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Final report

SheepLinks: Climate adaptation to ensure a sustainable WA sheep industry (FutureSheep)

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Abstract

This project aimed to enhance understanding of the evolving climate change challenges facing sheep-producing regions of Western Australia (WA) and identify adaptations for the projected climates in 2030 and 2050. Temperature increases and decreased annual growing season rainfall could escalate drought stress, reducing crop and pasture yields.

Integrated assessment of modelled representative farms, biophysical simulations, economic modelling, and case studies were conducted for Kojonup, Wagin, and Merredin. Producer case studies were conducted to understand current adaptations. Four major red meat processors were consulted to assess how future variations in farming systems in WA may impact sheepmeat supply chains.

Simulation modelling indicated pasture yield losses across all sites by 2050 under moderate climate change scenarios, although changes were relatively modest in Wagin and Kojonup whereas Merredin faces heightened vulnerability. While current pasture technology is likely to be sufficient for producers in Wagin and Kojonup to adapt, it will only provide a short to medium term solution in Merredin which will require new innovations by 2050 to remain viable. The economic analysis revealed that climate change will significantly impact the gross margin and variability of cropping enterprises in all three locations (without adaptation) compared to mixed farming systems.

Producers highlighted the need for additional options including pastures that are better adapted to projected future climate conditions; early and late feeding systems; novel feed options; earlier-maturing cultivars; perennial pastures, shrubs and confinement feeding. Support and training are needed in transitioning to new practices.

Red meat processors highlighted different degrees of concern about climate change. There is a growing emphasis on reducing GHG emissions for processors, driven by the increasing importance placed on this by customers and lending institutions.

The FutureSheep project has raised awareness about climate change among the industry. We provide recommendations on prioritising future research efforts on pasture species and farming systems for adapting to climate change. With increasing global demand for animal protein, WA is well-positioned to leverage its reputation as a reliable supplier of clean, safe, and high-quality food to domestic and international consumers.

Executive summary

Background

The sheep industry in Western Australia (WA) faces several significant challenges due to climate change impacts, including shorter growing seasons for pastures and crops, reduced stocking rates (due to reduced rainfall) and less reliable growing conditions, resulting in reduced pasture and crop yields, increased reliance on supplementary feeding, reduced runoff for filling dams, and environmental and social concerns around methane emissions and farming system intensification. The purpose of the research is to help protect the profitability of WA sheep production and the supply of sheep in the face of climate change. The main audiences for this research are producers, their networks, and the major red meat processors. Impacts of climate change at the farm level are then scaled up to an industry level to examine potential issues for sheep supply for domestic and export markets.

Objectives

The project aimed to enhance understanding of the evolving climate change challenges facing sheep-producing regions of and identify adaptations for the projected climates in 2030 and 2050.

Methodology

The FutureSheep project employed an integrated approach, using biophysical modelling (GrassGro™ and APSIM™), whole-farm analysis with Australian Farm Optimisation (AFO), economic modelling (Economic Valuation of Alternative Land Use Sequence (EVALUS), greenhouse gas (GHG) accounting (desktop), and case studies in three key sheep-producing regions (Kojonup, Wagin, and Merredin) to identify potential adaptations for projected hotter and drier climates in 2030 and 2050. The producer case studies help to inform future research and investment in grazing systems with higher resilience to climate challenges across WA.

Results/key findings

GrassGro™ simulations indicate that all three locations will likely experience decreased pasture productivity and increased seasonal variability by 2050. While Kojonup may see relatively small productivity losses, enabling sheep producers to adapt current technology (such as tactical use of highly productive forage crops), Wagin faces greater pasture yield reduction, albeit with feasible adaptation prospects. However, Merredin (low rainfall zone) is projected to suffer significant pasture productivity decline and heightened land degradation risks from overgrazing and potential erosion, without appropriate adaption. While current pasture technology is likely to be able to arrest the pasture decline in Merredin in the short to medium term, by 2050 the low rainfall zone will require new innovations to remain viable. Simulation of wheat production (APSIM™) under future climate scenarios using current cultivars yielded negative results for these locations.

The EVALUS bio-economic model forecast decreased gross margins for cropping enterprises without adaptation across all locations by 2050 under various climate change scenarios (RCP 4.5 and RCP 8.5). Gross margin (GM) variability is expected to increase significantly for cropping systems due to rainfall dependency and upfront costs (e.g. seeding, fertiliser). Conversely, sheep enterprises are less affected, as income is driven primarily by commodity prices (prime lamb and wool), which influence gross margins more than climate variations despite impacts on pasture yield.

Location significantly influences the impact of climate change on farming systems. Wagin is projected to experience a more pronounced negative impact on GM than Kojonup for cropping and sheep enterprises. Merredin exhibits the highest variability and notable decline in GM for cropping, with sheep enterprises facing reduced profitability under future climate scenarios without adaptation. The GHG emission desktop analysis revealed links to land use practices and location, with sheep enterprises emitting more than cropping. Kojonup, with its higher stocking rate, has the highest emissions during the pasture phase, followed by Wagin and Merredin. Kojonup's cropping system also has higher emissions due to increased nitrogen (N) fertiliser use for higher-yielding crops. Comparing continuous cropping with mixed cropping/livestock systems revealed lower emissions during the cropping phase of the mixed farming system due to organic N from legumes reducing N fertiliser needs. However, total emissions are higher due to direct sheep-related methane emissions.

Case studies involving eight sheep producers proved valuable in translating local insights for decision-making, risk management, and awareness creation regarding climate change adaptation. Producers exhibit diverse responses, innovations, and timelines in addressing climate change. In the medium and high rainfall zones, a combination of current practices and technology modifications, such as adopting more legume species suited to emerging climates (i.e. pink and yellow serradella) are used to mitigate short-term climate effects. However, developing mixed farming systems adapted to the future climate in the low rainfall zone will be challenging and require new systems and technologies, including earlier-maturing annual pasture species with specific traits for drought and heat tolerance. Revisiting and updating existing pasture packages and providing technical support are essential for producers transitioning to new systems.

Producers also highlighted the need for additional options and information on early and late feeding systems; novel feed options; perennial pastures, shrubs and confinement feeding. Producers are increasingly turning to confinement feeding and feedlotting for lamb finishing, preservation of pasture, and flock maintenance during drought conditions. However, there is limited economic analysis on the value of deferring pastures. Some producers view feeding grain, hay or silage in confinement feeding as a mere outgoing cost. Given the current low livestock prices, adopting new technology without clear financial benefits will unlikely gain traction. Additional case studies on feedlotting, confinement feeding, best practice management and tools like ration feed, weight gain and cost calculators for each livestock class would be beneficial for increasing industry uptake.

