	1,121	1,580
2013	5,417	5,971	5,739	5,642	0.00250	0.00267	0.00234	0.00257	1,083	1,326	1,294	1,207
2014	3,014	3,119	2,509	3,442	0.00254	0.00273	0.00238	0.00262	449	540	404	601
2015	2,039	2,301	2,337	2,502	0.00255	0.00275	0.00239	0.00261	192	315	473	454

Appendix D: Annual wheat yield, soil productivity and gross margin with upper-bound climate change

Year	Current yield (kg/ha)	Hydro yield (kg/ha)	Rotation yield (kg/ha)	Hydro rotate yield (kg/ha)	Current soil product (kg/ha)	Hydro soil product (kg/ha)	Rotation soil product (kg/ha)	Hydro rotate soil product (kg/ha)	Current GM ($/ha)	Hydro GM ($/ha)	Rotation GM ($/ha)	Hydro rotate GM ($/ha)
1960	4,394	4,403	4,834	5,014	0.00263	0.00263	0.00263	0.00263	923	637	1,045	1,034
1961	4,412	4,205	2,314	2,417	0.00270	0.00272	0.00275	0.00277	929	839	465	422
1962	4,047	3,943	4,796	4,498	0.00270	0.00272	0.00271	0.00275	828	767	1,034	892
1963	4,160	4,309	4,106	3,998	0.00268	0.00270	0.00270	0.00274	859	868	844	754
1964	5,190	5,362	3,219	5,765	0.00266	0.00269	0.00268	0.00271	1,143	1,158	796	1,646
1965	3,667	3,634	4,615	3,921	0.00267	0.00272	0.00267	0.00275	723	682	984	733
1966	5,590	5,766	5,185	5,878	0.00264	0.00269	0.00265	0.00272	1,253	1,269	1,142	1,272
1967	3,706	3,899	2,606	4,207	0.00265	0.00271	0.00266	0.00275	734	755	571	1,077
1968	5,796	6,253	6,103	4,003	0.00263	0.00269	0.00263	0.00274	1,310	1,404	1,395	755
1969	2,507	2,393	2,429	2,387	0.00265	0.00272	0.00265	0.00277	404	340	382	310
1970	5,413	6,092	3,876	7,318	0.00261	0.00266	0.00260	0.00270	1,204	1,359	1,036	2,214
1971	4,306	4,413	4,431	4,544	0.00259	0.00265	0.00259	0.00269	899	897	934	904
1972	4,604	5,090	4,071	5,330	0.00258	0.00264	0.00258	0.00267	981	1,083	834	1,121
1973	4,614	4,823	3,613	5,280	0.00257	0.00263	0.00256	0.00267	984	1,010	939	1,469
1974	2,430	2,530	4,603	1,961	0.00257	0.00265	0.00255	0.00270	382	378	981	193
1975	4,799	5,520	3,681	5,778	0.00254	0.00261	0.00255	0.00265	1,035	1,202	727	1,245
1976	5,068	5,406	3,594	5,773	0.00252	0.00260	0.00252	0.00264	1,109	1,170	933	1,649
1977	4,594	4,795	5,750	4,694	0.00253	0.00261	0.00251	0.00267	979	1,002	1,297	946
1978	2,697	2,825	2,283	2,571	0.00255	0.00265	0.00254	0.00270	456	459	342	361

1979	5,175	5,746	3,475	6,332	0.00251	0.00260	0.00250	0.00264	1,139	1,264	889	1,854
1980	3,062	3,084	5,766	1,803	0.00250	0.00261	0.00248	0.00268	556	530	1,302	149
1981	5,783	6,833	2,974	7,648	0.00247	0.00257	0.00251	0.00262	1,306	1,564	532	1,760
1982	3,934	3,812	3,982	3,481	0.00247	0.00259	0.00246	0.00265	797	474	1,075	811
1983	4,669	5,574	4,633	6,359	0.00245	0.00256	0.00246	0.00261	999	1,217	989	1,405
1984	1,747	1,539	2,569	1,632	0.00250	0.00264	0.00248	0.00269	194	104	420	102
1985	5,469	6,466	4,238	6,736	0.00245	0.00256	0.00243	0.00261	1,220	1,462	1,168	2,001
1986	4,547	4,592	5,210	3,790	0.00244	0.00257	0.00243	0.00265	966	946	1,148	697
1987	4,041	4,400	3,687	4,853	0.00244	0.00257	0.00243	0.00263	826	893	729	989
1988	4,399	5,083	4,002	5,538	0.00242	0.00254	0.00241	0.00261	925	1,081	1,082	1,563
1989	3,738	4,259	4,530	2,568	0.00241	0.00253	0.00240	0.00267	743	854	961	360
1990	4,168	4,392	3,441	5,147	0.00239	0.00251	0.00240	0.00259	861	891	661	1,071
1991	4,353	4,967	4,182	5,497	0.00238	0.00250	0.00237	0.00258	912	1,049	1,148	1,548
1992	4,544	4,490	4,962	4,597	0.00237	0.00250	0.00236	0.00258	965	918	1,080	919
1993	3,162	3,215	2,794	3,351	0.00240	0.00255	0.00240	0.00263	584	566	483	576
1994	5,283	6,025	3,356	6,499	0.00236	0.00250	0.00235	0.00257	1,168	1,341	845	1,915
1995	4,313	4,382	5,176	4,378	0.00238	0.00252	0.00235	0.00259	901	888	1,139	859
1996	3,747	4,083	3,237	4,228	0.00238	0.00252	0.00236	0.00260	745	806	605	817
1997	4,832	5,213	3,428	5,587	0.00235	0.00250	0.00233	0.00257	1,044	1,117	872	1,581
1998	4,307	4,895	4,947	4,387	0.00235	0.00250	0.00232	0.00258	899	1,029	1,076	861
1999	3,476	3,329	3,400	2,874	0.00235	0.00252	0.00233	0.00261	670	598	650	444
2000	4,218	4,562	3,278	5,004	0.00233	0.00249	0.00231	0.00255	875	938	817	1,368
2001	4,573	5,572	4,412	5,981	0.00231	0.00246	0.00230	0.00253	973	1,216	929	1,300
2002	4,365	4,762	4,087	4,973	0.00230	0.00246	0.00229	0.00253	915	993	839	1,023
2003	4,175	4,499	4,102	4,355	0.00229	0.00246	0.00227	0.00254	863	663	1,118	1,131
2004	4,766	4,749	4,964	2,597	0.00228	0.00245	0.00226	0.00257	1,026	989	1,081	368
2005	3,096	3,357	2,992	3,252	0.00231	0.00249	0.00228	0.00259	566	606	537	548

2006	5,519	6,057	3,493	3,563	0.00228	0.00245	0.00225	0.00257	1,233	1,350	896	841
2007	2,951	3,159	4,187	2,304	0.00228	0.00246	0.00225	0.00255	526	551	866	287
2008	3,244	3,468	3,086	2,770	0.00232	0.00250	0.00228	0.00257	607	636	563	415
2009	4,734	5,464	3,993	3,869	0.00229	0.00247	0.00225	0.00254	1,017	1,186	1,078	953
2010	2,924	3,118	4,873	1,421	0.00231	0.00249	0.00223	0.00257	518	540	1,056	44
2011	5,138	5,733	3,237	8,013	0.00228	0.00246	0.00224	0.00253	1,128	1,260	605	1,860
2012	3,976	4,523	4,043	5,797	0.00227	0.00245	0.00221	0.00255	808	927	1,097	1,658
2013	4,794	5,586	4,430	5,445	0.00225	0.00242	0.00220	0.00253	1,034	1,220	933	1,153
2014	3,703	3,909	3,576	3,976	0.00226	0.00245	0.00221	0.00256	733	758	698	748
2015	3,185	4,121	3,050	2,955	0.00227	0.00244	0.00223	0.00257	590	816	734	619

Appendix E: Zheng et. Al (2015) Agricultural Production Systems Simulator (APSIM) Wheat growth process

Crop Growth Processes

The Agricultural Production Systems Simulator (APSIM) Model simulates livestock and crop production land use. Modelling is segmented into modules which utilise a daily time step on a per hectare area basis responding to management practises, climatic and soil variation. The modules interact with each other, plant modules extract water and nitrogen from the soil changing the soil water and nitrogen balances, with soil inflows derived from irrigation, precipitation and temperature. Modules are calibrated according to the scenario, crop or livestock being analysed.

Phenology

Plant species have individual characteristics impacting soil water and nutrient extraction, growth rates and yield. The plant module is calibrated to individual plant species characteristics. The description of crop phenological processes will be calibrated to wheat crop requirements, based on the work of Zheng, et al. (2015) unless otherwise stated. All phenological calculations occur daily, for simplicity the daily timestep (t) is dropped throughout phenological process description. References to equations within the model will be made with the equation number in brackets, for example, (23). Alternative crop plant module calibration requirements can be found at: https://www.apsim.info/documentation/model-documentation/crop-module-documentation/plant/.

Table 1: Crop phenological stages.

Stage	Stage description
1	Sowing
2	Germination
3	Seedling emergence
4	End of the juvenile phase
5	Floral initiation
6	Appearance of the flag leaf
7	Start of linear phase of grain filling
8	End of linear phase of grain filling
9	Physiological maturity
10	Ready for harvest, harvest
11	Crop finished and absent from simulation

Within the crop module there are 11 phenological phases commencing with sowing and finishing with harvest, progression through the phases is dependent on climatic temperatures also known as thermal times. Thermal time is the minimum temperature accumulation required for a crop to complete a phase depending on the crop and cultivar. Thermal times are cumulative over the crop life, with a minimum and maximum thermal temperature for crop survival (FAO, 2006). The daily thermal time, ΔTT, (4) is calculated using the daily average of the maximum and minimum crown air temperatures (T_{cmax} and T_{cmin} respectively) adjusted to genetic and environmental factors. Crown temperatures are calibrated using site daily minimum and maximum non-freezing air temperatures (T_{min} and T_{max}), and snow depth in centimetres (H_{snow}).

$$T_{cmax} = \begin{cases} 2 + T_{max}\,(0.4 + 0.0018(H_{snow} - 15)^2), & T_{max} < 0 \\ T_{max} & T_{max} \geq 0 \end{cases} \tag{1}$$

$$T_{cmin} = \begin{cases} 2 + T_{min}\,(0.4 + 0.0018(H_{snow} - 15)^2), & T_{min} < 0 \\ T_{min} & T_{min} \geq 0 \end{cases} \tag{2}$$

The daily crown mean temperature, T_c, (3), is calculated by the maximum (T_{cmax}) and minimum (T_{cmin}) daily crown temperature.

$$T_c = \frac{T_{cmax} + T_{cmin}}{2} \tag{3}$$

The daily thermal time is calculated every 3 hours in crop modules except wheat, where it is calculated daily. Both methods use default values for cardinal temperatures and relative thermal times (Zheng, et al., 2015).

$$\Delta TT = \begin{cases} T_c, & 0 < T_c \leq 26 \\ \frac{26}{8}(34 - T_c), & 26 < T_c \leq 34 \\ 0, & T_c \leq 0 \; or \; T_c > 34 \end{cases} \tag{4}$$

For each phenological stage the daily thermal time, *TT'* (5), is calculated cumulatively from the start of the phase, reduced by a function for daylight hours (f_D, equation 7), vernalisation factor (f_V, equation 11), soil water stress ($f_{W,pheno}$, equation 97), nitrogen stress ($f_{N,pheno}$, equation 103). The target thermal time is when the stage reaches the adjusted daily thermal time (*TT'*) for the crop.

$$TT' = \sum [\Delta TT \times \min(f_D, f_V) \times \min(f_{W,pheno}, f_{N,pheno})] \quad (5)$$

The second phase, seed germination, commences after seed sowing when soil layer water availability, reaches the required minimum for the crop. If this does not occur within a predetermined time period the crop will die, in wheat germination must occur within 40 days.

The germination to emergence thermal time target is influenced by the depth of the seed placement at sowing (D_{seed}). When germination has occurred the initial shoot elongation rate is slow (T_{lag}), before a linear period where the rate of shoot elongation towards the soil surface is linearly related to the air temperature. The crop will die if emergence has not occurred by the time the cumulative thermal time has reached 300°C. Shoot elongation thermal time is set at 40°impacted by the crop specific shoot elongation rate, r_ϵ, Table 2. The period for germination to emergence, T_{emer} (6), is calculated by:

$$T_{emer} = T_{lag} + r_\epsilon D_{seed} \tag{6}$$

Table 2: Root Growth Rates

Shoot growth rate (r_ϵ)		*(mm/d^{-1})*		
	Canola	*Wheat*	*Barley*	*Field Pea*
Control	5.0	1.5	1.0	5.0
Hydropriming	6.11876	1.603398	1.0689	11.53846

Source: (APSIM, 2019, Farooq, et al., 2006, Farooq, et al., 2020, Farooq, et al., 2019, Holzworth, et al., 2014, Jisha, et al., 2013, Kaur, et al., 2002, Khazaei, et al., 2009, Mahawar, et al., 2016, Patra, et al., 2016, Robertson and Lilley, 2016, Zheng, et al., 2015)