Spatial diversification is a sound risk-spreading strategy, given seasonal and commodity price volatility, and a profit-enhancing strategy. Lamb production in low rainfall environments can be viable, assuming infrequent droughts, with finishing in regions with longer growing seasons and access to affordable feed grain. Producers keen on maintaining exposure to sheep production find the combination of properties appealing, provided transport costs are manageable. Long-term producer decisions, such as land purchases in other regions, will increasingly be influenced by climate change as its impacts become more apparent.

The project aimed to enhance understanding of climate change impacts on the WA sheep supply chain, considering supply and service provisions for quality sheep meat to customers. All four meat processors interviewed expressed concerns about climate change and GHG emissions, with varying timelines for sustainability strategy implementation, ranging from immediate action to 3–5 years to yet to undertake feasibility studies. Processors are at different stages of implementing strategies, including the adoption of renewable energy (solar power), carbon offsetting, tree planting for carbon sequestration, and methane emissions accounting programs. Environmental, social and governance (ESG) practices are significant concern for all processors, as financial institutions increasingly use them as loan approval criteria. At the time of the interviews, processors were seeking clearer guidance on live sheep export policies (by sea) to aid supply chain planning. Uncertainty surrounding live sheep export was cited to complicate the long-term planning for the red meat industry, potentially discouraging investments in new infrastructure and equipment.

The poor seasonal conditions experienced in 2023, which may become more frequent due to climate change, prompted many producers to turn-off sheep in anticipation of lower carrying capacity. This unexpected destocking, compounded by limited abattoir space and low livestock prices, decreased industry sentiment and confidence among producers. Additionally, in response to these conditions and the failed 2023 spring, many producers opted not to join all or part of their ewe flock. If widespread adoption of this “not joining ewes” approach occurs, it will impact lamb supply in 2024 and have long-term consequences, affecting the flock’s ability to self-replace. This reduction in the number of lambs born for processing will also affect service industries, such as shearers, transporters, and livestock feed providers.

The literature review on barriers to adaptation found that most barriers (and enablers), including lack of self-efficacy and financial constraints such as cost, uncertainty of returns, commodity prices, and financial markets, were related to adaptive capacity. However, limited work has addressed key knowledge and extension gaps in WA, which is essential for preparing effective adaptation strategies for the livestock industry. Producers emphasised the importance of localised decision-making and how other producers can champion R&D.

Benefits to industry

Livestock producers and industry representatives had the opportunity to learn about research from the FutureSheep team at eight field days and 16 industry events, significantly raising awareness of the project. This information was also disseminated through social media platforms like X and rural print media. Journal articles on the economics, carbon emissions and climate resilience of a farm in WA and the impact of consecutive drought years on farm business under future climate scenarios in southwestern WA have also been published. DPIRD will also continue to develop adaptation strategies for the WA sheep industry as part of core business beyond the life of this project.

In conclusion, addressing climate change will require changes in farming systems, potentially involving modifications to current systems or the development of new technologies, cultivars, species or crops. Maintaining rainfed water supply to livestock will be challenging, particularly in low rainfall zones. There will be increased opportunities to promote confinement and feedlotting to producers. Building stronger relationships across the supply chain and continued engagement with processors are crucial for adapting to climate change. Moreover, there is a need to examine ESG practices and map GHG emissions across the entire processing supply chain to mitigate environmental impacts.

Future research and recommendations

Ensuring the resilience of the WA sheep industry in the face of climate change relies on identifying key proposals for future research and development (R&D) and adoption investments, including short, medium, and long-term investment priorities. These recommendations, shaped by modelling inputs, producer feedback, grower groups, livestock consultants, and DPIRD staff, are crucial for guiding industry responses.

Short-term investment is needed for additional biophysical modelling studies and analysing plant adaptations required for future climates, including altered pasture growth profiles across the growing season. Standard site descriptions are necessary to better represent low rainfall zone regions and incorporate new pasture species. Models can be improved by validating them with better descriptions and additional trial crop and pasture data. Online tools and extension services are also essential to enable producers to access climate data for in-season tactical management.

Medium-term strategies (5–10 years) should focus on funding research for more feedbase options adapted to a drying climate and summer-active forages. Accessing and utilising saline groundwater resources for intensive feeding systems and pasture irrigation is a strategic project with significant potential for the sheep industry. By combining desalination with affordable solar electricity, the cost of high-quality water for livestock or forage irrigation could be further reduced. This would make the intensification of farming systems (feedlotting and confinement feeding) more viable by providing a secure water source independent of rainfall.

Long-term investment (>10 years) should adjust plant breeding goals now towards earlier flowering and drought-resistant pasture species and also focusing on seedling-stage drought tolerance. Prioritise breeding sheep for resilience to variations in feed supply with greater energy reserves can help manage risks associated with greater seasonal variation in feed. Sheep that seasonally lose their fleece and do not require shearing or do not grow wool represents another opportunity for the industry to adapt.

In the period between now and 2050 producers in all rainfall zones would benefit from greater extension support that provides them with proven technology that will maintain livestock profitability in the face of a changing climate. Examples include confinement and feedlotting systems, summer-active perennials, high yielding short season forage crops, mixtures of forage rye/barley, oats/vetch, and tillage radish can fill early feed gaps, while serradella/vetch can provide later feed. Grazing crops in winter can also help reduce the feed gap.

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Background

The Western Australia (WA) sheep flock, numbered 12.4 M head at the end of 2021–22, producing high-quality meat and wool for international markets (ABARES, 2021–2022a). With about 4,300 sheep farms in WA, livestock is an established sector of the economy, valued at $2.3 billion (ABARES, 2021–2022b), making it the second-largest agricultural industry behind the grains sector. Climate change will influence livestock production globally, challenging existing production systems in WA. Agriculture in WA's southern regions is predominantly broadacre dryland farming with a Mediterranean-type climate and autumn to spring growing season.