The crop photoperiod is calculated using the site latitude and calendar day, impacting the phenological stages between emergence and floral initiation. Floral initiation will not occur in a crop if daylight hours are insufficient. Thermal time is affected by a photoperiod factor, f_D, (7), where L_p is the site day length (hours), and R_p, the cultivar specific sensitivity to the photo period, Table 3.

$$f_D = 1 - 0.002R_p\left(20 - L_p\right)^2 \tag{7}$$

Table 3: Crop Photoperiod Sensitivity

Crop	**Sensitivity to the photoperiod (R_p)**
Wheat	3.1
Barley	4
Canola	5
Field Peas	3.6

Sources: Major (1980), Robertson and Lilley (2016), YAN and WALLACE (1998)

Vernalisation Impact on Phenology

Vernalisation is the exposure of a seed or plant to colder temperatures and is necessary in some species to induce flowering. Vernalisation, *V,* (10) occurs in APSIM modelling after the emergence phase and before flowering, impacting daily thermal temperatures, f_V, (11). The change in vernalisation, ΔV, (8), depends on temperature variation.

$$\Delta V = \min\left(1.4 - 0.0778T_c, 0.5 + 13.44\frac{T_C}{(T_{max} - T_{min} + 3)^2}\right)\ when,$$

$$T_{max} < 30℃\ and\ T_{min} < 15℃ \qquad (8)$$

Devernalisation, ΔV_d, (9), occurs when the daily temperature exceeds 30°C and total vernalisation, (10), is less than 10:

$$\Delta V_d = \min(0.5(T_{max} - 30), V)\ when, T_{max} > 30℃\ and\ V < 10 \qquad (9)$$

The total vernalisation, V (10), is calculated using the cumulative daily vernalisation and devarnalisation from germination to floral initiation:

$$V = \sum(\Delta V - \Delta V_d)\ \ (10)$$

The vernalisation factor, f_V, (11), is calculated from emergence to floral initiation, where R_v is the cultivar specific sensitivity to vernalisation, with a range between -0.055 – 5, with a default value of 1.5.

$$f_V = 1 - (0.0054545R_v + 0.0003) \times (50 - V) \qquad (11)$$

Photosynthesis

Daily biomass accumulation, ΔQ, (22) is dependent on the above ground biomass and is calculated using the radiation interception, *I*, (13), by above ground biomass, ΔQ_r, (12), limited by soil water availability, radiation use efficiency, RUE, Table 4, a stress factor, f_s, (15), and a carbon dioxide factor, f_c, (18).

$$\Delta Q_r = I\ \times RUE\ \times\ f_d\ \times f_s\ \times f_c \qquad (12)$$

Table 4: Radiation Use Efficiency

Crop	**Radiation Use Efficiency (RUE)**

Wheat	1.51
Barley	1.05
Canola	1.40
Field Peas	0.54

Source: Sinclair and Muchow (1999)

Plant radiation interception is calculated using leaf area index (LAI, m^2 m^{-2}), (60), an extinction coefficient, *k*, (14), total daily radiation derived from site weather records (MJ) and a light interception, coefficient f_h, Table 5, to allow for shading by crops planted in adjacent rows.

$$I = I_o\left(1 - \exp\frac{(-k \times LAI \times f_h)}{f_h}\right) \tag{13}$$

Table 5: Light Interception Coefficient

Crop	Light Interception Coefficient (f_h)
Wheat	0.36
Barley	0.33
Canola	0.28
Field Peas	0.093

Source: Assaeed, et al. (1990), Charles-Edwards (1982), Kleemann and Gill (2010)

The extinction coefficient, *k,* (14), varies with row spacing, W_r, which is dependent on management crop planting decisions, and a parameter dependent on row spacing, h_e, set at 0.5.

$$k = h_e(W_r) \tag{14}$$

Daily biomass accumulation is influenced by crop response to mean daily temperature variations, $f_{T,photo}$, (16), oxygen, $f_{O,photo}$, nitrogen, $f_{N,photo}$, (17) availability ,captured using a stress factor, f_s (15).

$$f_s = \min(f_{T,photo}, f_{N,photo}, f_{O,photo})) \tag{15}$$

The temperature factor is the mean daily temperature, T_{mean}, (3) and a crop specific stress response factor $h_{T,photo}$, set at 0.05, applied from sowing to harvest.

$$f_{T,photo} = h_{T,photo}(T_{mean}) \tag{16}$$

The impact of nitrogen availability on plant biomass accumulation is determined using the different between leaf nitrogen concentration, C_N, (104) and leaf minimum, C_N, min, Table 20, and critical, $C_{N,crit}$, Table 19, crop specific leaf nitrogen requirement, with a crop specific multiplier effect, $R_{N,photo}$, for nitrogen deficits on biomass accumulation, with a default value of 1.5.

$$f_{N,photo} = R_{N,photo} \sum_{leaf} \left(\frac{C_N - C_N, min}{C_{N,crit} - C_N, min}\right) \tag{17}$$

The impact of atmospheric carbon dioxide concentration (*C*, *ppm*), (19), on above ground biomass reproduction is calculated using daily mean temperature and the temperature dependent carbon dioxide concentration point (ppm) (C_i).

$$f_c = \frac{(C - C_i)(350 + 2C_i)}{(C + 2C_i)(350 - C_i)} \tag{18}$$

$$C_i = \frac{163 - T_{mean}}{5 - 0.1TT_{mean}} \tag{19}$$

The actual daily biomass, ΔQ, (22), accumulation is influenced by the water availability impact on biomass production, ΔQ_w, (20). The impact of plant water stress on biomass production is captured using a ratio of the daily water uptake and water demand. Leaf and head water demand, W_d, *mm/hr* (21), depends on the plant transpiration efficiency, TE, (86) and crop specific respiration rate, R, Table 7. When soil water is non limiting, plant biomass accumulation is limited by radiation (ΔQ_r). Total biomass, Q, (23), is the daily change in biomass, ΔQ, less any leaf, $\Delta Q_{si,z}$, (81) and root biomass senescenced, $\Delta Q_{sen,root,z}$, (82).

$$\Delta Q_w = \Delta Q_r f_{W,photo} = \Delta Q_r \frac{W_u}{W_d} \tag{20}$$

$$W_d = \frac{\Delta Q_r - R}{TE} \tag{21}$$

$$\Delta Q = \begin{cases} \Delta Q_r, & W_u = W_d \\ \Delta Q_w, & W_u < W_d \end{cases} \tag{22}$$

$$Q = Q_{z-1} + \Delta Q_z - \Delta Q_{sen,root,z} - \Delta Q_{si,z} \tag{23}$$

Table 7: Crop Mean Respiration Rate

Crop	Respiration Rate (mg CO^2 m^{-1} d^{-1})
Wheat	500
Barley	600
Canola	440
Field Peas	205

Sources: Amthor (1989), Irving and Silsbury (1987), Kleemann and Gill (2010), Lee, et al. (1976), Pal, et al. (1973), Patanè, et al. (2006)

Biomass partitioning

Biomass is divided into four different components: roots, leaf, stem and head. Leaf includes the lead blades, stem includes plant stems, leaf sheaves and stem-like petioles. Head is divided into grains and pods with grain further separated into meal and oil. On the day of emergence from the soil, plant biomass is initialised in APSIM with root set at 0.01 g plant $^{-1}$, leaf 0.003 g plant $^{-1}$, stem 0.0016g plant $^{-1}$, pods 0.00g plant $^{-1}$, oil 0.00g plant $^{-1}$. Daily above ground biomass production (22) is allocated to different plant components hierarchically from the head, leaf and finally stem. If biomass production is insufficient to meet biomass demand, biomass production is limited. Daily biomass allocation to the root system, ΔQ_{root}, (24), is separate from above ground allocation and is a stage dependent function, with root biomass unable to be translocated within the plant.

Roots

Daily root biomass growth uses a ratio, $R_{Root:Shoot}$, Table 8, depends on the phenological growth stage to allocation daily biomass production, ΔQ (22), to roots.

$$\Delta Q_{root} = \Delta Q \times R_{Root:Shoot} \tag{24}$$

$$Q_{root,z} = Q_{root,z-1} + \Delta Q_{root,z} - \Delta Q_{sen,root,z} \tag{25}$$

Table 8: Ratio of daily biomass allocation to roots

Stage	Ratio of root to shoot biomass allocation ($R_{Root:Shoot}$)
1	0
2	0
3	1.0
4	1.0
5	0.3
6	0.3
7	0.1
8	0.0
9	0.0
10	0.0
11	0.0

Source: Zheng, et al. (2015)

Head (Pod and Meal)

Daily biomass partitioning, ΔQ, (22), into the head depends on the growth stage and total demand of the head (grain, pod and oil). Biomass partitioning into the pod or grain cannot be re-translocated. Daily biomass allocated to the head, ΔQ_{head}, (26), depends on the grain, D_g, (48), and pod, D_p, (49) demand and above ground translocation of biomass from other areas to the pod, $\Delta Q_{retrans\ to\ pod}$, (43).

$$\Delta Q_{head} = \min\left(\Delta Q, D_g + D_p\right) \tag{26}$$

$$\Delta Q_{grain} = \frac{D_g}{D_{head}} \Delta A_{head} \tag{27}$$

$$\Delta Q_{pod} = \frac{D_p}{D_{head}} \Delta A_{head} \tag{28}$$

$$Q_{head} = Q_{head,t-1} + \Delta Q_{head,t} - \Delta Q_{retrans\ to\ pod,t} \tag{29}$$

Leaf and Stem

Daily biomass partitioning to the leaf, ΔQ_{leaf}, (30), is a phenological stage dependent function, with a fraction of available biomass partitioned to the leaf, F_{leaf}, Table 9. Leaf biomass is structural and cannot be remobilised.

$$\Delta Q_{leaf} = (\Delta Q - \Delta Q_{head}) \times F_{leaf} \tag{30}$$

$$Q_{leaf,z} = Q_{leaf,z-1} + \Delta Q_{leaf,z} - \Delta Q_{si,z} \tag{31}$$

Table 9: Ratio of Daily Biomass Allocated to Leaves

Stage	Ratio of biomass allocation to leaves (F_{leaf})
1	0
2	0
3	1.0
4	1.0
5	1.0
6	0.45
7	0.0
8	0.0
9	0.0
10	0.0
11	0.0

Source: Zheng, et al. (2015)

The remaining above ground biomass unallocated is partitioned in the stem, until stage 7, with 65% of daily stem biomass, ΔQ_{stem}, (32), allocated to daily structural biomass $\Delta Q_{stem.structural}$, (33), with the remaining daily non-structural biomass, $\Delta Q_{stem.non-structural}$, (34). After stage 7 has commenced all stem biomass available is allocated to non-structural stem biomass. Structural biomass allocation ($h_{structural}$) is an exogenously determined parameter set at 65% during phenological stages 2 – 6 and in other stages the parameter is 0 %. Biomass is the sum of the previous day's stem biomass, daily stem biomass additions less any stem biomass retranslocated, $\Delta Q_{retrans,stem}$, (37), within the above ground biomass.

$$\Delta Q_{stem} = \Delta Q - \Delta Q_{head} - \Delta Q_{leaf} \tag{32}$$

$$\Delta Q_{stem.structural} = \Delta Q_{stem} \times h_{structural} \tag{33}$$

$$\Delta Q_{stem.non-structural} = \Delta Q_{stem} \times (1 - h_{structural}) \tag{34}$$

$$Q_{stem,t} = Q_{stem,t-1} + \Delta Q_{stem,t} - \Delta Q_{retrans,stem,t} \tag{35}$$

Re-translocation

If the supply of daily biomass is insufficient to meet daily grain demand, D_g, (48), energy stored in non-structural stems and pods may be translocated to meet unfilled head demands, $D_{diff,head}$, (36), up to a maximum of 20% of total non-structural stem dry biomass, $\Delta Q_{retrans,stem}$, (37), may be translocated to meet grain and pod demand.

$$D_{diff,head} = \left(D_{grain} - \Delta Q_{grain}\right) + \left(D_{pod} - \Delta Q_{pod}\right) \tag{36}$$

$$\Delta Q_{retrans,stem} = \min(D_{diff,} \Delta Q_{stem.non-structural} \times 20\%) \tag{37}$$

Equation 29 is updated to allow for translocation that occurs in (37)

$$D_{diff,head} = D_{diff,head} - \Delta Q_{retrans,stem} \tag{38}$$

The pod demand is the minimum of the grain and pod demand and non-structural pod daily biomass, $\Delta Q_{pod,non-structural}$, (44), translocated. The total biomass energy translocated is the sum of daily stem and pod, $\Delta Q_{retrans,pod}$, (43), energy biomass translocated (44):

$$\Delta Q_{retrans,pod} = \min\left(D_{diff,head}, \Delta Q_{pod,non-structural}\right) \tag{39}$$

$$D_{diff,head} = D_{diff,head} - \Delta Q_{retrans,pod} \tag{40}$$

$$\Delta Q_{retrans} = \Delta Q_{retrans,stem} + \Delta Q_{retrans,pod} \tag{41}$$

The total daily biomass allocated to non-structural grain and pods is the daily incremental increase in in non-structural grain biomass, $\Delta Q_{grain,non-structural}$, (42), and pod biomass $\Delta Q_{pod,non-structural}$, (44).