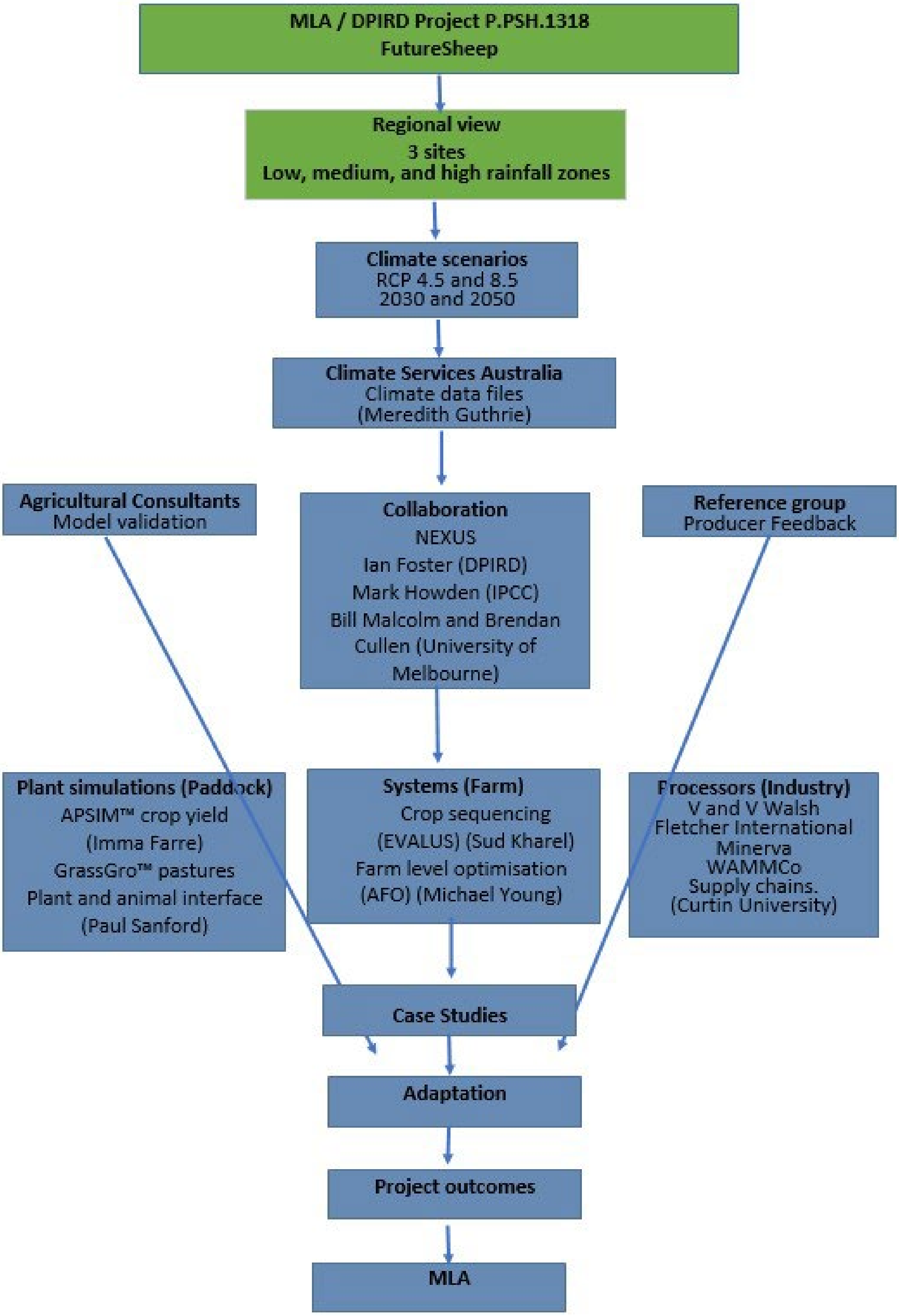
The projected impacts of climate change are expected to be greatest in the medium to low rainfall zones, where substantial changes in temperature and rainfall are anticipated. Sudmeyer *et al*. (2016) proposed reduced rainfall and higher temperatures could reduce forage production by up to 10% over the northern and eastern agricultural areas, but the overall decline in livestock productivity and profitability could be greater than the decline in pasture growth due to the need to maintain minimum pasture cover to prevent soil erosion.

Pastures are crucial in WA's agricultural enterprises, contributing to livestock and grain production. Southwestern Australia supports 20% of the nation's sheep population (Pritchett 2023), making WA the third-largest sheep-producing state behind New South Wales and Victoria. Eighty four percent of the WA flock is made up of Merino breeds higher than any other state and it turns off more mutton than lamb. Farm productivity in WA is highly influenced by climate conditions (Ritchie and Nesmith 1991), particularly rainfall events, as rainfall is often the main limiting factor for crop and pasture yields (Stephens *et al*. 1994). The feedbase in WA predominantly relies on annual pastures for sheep enterprises, predominantly shallow-rooted annual pastures such as subclover and ryegrass, which have relatively low drought resistance. However, these pasture species may not be sustainable in the medium- to long-term across much of the low rainfall zone (LRZ), leading to a potential decrease in sheep numbers on some farms as rainfall declines and temperatures rise.

Existing supply chains in WA have been developed over the past century or more based on historical weather and climate patterns, with regular and predictable lambing turn-off times. However, climate change is expected to lead to more variable forage production and sharper finishes to the season, shifting the peaks in supply. Increased variability in the seasonal supply of lamb for processors, driven by climate change, poses challenges, especially in maintaining or accessing a workforce and capital for business growth and improvement. Some processors have turned to operating feedlots to secure supply and control quality, a trend likely to increase in the future. Adopting new farming practices requires producers to be confident in the reality of climate change, motivated to change to avoid risks, and provided with demonstrated technologies and support during transitions to new production systems.

Climate change, anticipated market changes, the need to optimise meat production systems, and consumer and bank expectations around environmental, social and governance (ESG) practices and methane mitigation are still evolving. ESG considerations need to be integrated into the strategic plan for all processors, and the industry must proactively address messaging around confinement and feedlotting to avoid negative connotations. Moreover, significant changes in animal housing protocols, such as livestock sales yards and transport conditions, may be necessary due to increased temperatures caused by climate change.

Figure 1. FutureSheep project flow chart.



1 Meeting project objectives

1. **Achieved**. *Provided a report detailing the outcomes of climate scenario modelling for each case study location (3) that forecasts pasture growing conditions in 2030 and 2050.*

   While all three case study locations will experience a loss of pasture productivity by 2050 the magnitude of that loss at Kojonup may be small enough that sheep producers will be able to adapt with current technology such as highly productive forage crops. Wagin is not too dissimilar to Kojonup even though the loss of yield will be greater, adaption to the climate conditions in 2050 is highly feasible. Without a change in management the simulations suggest that the low rainfall region typical of Merredin is possibly facing a significant loss of pasture productivity and possibly a marked increase in land degradation.