$$\Delta Q_{grain,non-structural} = \Delta Q_{retrans,grain} = \frac{D_{diff,grain}}{D_{diff,head}} \Delta Q_{retrans} \tag{42}$$

$$\Delta Q_{retrans\ to\ pod} = \frac{D_{diff,pod}}{D_{diff,head}} \Delta Q_{retrans} \tag{43}$$

$$\Delta Q_{pod,non-structural} = \Delta Q_{retrans\ to\ pod} - \Delta Q_{retrans,pod} \tag{44}$$

Grain Demand

Grain Development depends on the number of grains per plant, N_g, (45), and is determined by the stem weight, $Q_{stem,z}$, (35), at antithesis and the number of grains per stem, R_g, Table 10.

$$N_g = R_g \cdot Q_{stem,z} \tag{45}$$

Table 10: Grains per stem

Crop	Grains per stem (R_g, g^{-1})
Wheat	25
Barley	65
Canola	111
Field Peas	94

Sources: (Kariuki, et al., 2014, Lee, et al., 1976, Movahhedy-Dehnavy, et al., 2009, Patanè, et al., 2006)

The grain (or meal) demand, D_g, (48) is calculated in phenological phases 6-8 and is set to 0 in the preceding stages. It is dependent on the potential grain filling rate, R_p, which is set to 0.0010 grain $^{-1}$ day $^{-1}$. In stage 7 it increases to 0.0020 grain^{-1} day^{-1} for the remaining stages.

Daily mean temperature affects grain filling through a function ($h_g(T_{mean})$) which has a value between 0.0 -1.0, Table 11. No grain filling occurs when the function is 0, optimal grain filling occurs at 1.0. The grain filling function is dependent on the nitrogen concentration for stem and leaf components, C_N, (102), critical nitrogen, $C_{N,crit}$, Table 19, the minimum nitrogen concentration, $C_{N,min}$, Table 20, required for stem and leaf growth and grain nitrogen deficits, $f_{N,grain}$, (47). The potential grain filling rate ($h_{N,poten}$) and minimum grain filling rate ($h_{N,min}$) are crop specific parameters, set to 0.000055 g grain $^{-1}$ d^{-1} and 0.0000015g grain $^{-1}$ d^{-1} respectively.

$$D_g = N_g R_p h_g(T_{mean}) f_{N,grain} \tag{46}$$

$$f_{N,grain} = \frac{h_{N,poten}}{h_{N,min}} h_{N,grain} \sum\nolimits_{stem,leaf} \frac{C_N - C_{N,min}}{C_{N,crit} \times f_{c,N} - C_{N,min}} \left(0 \leq f_{N,fill} \leq 1\right) (47)$$

Table 11: Grain filling response to temperature

Temperature	Grain filling factor ($h_{N,grain}$)
0	0.0
5	0.1
10	0.3
15	0.4
20	0.6
25	0.8
30	1.0
35	1.0
40	1.0

Source: Zheng, et al. (2015)

Grain demand, D_g, (48), is limited by a maximum grain size (S_{gm}), Table 12, calibrated to the crop, cultivar type, dry weight grain (meal) size (Q_{meal}) and grain number, N_g, (45).

$$D_g = \min\left(D_g, D_{gm}\right) \tag{48}$$

$$D_{gm} = N_g S_{gm} - Q_{meal}, \qquad (D_{gm} \geq 0)$$

Table 12: Grain size

Crop	Grain size ($S_{gm} g^{-1}$)
Wheat	4
Barley	4.2
Canola	7.5
Field Peas	19

Source: Charles-Edwards (1982), Kariuki, et al. (2014), Schwenke, et al. (1998)

Pod Demand

Pod demand, D_p, (49), depends on grain demand, D_g, (48), or daily biomass accumulation, ΔQ, (22), tempered by a function of the growth stage $h_p(S)$, set to 0.3 in phenological stages 5 – 7, otherwise 0.

$$D_p = \begin{array}{l} D_g h_p(S),\ if\ D_g > 0 \\ \Delta Q h_p(S),\ if\ D_g = 0 \end{array} \tag{49}$$

Leaf and Node appearance and Crop Leaf Area

In APSIM software plants are assumed to have a single stem, therefore tillering is not simulated, nodes appearing in APSIM on the main stem is representative of all phytomers (nodes with leaves attached) appearing simultaneously on different tillers in the real world.

At the emergence phase a number of initial leaves are specified dependent on the crop type and cultivar, with a default value of 2 and an identical number of nodes. During tiller formation up to the harvest stage, nodes, P_n, (50), appear at a set thermal time interval that depends on the node number of the main stem ($h_p(n_t)$), with no effect from water on nitrogen stresses on leaf appearance.

$$P_n = h_p(n_t) \tag{50}$$

The increase in daily node increase, $\Delta n_{t,p}$, (51), for the stem is calculated using the daily thermal time, ΔTT_t, C°d, (4).

$$\Delta n_{t,p} = \frac{\Delta TT_t}{P_n} \tag{51}$$

The daily potential leaf number, $N_{t,p}$, (52), is a function of the daily node increase, the position and number of leaf nodes the previous day, $h_l(n_{t-1})$, Table 13, total number of nodes the previous day, $N_{n,t-1}$, (52) and environmental stresses, $f_{s,expan}$, (53), including soil water, $f_{w,expan}$, (99), nitrogen, $f_{N,expan}$, and phosphorous availability, $f_{p,photo}$ (120).

$$N_{t,p} = \min\left[N_{n,t-1}, h_l(n_{t-1})\right] + \left[h_l\left(n_{t-1} + \Delta n_{t,p}\right) - h_l(n_{t-1})\right] \times f_{s,expan} \tag{52}$$

$$f_{s,expan} = \min\left\{\left[\min\left(f_{N,expan}, f_{p,photo}\right)^2, f_{w,expan}\right]\right\} \tag{53}$$

$$\Delta N_{t,p} = N_{n,t} \times \Delta n_{t,p} \tag{54}$$

Table 13: Leaves per stem node

Node number on main stem	**Number of leaves per node ($h_l(n_{d-1})$)**
0	1
1	1
2	1
3	2
4	3
5	4
6	6

Source: Zheng, et al. (2015)

The daily increase in actual leaf numbers, $\Delta N_{t,LAI}$, (55), uses the ratio between daily leaf area index biomass accumulation, ΔLAI_t (57), and daily stressed leaf area index biomass accumulation, $\Delta LAI_{t,s}$, (59), where h_{LAI} is a function of the leaf area index (LAI) ratio, (60), and the leaf number.

$$\Delta N_{t,LAI} = \Delta N_{t,p} \times h_{LAI}\left(\frac{\Delta LAI_t}{\Delta LAI_{t,s}}\right) \tag{55}$$

At the emergence phenological phase, an initial leaf area is specified according to plant type and cultivar with a default value of 200mm^2 plant^{-1}, during tiller formation the daily increase in the LAI biomass is the minimum between the stressed LAI and the carbon limited LAI.

$$\Delta LAI_t = \min\left(\Delta LAI_{t,s}, \Delta LAI_{t,c}\right) \tag{56}$$

The stressed LAI is calculated as the potential LAI reduced by nitrogen, soil water, phosphorous stresses and manganese deficiency, $f_{M,leaf}$, (139). Increases in LAI are calculated by the potential daily increase in leaf number, $\Delta N_{t,p}$, (54), and potential leaf area potential for the current leaf, L_n, (59). The potential leaf area depends on a function of the leaf size and node number ($h_{t,s}(n_t)$) and the growing leaf number in the sheath (n_0), which has a default value of 2.

$$\Delta LAI_{t,s} = \Delta LAI_{t,p} \times \min\left(f_{N,expan}, f_{p,photo}, f_{w,expan}\right) \tag{57}$$

$$\Delta LAI_{t,p} = \Delta N_{t,p} \times L_n \tag{58}$$

$$L_n = h_{t,s}(n_t + n_0) \tag{59}$$

$$LAI_t = LAI_{t-1} + \Delta LAI_t \tag{60}$$

Carbon production by plants, $\Delta LAI_{t,c}$, (61), is dependent on the increase in dry leaf biomass weight, ΔQ_{leaf}, (30), and maximum specific leaf area, SLA_{max},

($mm^2\ g^{-1}$), (62), which is related to the cultivar and crop specific leaf area index, h_{SLA}, Table 14.

$$\Delta LAI_{d,c} = \Delta Q_{leaf} \times SLA_{max} \tag{61}$$

$$SLA_{max} = h_{SLA}(LAI) \tag{62}$$

Table 14: Maximum Crop Leaf Size

Crop	Maximum Leaf size (h_{SLA}) (mm)
Wheat	20
Barley	31
Canola	10
Field Peas	60

Source: Amthor (1989), Irving and Silsbury (1987), Lee, et al. (1976), Pal, et al. (1973), Patanè, et al. (2006)

Root Growth and Distribution

Between germination and the start of grain filling the increase in the root depth is calculated daily dependent on daily root growth depth, ΔD_r, (64), utilising root growth depth rates, R_r, Table 15, a temperature factor, f_{rt}, (65), soil water factor, f_{rw}, (66), available soil water factor, f_{rwa}, (67), and root exploration factor, B_i, (207). The root growth depth function is a linear relationship between root growth depth rate and the phenological stage with a range between 0 – 30, with maximum growth at 30, between stages 3 – 7.

$$\Delta D_r = R_r \times f_{rt} \times \min(f_{rw}, f_{rwa}) \times B_i \tag{64}$$

Table 15: Root Growth Rates

Stage	Root growth rate (R_r) (mm/d^{-1})
1	0.0
2	5.0
3	30
4	30
5	30
6	30
7	0.0

8	0.0
9	0.0
10	0.0
11	0.0

Source: Zheng, et al. (2015)

The root growth temperature factor, f_{rt}, (65), is calculated using daily mean temperature and a ratio function of the impact of temperature on root growth, h_{rt}, Table 16, with 1.0 the maximum potential root growth.

$$f_{rt} = h_{rt} T_{mean} \tag{65}$$

Table 16: Root growth temperature variation

Temperature	**Temperature factor (h_{rt})**
0	0.0
5	0.1
10	0.3
15	0.5
20	0.8
25	1.0
30	0.7
35	0.0
40	0.0

Source: Zheng, et al. (2015)

Soil water stress, f_{rw}, (66), influences root growth depth in response to soil water stress on photosynthesis, $f_{w,photo}$, (98). A ratio between 0 – 1.0 is used, with 1.0, no water stress impeding root growth depth, B_i, (207). Available soil water impact on root and plant growth, f_{rwa}, (67), is amended by the fraction of available soil water, θ_i, (202), and soil porosity, α, (194).

$$f_{rw} = B_i(f_{w,photo}) \tag{66}$$

$$f_{rwa} = \alpha(\theta_i) \tag{67}$$

The fraction of available soil water in layer i $\theta(i)$, (202) is calculated using a fraction of root depth in the soil layer (*i*) and depth of soil layer. The deepest layer of soil where roots are present, $D_r(i)$, (72) and the thickness of the soil layer, $D_s(i)$, exogenously determined dependent onsite soil conditions.

$$\theta = \frac{D_{r,z}(i)}{D_s(i)}\theta(i+1) + \left(1 - \frac{D_{r,z}(i)}{D_s(i)}\right)\theta(i) \tag{68}$$

$$\Delta D_r = R_r \times f_{rt} \times f_{rwa} \times B_i \tag{69}$$

Equation 68 for daily root growth depth is simplified to daily root length growth, ΔL_r, (70) is calculated by daily growth of the root biomass, ΔQ_{root}, (24) and specific root length, SRL, in wheat is has a default value of 105,000 mm g^{-1}. The daily root growth length is distributed to each soil layer *i* using root growth depth, soil water availability, a soil root exploration factor, B_i, (207), root branching factor, $f_b(i)$, (74), set using the default value h_b, 0.00030 *(mm^3/plant)*, and a factor of root growth length, f_{rl}, (73).

$$\Delta L_r = \Delta Q_{root} \times SRL \tag{70}$$

$$\Delta D_r(i) = \frac{f_{rl}(i)}{\sum_{j=1}^{N} f_{rt}(j)} \tag{71}$$

$$D_{r,t} = D_{r,t-1} + \Delta D_{r,t} \tag{72}$$

$$f_{rl}(i) = f_{rwa} \times f_b(i) \times B_i \times \frac{D_s(i)}{D_r} \tag{73}$$

$$f_b(i) = h_b\left(\frac{L_r(i)}{D_p D_s(i)}\right) \tag{74}$$

Senescence

Leaf senescence begins when the crop is between end of juvenile and floral initiation phenological stages, with leaf senescence ending at the harvest stage. Total daily leaf senescence, $\Delta N_{t,sen}$, (75), is calculated using daily thermal time, *TT*, (4), the total number of leaves that day, N_t, (52), an exogenously determined parameter capturing the fraction of leaves senescing per main stem node, set at 60.0 °Cd node $^-$

[1], $f_{sen,l}$, and the exogenously determined crop specified parameter for the rate of total senescence, set to 0.035, $r_{sen,l}$.

$$\Delta N_{t,sen} = \Delta TT \times \frac{f_{sen,l} \times N_t}{r_{sen,l}} \tag{75}$$