2. **Achieved**. *Completed an economic analysis calculating future profitability under modelled climate change projections comparing current practises and possible adaptation strategies (feedbase, animal genetics and management, farm systems, enterprise mix)*.

   The economic analysis using EVALUS provided valuable insights into the profitability impacts of current and modelled future climate scenarios (RCP 4.5 and RCP 8.5) for different crop rotations at each study location using data from GrassGro™ and APSIM™ models. Preliminary analyses indicate that climate change will significantly impact the gross margin of cropping enterprises more than sheep enterprises without adaptation measures in all three locations.

3. **Achieved**. *Calculated greenhouse gas emissions on each simulated case study farm for a range of sheep production systems now and projected in 2050 based on climate predictions*.

   The completion of GHG emissions intensity at each location was achieved through the use of modelled data. Sud Kharel undertook a case study on modelling sheep reproduction and methane emissions at a high rainfall site at DPIRD's Katanning research facility. Field benchmarking within the Zero Net Emissions CRC will enhance the accuracy of emissions assessments and contribute to a better understanding of the value of incorporating anti-methanogenic legumes into the feedbase.

4. **Achieved.** *Evaluated how sheepmeat supply chains from farm to the processing entry point may be impacted by future variations to the farm systems in WA. This will include how farm turn-off (numbers, location, age and weights) could change and therefore affect supply to feed-lotters and processors.*

   Four of the major accredited export abattoirs have been engaged for this report. Also, a livestock sales yard and an expert on supply chains (Curtin University). Some flattening of the traditional spring lamb turn off peaks for processors with supply more evenly split between the spring flush and the first quarter. Different turn-off dates could become a key component of adaptation to future climates. However, climate change could mean that the forecasting for future supply from the LRZ is less reliable. This information will be critical for ensuring the industry's resilience under projected climate change.

5. **Partially Achieved.** *Conducted a suite of adoption program activities involving workshops, partner farm activities, on-farm walks and case studies. Key outcomes include*:

   Verbal agreement was made with MLA to replace the partner farms activity and workshops with eight case studies. The evaluation report can be found in Appendix 1. It was premature to promote specific adaptation practices without comprehensive climate projections, a thorough understanding of the impacts on sheep production systems across rainfall zones and insights from case studies on current effective adaptation strategies. Adaptation practices will be an ongoing process that continues beyond the project's duration.

a. *DPIRD and 500 producers understand the impact of climate change scenarios against two time horizons - indicatively 2030 and 2050*.

There was a high level of introductory engagement with producers to raise awareness of climate projections. Team members engaged with 1,300 producers, 291 students, 187 researchers and 129 DPIRD staff through their attendance at eight field days and 16 industry events where climate projection maps were displayed and discussions held with producers.

b. *At least 250 producers understand the profitability and resilience of their production systems against future climate change scenarios and have understanding of the greenhouse gas emissions in different sheep systems and how they are likely to change in the future*.

Journal articles, conference papers and web pages have been published on the economic impact of climate change projections, carbon emissions, climate resilience, sheep reproduction and methane emissions, and the impact of consecutive drought years on farm businesses under future climate scenarios.

c. *At least 20 large mixed producers and the four key farm business consultancies (representing 50% of large mixed farmers) understand in detail the impact of climate change by 2030 and 2050 on sheep production systems and have the capacity and confidence to continue to run sheep and adapt their businesses to the changes expected by 2050*.

Three formal meetings were held with the reference group comprising nine producers and two consultants and eight case study interviews with different farming businesses. The team had many one-to-one conversations with producers, consultants and reference group members seeking information and provided advice. Kevin Foster had many one-to-one conversations with producers, processors, consultants and reference group members to seek information and provide advice. This allowed stakeholders better understand the impacts of climate change on sheep production systems and for consultants to inform their clients.

d. Government and processors understand how WA sheepmeat supply chains may be impacted in the future as producers adapt their farm system in response to climate changes at the level of (I) farm business operations and (ii) supply into domestic and export markets.

We built strong relationships with four of the major red meat processors in WA and we discussed emerging issues from the climate modelled projections. All now have a better understanding of the potential changes to their supply chains to ensure the continued supply of quality animals over time. Additionally, we presented climate projection data to the WA Meat Industry Association board to discuss climate change and processing at stockyards.

6. **Achieved***. Presented the findings of the project at a minimum of two industry events.*

   The FutureSheep team attended eight field days and 16 industry events, and these discussions provide the basis for a strong network of engagement. Additionally, we participated in the WA Farmers Federation annual general meeting. These events were reported on social media platforms, further broadening our outreach. We also met with representatives from Australian Association of Agricultural Consultants.

7. **Achieved***. Submitted a presentation of key project findings and activities to MLA for ongoing use.*

   One paper has been published in a peer-reviewed journal, and another manuscript has been accepted. Several conference papers, presentations, and flyers on climate change have been delivered at industry conferences and field days, with additional resources available on the DPIRD website. As part of the project, more data is being collected for a PhD titled "Integrating Climate Thinking into Agricultural Decision-Making." An updated literature review on barriers to adoption will be provided to MLA, along with PowerPoint presentations.

8. **Achieved.** *Submitted an M & E report on the impact of adoption activities to build awareness, knowledge*.

   The M and E report was completed and is included in the Appendices.

9. *Complied a public summary and call to action which includes:*

   a. **Achieved.** *An explanation of the outcomes and recommendations of the project*.

   Various stakeholders and knowledge sources helped identify priority recommendations for future RD & A investments, including computer modelling, producer feedback, case studies, grower groups, livestock consultants and DPIRD staff. Short, medium, and long-term priorities were identified, highlighting the importance of strategic preparation and tactical responses to climate change. Several key knowledge gaps need to be addressed to prepare the livestock industry.

   b. **Not achieved**. *A detailed financial summary of the cost and benefits of the recommendations.*

   Not undertaken but is being considered as a subject in potential FutureSheep II project.

   c. **Not achieved**. *Supply model outputs and the expected impact on processor and market supply.*

   Due to commercial confidentiality, most processors did not provide detailed information to predict the impacts on their market supply and outputs. New models will need to be developed.