There are five factors causing leaf senescence: age, $\Delta LAI_{sen,age}$, water stress, $\Delta LAI_{sen,sw}$, (77), light intensity, $\Delta LAI_{sen,light}$, (78), frost, $\Delta LAI_{sen,frost}$, (79) and heat, $\Delta LAI_{sen,heat}$, (80). The maximum of these factors is the day's total leaf area senescence index in the APSIM model. Leaf senescence age is related to the leaf area of the number of leaves senesced, $\Delta N_{t,sen}$, (75), from the lowest leaf position. Soil water leaf senescence is calculated using a linear equation relating soil water stress, $k_{sen,sw}$, to the senescence rate impacting crop photosynthesis, $f_{sw,photo}$. Light intensity leaf senescence, ($LAI_{c,light}$), is sensitive to shading, $k_{sen,light}$, with the default sensitivity 0.002.

$$\Delta LAI_{sen} = \max\left(\Delta LAI_{sen,age}, \Delta LAI_{sen,sw}, \Delta LAI_{sen,frost}, \Delta LAI_{sen,light}, \Delta LAI_{sen,heat}\right) \tag{76}$$

$$\Delta LAI_{sen,sw} = k_{sen,sw} \times \left(1 - f_{sw,photo}\right) \times LAI \tag{77}$$

$$\Delta LAI_{sen,light} = k_{sen,light} \times \left(LAI - LAI_{c,light}\right) \times LAI, \qquad LAI > LAI_{c,light} \tag{78}$$

Leaf senescence caused by frost is influenced by the daily minimum temperature factor, Table 17, increasing as temperature decreases below zero. Heat induced senescence similar to frost LAI senescence has a maximum temperature factor, Table 18, which increases linearly with temperature increases.

$$\Delta LAI_{sen,frost} = k_{sen,frost} \times LAI \tag{79}$$

$$\Delta LAI_{sen,heat} = k_{sen,heat} \times LAI \tag{80}$$

Table 16: Frost impact on root growth

Temperature	**Temperature factor ($k_{sen,frost}$)**
-10	1.0
-7	0.8
-5	0.4
-2	0.2
0	0.0

Table 17: Heat impact on root growth

Temperature	**Temperature factor ($k_{sen,heat}$)**
35	0.0
38	0.1
40	0.3
42	0.5
44	0.8

Source: Zheng, et al. (2015)

Total leaf area senesced must be less than the total leaf area of the plant. Nitrogen present in leaves prior to senescence may be re-translocated to stem areas. Leaf biomass senescence, ΔQ_{si}, (81), reduces daily biomass increases, ΔQ, (22), using the ratio of the leaf area index senesced, ΔLAI_{sen}, (76) and total leaf area index, $LAI_{t,c}$, (61).

$$\Delta Q_{si} = \Delta Q_l \frac{\Delta LAI_{sen}}{LAI_{t,c}} \tag{81}$$

Root senescence has a rate of root biomass, ΔQ_{root}, (24) and root length senesced, $\Delta L_{sen,root}$, (83), to determine the daily root senescence, $\Delta Q_{sen,root}$, (82) reducing the root biomass by a constant rate of 0.05, $f_{sen,root}$. The daily root senescence balance increases soil nitrogen and fresh organic matter in the soil profile. The specific root length (SRL) impacts daily quantity of root senescence sent to soil organic material with a default exogenous value of 105,000 mmg^{-1}. Total root senescence $\Delta L_r(i)$, (70) is a fraction of the sum of all the root lengths senesced in each layer *i* of the soil.

$$\Delta Q_{sen,root} = \Delta Q_{root} \times f_{sen,root} \tag{82}$$

$$\Delta L_{sen,root} = \Delta Q_{sen,root} \times SRL \tag{83}$$

$$\Delta L_{sen,root}(i) = \Delta L_{sen,root} \times \frac{\Delta L_r(i)}{\sum_{j=1}^{N} \Delta L_r(j)} \tag{84}$$

Crop Water Relations

Crop water demand, W_d, (85) is modelled as a function of the daily crop potential growth rate, estimated using above ground biomass radiation interception, ΔQ_r (12), crop specific respiration rate, R, Table 7; divided by transpiration efficiency, TE, (86). Transpiration efficiency is calculated using daylight average vapour pressure deficit, VPD, (87) and a carbon dioxide transpiration efficiency factor, f_c, (18) and a transpiration efficiency function, $f_{k,pheno}$, (129) which captures the change in crop transpiration efficiency.

$$W_d = \frac{\Delta Q_r - R}{TE} \tag{85}$$

$$TE = f_{c,TE} \frac{f_{k,pheno}}{VPD} \tag{86}$$

Vapour Pressure Deficit is estimated using daily maximum and minimum temperatures and daily vapour pressure deficit (f_v) derived from inputted weather data.

$$VPD = f_v[6.1078 \times \exp\left(\frac{17.269 \times T_{max}}{237.3 + T_{max}}\right)$$

$$- 6.1078 \times \exp\left(\frac{17.269 \times T_{min}}{237.3 + T_{min}}\right) \#(87)$$

Potential extractable soil water, ESW_p, (88), and actual extractable soil water, ESW_a, (89), is the balance between the soil saturated water content, $\theta_{s,i}$, (195), and residual soil water content, $\theta_{r,i}$, (182) of plant extractable soil water for each soil layer, θ_i, (202).

$$ESW_p(i) = \theta_{s,i} - \theta_{r,i} \tag{88}$$

$$ESW_a(i) = \theta_i \tag{89}$$

$$ESW_p = \sum_{i=1}^{I} [\theta_{s,i} - \theta_{r,i}] \ (90)$$

$$ESW_a = \sum_{i=1}^{I} \theta_i \tag{91}$$

Crop water supply, W_s, (92), is generated through the soil water module and integrated into the crop module and is the difference between the soil available water and lower limit. At the lowest soil layer crop water supply is the amended by a ratio of root depth, ΔD_r (64) and the exogenously determined soil layer thickness, D_s. Soil water supply can also be calculated using soil water content, θ_i, (202), soil water evaporation, E_i, (205) and actual daily rainfall, S_t, (177).

$$W_s(i) = [\theta(i) - LL(i)], if\ i \leq I - 1$$

$$= \frac{D_r(i)}{D_s(i)}[\theta(i) - LL(i)], if\ i = I \tag{92}$$

$$W_s(i) = \theta_i - E_i + S_t \tag{93}$$

$$W_s = \sum_{i=1}^{I} W_s(i) \tag{94}$$

The actual crop water uptake is the lesser of the soil water supply, W_s, (94), and crop soil water demand, W_d, (85), determine whether daily biomass production is constrained by soil water uptake in each soil layer, $\Delta W_s(i)$, (96) or solar radiation.