2 Methodology

The FutureSheep project used various models to simulate farming systems and assess the potential impact of future climate conditions. Farm modelling is a diverse field that reflects or represents different aspects of farming operations. Collaboration with industry consultants with specialised knowledge of farming systems was integral to the project. These consultants provided valuable insights and expertise, particularly in validating the computer models used for analysis. The project also engaged with stakeholders through a regional reference group and individual meetings with producers and processors to ensure that the modelling approaches and adaptation strategies considered were relevant to real-world farming contexts and that the project outputs were robust. The modelling analysis focused primarily on assessing the impact of future climate conditions on farming systems. However, any effects of high temperatures on livestock health, reproduction and water requirements were not included.

2.1 Climate modelling

The FutureSheep project used modelling to assess the potential impact of future climate conditions on sheep farming systems. Three locations were chosen for modelling, representing mixed farming systems in different rainfall zones. Merredin is characterised by low annual rainfall, with growing season rainfall (April–October) averaging 214 mm (2000–2021). Farms in this district are typically large (~5500 ha, Planfarm (2022)) and predominantly focus on cropping activities. Wagin is characterised by medium annual rainfall, with growing season rainfall averaging 290 mm (2000–2021). Most farms in this district are mid-sized (~2500 ha, Planfarm (2022)) and feature sheep and grain production, with a relative emphasis on cropping. Kojonup is characterised by relatively high annual rainfall, with growing season rainfall averaging 375 mm (2000–2021). Most farms in this district are mid-sized (~2000 ha, Planfarm (2022)), focusing on oilseed (canola) and sheep prime lamb and wool production.

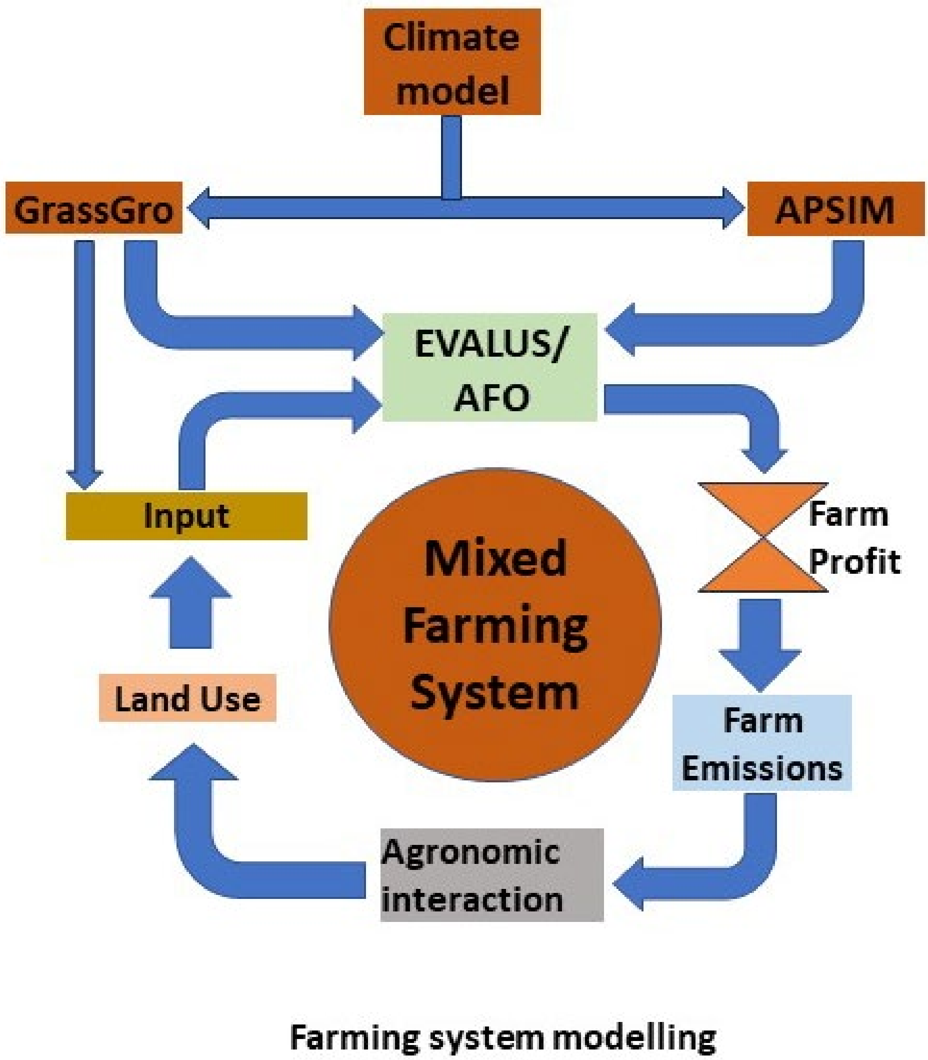
Future climate scenarios for 2030 and 2050 were simulated under future GHG 4.5 and 8.5 Representative Concentration Pathways (RCP) using a climate change factor obtained from the

Climate Change in Australia website. Daily rainfall and temperature projections were calculated using a method developed by Matthew Harrison from the University of Tasmania, aligning with an MLA NEXUS project (Exploring profitable, sustainable livestock businesses in an increasingly variable climate) in the eastern states.

Enterprise GHG and intensity benchmarking at each location.

The economic analysis used EVALUS (Economic Valuation of Alternative Land Use Sequence) a mixed farm bio-economic model (Kharel *et al*. 2022). Cropping and livestock production data was generated over 20 years by the APSIM™ (v. 7.10) and GrassGro™ models (v. 3.3.11), respectively. Using this data, EVALUS simulated a mixed farming system and calculated GHG emissions. Key farming systems were identified for each location using Planfarm (2016-2020) and Harries *et al*. (2015). Farms in Kojonup and Wagin varied from slightly crop-dominant to almost entirely livestock-focused, while farms in Merredin were either 100% cropping or included a small portion of livestock. Consequently, three different cropping rotations were used for each location: 100% cropping, 100% pasture, and 50:50 cropping and pasture. For Kojonup and Wagin, the rotation was pasture (P), pasture (P), canola (C) and wheat (W), while Merredin had a PCWW rotation.

Figure 2. Modelling framework for the FutureSheep project.



2.2 Biophysical and whole-farm computer modelling

The modelling approach used APSIM™ to generate the crop data and GrassGro™ to produce pasture and livestock data, with both models used to simulate production for current and future climate scenarios across the selected locations. For GrassGro™ the dominant soil types in the relevant DPIRD catchment reports were found in the Soil Mapp App, which provided a detailed soil descriptions in the target areas and was then matched with Pastures from Space (PfS) data (https://pasturesfromspace.dpird.wa.gov.au/#/).

The APSIM™ model was used to simulate the production of single crops and is a well-established model (http://www.apsim.info) that accurately represents crop behaviour. No further validation was conducted as the model's performance has been thoroughly tested. GrassGro™ was used to simulate pasture and sheep production (https://grazplan.csiro.au/grassgro/).

Simulation modelling aims to replicate system behaviour and is frequently applied to biological systems encompassing part or all of a farm. However, they do not offer an optimisation function. The Australian Farming Optimisation (AFO) model is a whole-farm bio-economical optimisation model, which succeeded the well-known MIDAS model (Model of an Integrated Dryland Agricultural System). The AFO model represents an Australian farming system's biological and economic details, including modules for rotations, crops, pastures, sheep, crop residues, supplementary feeding, machinery, labour, and finance. It identifies the most profitable solutions using optimisation techniques and accounts for weather uncertainty and variability. AFO was applied to assess the economic impact and identify potential management changes under future climate scenarios at the high (Kojonup) and low (Merredin) rainfall sites.

2.3 Economic modelling, climate and GHG accounting

Production data from APSIM™ and GrassGro™ were integrated into EVALUS to calculate overall farm profitability and other system outputs, such as GHG emissions, under current and future climate scenarios. The model uses real-time observed prices for a given year, or prices fixed to 2020, linked to specific crops and pastures based on land use. All profits and expenses are standardised to 2020 dollars. EVALUS calculates income and costs for each enterprise annually, with emissions based on the Primary Industries Climate Challenges Centre Sheep (PICCC) and Beef Greenhouse Gas (GHG) Accounting Framework (SB GAF) and the Cropping GHG Accounting Framework (C GAF) (Further information can be found in Lopez *et al*. (2022) and Lopez *et al*. (2023). EVALUS calculates all Scope 1 (On-farm), scope 2 (Electricity) and Scope 3 (Off-farm) emissions.

2.4 Case studies

Eight case studies were conducted with producers, with six located near Wagin, Kojonup and Merredin and two outside these regions (Table 1). The semi-structured interviews provided insights into how producers are adapting to climate challenges (https://www.mla.com.au/news-and-events/industry-news/future-climates-no-stretch-with-resilient-strategies/). The case study approach aligned with the NEXUS project and also focused on social science aspects and understanding practice changes related to climate adaptation. These case studies helped identify livestock grazing systems with higher resilience to climate challenges and informed the investment priorities for RD&A initiatives across WA.

Table 1. Location, property size and current annual rainfall of the eight case study farms.

Location	Property size (ha)	Current annual rainfall (mm)
Bruce Rock	4600	294
Varley	8300	318
South Kumminin	4000	329
Corrigin	3000	348
Dongara	3000	366
Wagin	4000	392
Mobrup	3200	538
Westbourne	2100	629

2.5 Monitoring and evaluation plan

The monitoring and evaluation (M&E) plan for the FutureSheep project was developed based on the MLA Program Evaluation Framework (MLA 2005), which reflects Bennett's Hierarchy (Bennett 1975). Key evaluation questions were formulated to assess the project's success against its original plan and its impact on participants. Stakeholder engagement was also prioritised to inform project development and future research directions. The M&E plan underwent modifications after discussions with the NEXUS social scientist team, input from the project team and the reference group to ensure continuous improvement and improve our understanding of the barriers to climate change adaptation (Future Sheep Evaluation Appendix 1).

2.6 Regional reference group

The project engaged with a regional reference group comprising 11 stakeholders from the sheep industry. The first online workshop in October 2022 was attended by six of the 11 stakeholders, with each FutureSheep team member presenting their respective area, overviewing climate changes currently affecting southern WA and the modelled climate scenarios for 2030 and 2050. The reference group also met for a networking event in April 2023 and individual discussions with reference group members occurred throughout 2023–24.

2.7 Collaboration with industry consultants on model validation.

Industry consultants played a crucial role in validating model parameters and outputs, enhancing confidence in the model findings. Their specialised knowledge of farming systems and decision-making processes contributed to refining bio-economic models like EVALUS. Collaborations with consultants offer an objective perspective on modelling assumptions and limitations. Additionally, discussions with Ross Kingwell (DPIRD Chief Economist) aided in understanding future market trends and potential on-farm and industry-wide adaptations. The models were also used to investigate the effects of two consecutive drought years (decile 1) on farm profitability (Farm business impacts of consecutive drought years under current and future climate scenarios in southwestern Australia).

2.8 Literature review on barriers to adoption

The FutureSheep project conducted a literature review to identify key barriers to climate change adaptation in the context of WA sheep farming. While there is a growing body of international and national literature on this topic, limited research has been conducted specifically in WA. However, Kragt *et al*. (2013) developed an interdisciplinary conceptual framework based on the literature review and expert interviews. This framework highlights various barriers to climate change adaptation, including the inherent uncertainty of climate change, availability of viable adaptation strategies, barriers to adaptive capacity (institutional, technological, financial, knowledge and social), and barriers to adoption (risks, values, goals, attitudes and beliefs).

3 Results

3.1.1 Climate change scenario modelling

Future climate projections used in this study are summarised in Table 2. There is a large variation in future rainfall projections, for example January rainfall is projected to increase by as much as 15%, whilst May rainfall may be reduced by 10 to 15% depending on the greenhouse gas scenario. To better understand how future climate will influence the wool-belt, maps were generated looking at current April-October rainfall (averaged for 2000-2021) (Fig. 3), and future projections, in this example for 2050 under greenhouse gas scenario RCP 4.5 (data from Climate Services for Agriculture website, now known as My Climate View) (Fig. 4.).

Figure 3. Average rainfall from April to October 2000–2021 for locations of Merredin (low rainfall zone), Wagin (medium rainfall zone) and Kojonup (high rainfall zone).