$$W_u = \min(W_s, W_d) \tag{95}$$

$$\begin{aligned} \Delta W_s(i) &= W_s(i) \times \frac{W_d}{W_s}, && if\ W_s < W_d \\ \Delta W_s(i) &= -W_s(i), && if\ W_s > W_d \\ \Delta W_s(i) &= 0, && if\ W_s = W_d = 0 \end{aligned} \tag{96}$$

Soil water deficits impacts biomass production, a stress factor ratio captures the impact of soil water deficits on crop photosynthetic processes, $f_{W,photo}$, (98), leaf expansion, $f_{W,expan}$, (99) and phenological processes, $f_{W,pheno}$, (97), capturing the impact of soil water deficits on crop flowering and grain filling. Soil water content and leaf stress is a function, $f_{k,pheno}$, (129), capturing the impact of soil nutrient deficits on crop water uptake.

$$f_{W,pheno} = \left(\frac{esw_a}{esw_p}\right) \tag{97}$$

$$f_{W,photo} = \frac{W_u}{W_d} \tag{98}$$

$$f_{W,expan} = \left(\frac{W_u}{W_d}\right) \tag{99}$$

Crop Nutrient Requirements

Nitrogen is necessary for plant vegetative growth. It is a key component of chlorophyll which plants use to transform radiation and water into energy for growth and biomass maintenance (Hofman, 2004). Plant nitrogen demands begin before floral initiation and finishes at harvest. Soil nitrogen supply is calculated for each soil layer, $N_{s,t,i}$, $g\ m^{-2}$, (100), using extractable soil nitrogen balance in the soil layer, $\eta_{N,t,i}$, (223).

$$\boldsymbol{N_{s,t,i}} = \sum_{i}^{I} \boldsymbol{\eta_{N,t,i}} \tag{100}$$

Grain nitrogen demand, $N_{D,grain,t}$, (101), starts at antithesis and is calculated from grain number, N_g, (45) , the crop specific exogenous parameter for the nitrogen filling rate, 0.000055 g $grain^{-1}$ °Cd^{-1}, $R_{N,poten}$, a nitrogen grain filling factor, $f_{N,grain}$, (47) and factor reducing grain filling as temperature increases, $h_{N,grain}$, Table 11.

$$N_{D,grain,t} = N_g \cdot R_{N,poten} \cdot f_{N,grain} \cdot h_{N,grain} \tag{101}$$

Leaf, stem and pod nitrogen demand for maintaining crop function is the sum of the existing biomass nitrogen requirements to produce the daily increment in biomass, $N_{d,t}$, (103). Nitrogen demand, $N_{D,part}$, (Leaf, stem, root), (102), is calculated using the dry weight of the plant part, leaf, stem, pod, Q_{part}, (30, 32, 35), dry weight nitrogen content, $C_{N,part}$, (104), soil water stress, $f_{W,photo}$, (98) critical daily nitrogen uptake rates to maintain biomass, $C_{N,crit}$, Table 19, and a nitrogen deficit function reducing uptake, f_n, set at 0.0001.

$$N_{D,part,t} = \frac{\Delta Q_{part} C_{N,crit,t}}{f_{W,photo}} + f_n\left(C_{N,crit,t} - C_{N,part,t}\right) \tag{102}$$

$$N_{d,t} = N_{D,grain,t} + N_{D,leaf,t} + N_{D,stem,t} + N_{D,root,t} \tag{103}$$

$$C_{N,part,t} = N_{D,part,t-1} \tag{104}$$

Table 19: Crop critical daily nitrogen demand

Crop	Nitrogen ($C_{N,crit,}$) (kg/ha d^{-1})
Wheat	0.040367
Barley	0.04
Field Peas	0.220773
Canola	0.125234

Source: Brennan (2017), IPNI (2019)

Daily nitrogen uptake, $N_{u,t}$, $(104a)$ is the minimum of nitrogen demand, $N_{d,t}$, (89) and the sum of daily supply, $N_{s,t,i}$, (100).

$$N_{u,t,} = \min(N_{d,t}, N_{S,t}) \tag{104a}$$

Nitrogen stress on phenology, $f_{N,pheno}$, (105), is determined by the difference in actual nitrogen content, minimum, $C_{N,min,t}$, Table 20, and critical nitrogen content for stem and leaf plant parts, $C_{N,part,t}$, multiplied by a stress factor, $h_{N,pheno}$, set at 83 based on the findings of Uhart and Andrade (1995) and a function for atmospheric carbon dioxide levels impact on biomass development, f_c, (18).

$$f_{N,pheno} = h_{N,pheno} \cdot \sum\nolimits_{stem,leaf} \frac{C_{N,leaf,t} - C_{N,min,t}}{C_{N,crit} \times f_c - C_{N,min,t},} \tag{105}$$

Table 19: Crop minimum daily nitrogen demand

Crop	Nitrogen ($C_{N,min,t}$) (kg/ha d^{-1})
Wheat	0.0330

Barley	0.0327
Field Peas	0.1703
Canola	0.0966

Source: Brennan (2017), IPNI (2019)

Nitrogen demand impact on biomass accumulation and photosynthesis uses a function, $f_{N,photo}$, (17), with a parameter ($h_{N,photo}$) to multiply the sum of the leaf nitrogen balance ratio. Nitrogen stress impacts biomass accumulation and grain filling using the difference between grain nitrogen concentration and critical grain nitrogen concentration amounts, using the potential grain filling rate ($h_{N,poten}$) and the minimum grain filling rate ($h_{N,min}$) multiplying the nitrogen deficit effect ($h_{N,grain}$).

$$f_{N,grain} = \frac{h_{N,poten}}{h_{N,min}} h_{N,grain} \cdot \sum\nolimits_{stem,leaf} \frac{c_N - c_{N,min}}{c_{N,crit} \times f_{c,N} - c_{N,min}}, \left(0 \le f_{N,fill} \le 1\right) \quad (105a)$$

Leguminous crops utilise atmospheric nitrogen in their growth processes, extracting it from the atmosphere and fixing it in the root system. The daily rate of potential nitrogen fixation is dependent on the phenological stage, crop leaf biomass, Q_{leaf}, (30) and soil water stress $\left(\frac{esw_a}{esw_p}\right)$ $(90, 91)$, with a multiplier, $f_{M,pheno}$, (140), reducing fixation rates as soil water stress increases and a crop specific daily nitrogen fixation rate, $f_{N,fix}$, between 0.103825137 – 0.934426 kg/ha d-1 no^3 (Schwenke, et al., 1998).

$$N_{s,f} = f_{N,fix} \times Q_{leaf} \times f_{M,pheno} \left(\frac{esw_a}{esw_p}\right) \qquad (106)$$