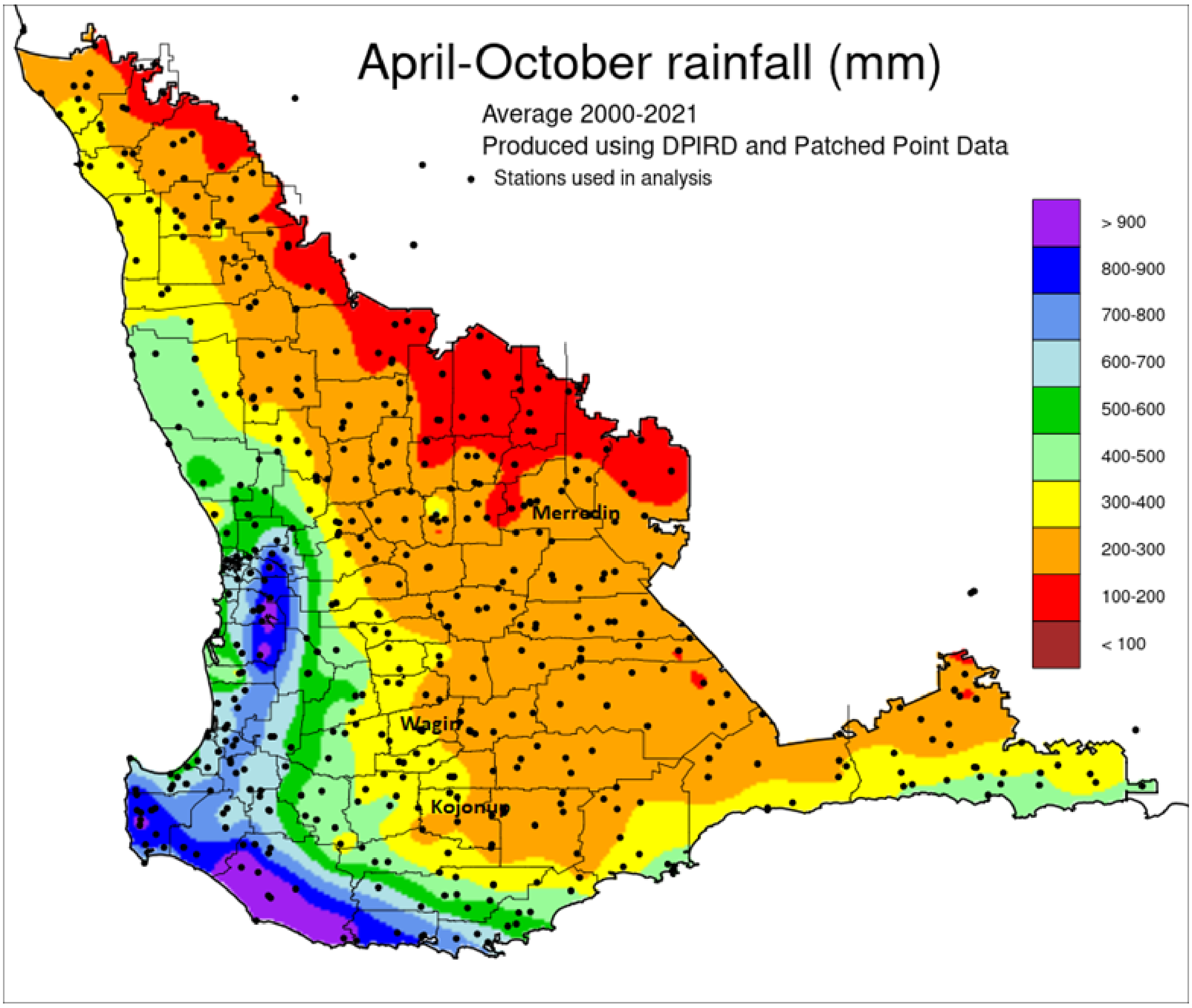


Figure 4. Projected rainfall under the moderate emission scenario (RCP 4.5) in 2050 from 1991-2020 baseline, data from My Climate View website.

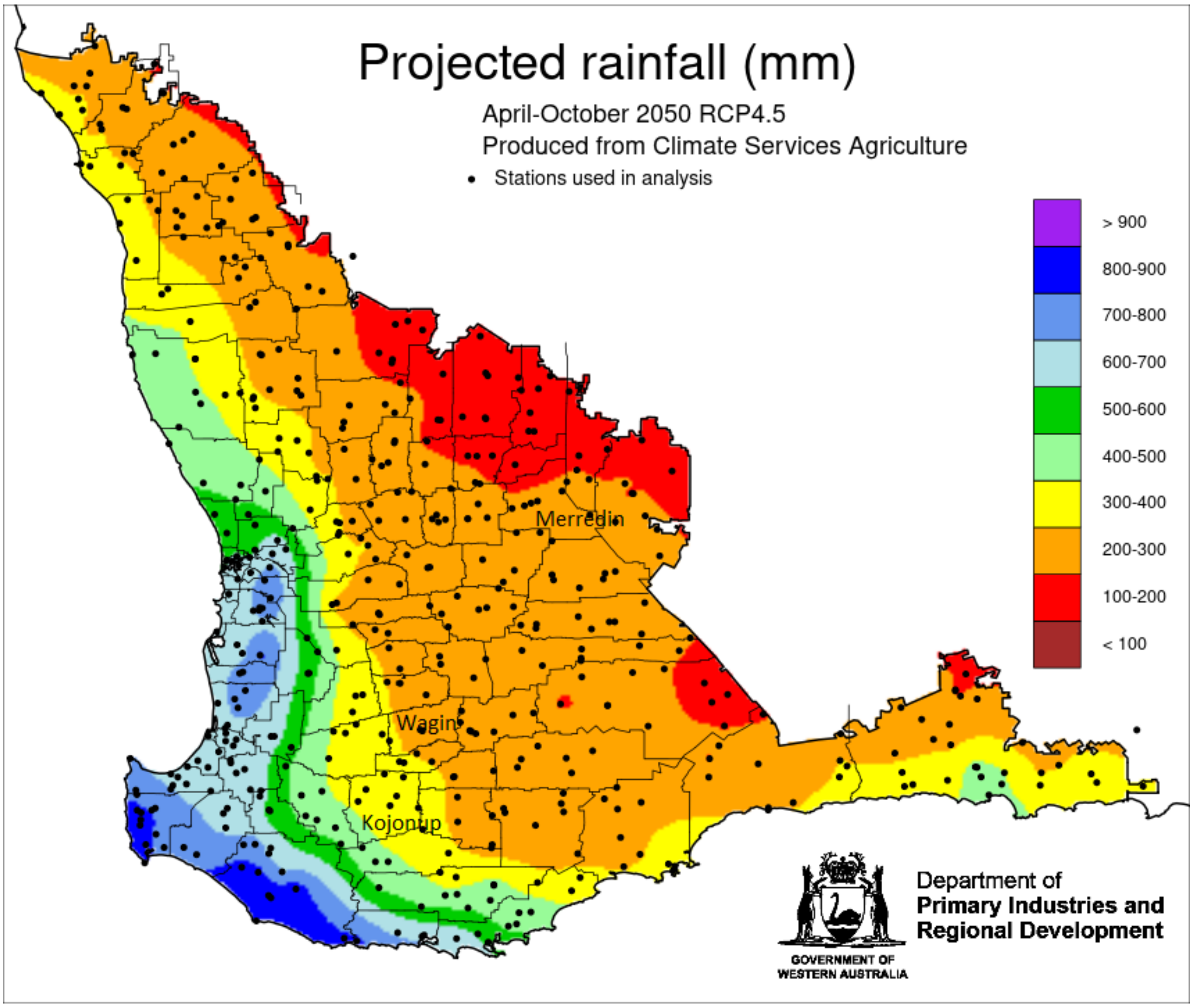


Table 2. Future climate projections for the South-West Land Division (data source: Climate Change in Australia website: https://www.climatechangeinaustralia.gov.au/en/) from baseline of 2000-2021.

RCP 4.5 2030	**RCP 4.5 2050**	**RCP 8.5 2030**	**RCP 8.5 2050**
Rainfall			
Apr–Oct (–10%)	Jan (+15%)	Jan (+15%)	All months (–15%)
Nov–Mar (–15%)	Feb, Apr–May (–15%)	Feb, Mar (+10%)	
	Aug–Dec (–15%)	Apr, May, Dec (–15%)	
	Mar (+10%)	June, Jul, Sept, Nov (-10%)	
	Jun–Jul (–10%)	Aug, Oct (no change)	
Temperature			
All months (+1°C)	Jan, Mar (+1°C)	All months (+1°C)	All months (+2.25°C)
	May–Sep (+1°C)		
	Feb, Apr, Oct–Dec (+2.25°C)		

Summary tables provide detailed projections of rainfall, calculated soil water, potential crop yield, days below 2°C from August to October (frost indicator), days above 32°C from August to November (heat stress impacting crops and sheep), break of season, and number of days between break of season and next rainfall event (Tables 3 and 4).

The break of season or sowing rule in WA's grainbelt has changed over time. Twenty years ago, the standard sowing rule was 25 mm of rainfall over three days after 25 April (https://www.agric.wa.gov.au/climate-weather/soil-water-tool/). With technological advancements, new cultivars and dry sowing methods, the rule for cereals changed to 15 mm over three days after 1 April. A potential reduction to 10 mm over 3 days is being considered, though it is risky due to high temperatures and evaporation potentially not providing sufficient moisture for seedling survival.

Table 3. Average April–October and November–March rainfall, soil water (one-third of Nov–Mar rainfall), potential yield (Apr–Oct rainfall plus stored soil water at 1 April with 110 mm evaporation and 15 kg/ha/mm water use efficiency; French and Shultz 1984), days below 2°C from August to October and days above 32°C from August to November for Merredin, Wagin and Kojonup from 2000–2021 (historical) and future climate projections in 2030 and 2050 under RCP 4.5 and RCP 8.5.

	Apr–Oct (mm)	Nov–Mar (mm)	Soil water (mm)	Potential yield (t/ha)	Days below 2°C (Aug–Oct	Days above 32°C (Aug–Nov)
Merredin						
2000–2021	214	102	34	2.1	9	14
RCP 4.5 2030	193	86	29	1.7	9	16
RCP 4.5 2050	186	101	34	1.6	9	23
RCP 8.5 2030	196	106	35	1.8	9	16
RCP 8.5 2050	182	86	29	1.5	9	23
Wagin						
2000–2021	290	99	33	3.2	7	6
RCP 4.5 2030	260	82	27	2.6	6	10
RCP 4.5 2050	251	94	31	2.6	6	15
RCP 8.5 2030	264	100	33	2.8	6	10
RCP 8.5 2050	246	82	27	2.4	6	15
Kojonup						
2000–2021	375	104	35	4.4	6	4
RCP 4.5 2030	346	88	29	4.0	5	6
RCP 4.5 2050	334	100	33	3.8	5	10
RCP 8.5 2030	352	105	35	4.1	5	6
RCP 8.5 2050	327	88	29	3.7	5	11

Table 4. Average dates for break of season (15 mm over 3 days after 1 April; 5 mm over 3 days after 5 June) and number of days between break of season and next rain (5 mm) from 2000–2021 (historical) and future climate projections in 2030 and 2050 under RCP 4.5 and RCP 8.5.

	Merredin		Wagin		Kojonup	
	Break of season	Days to next rain	Break of season	Days to next rain	Break of season	Days to next rain
2000–2021	12 May	20	5 May	9	28 Apr	10
RCP 4.5 2030	13 May	24	6 May	11	2 May	14
RCP 4.5 2050	14 May	25	7 May	11	6 May	12
RCP 8.5 2030	14 May	25	7 May	11	6 May	12
RCP 8.5 2050	14 May	26	10 May	12	7 May	12

Professor Mark Howden proposed the current emissions trajectory and suggested that future climate projections should focus on RCP 4.5, considering the reduction in emissions due to the faster uptake of renewables and reduced fossil fuel use. However, the current global climate models (GCM) trends still suggest that emissions are not decreasing as rapidly as hoped, aligning more closely with RCP 8.5. Therefore, for this analysis, we used RCP 4.5 as the best-case scenario and RCP 8.5 as the worst-case. The NEXUS project also included RCP 8.5 in its analysis, supporting the broader scope of understanding under more severe climate conditions. Recent publications and the International Panel on Climate Change (IPCC) reports indicate that the current climate trajectory aligns more with RCP 8.5 (https://www.pnas.org/doi/10.1073/pnas.2007117117).

3.1.2 Simulating the impact of future climate on pasture and sheep production

The following section reports on the analysis of the impact of future climate on pasture and sheep production at the three locations Merredin, Wagin and Kojonup (Table 5). Details the pasture and soil types used in this specific GrassGro™ simulations.

Table 5. Pasture and soil types used for GrassGro™ simulations.

Location	Pasture type	Soil type
Merredin	Subterranean clover, annual ryegrass and capeweed	Sandy clay
Wagin	Subterranean clover, annual grasses and capeweed	Sand over clay loam
Kojonup	Subterranean clover, annual ryegrass and capeweed	Loamy sand over sandy clay loam

The grazed analysis used a dual-purpose Merino system with a July lambing, November weaning, and a lamb finishing weight of 45 kg live weight, run at various stocking rates. Supplementary feeding (lupins) was provided to ewes and lambs.

3.1.2.1 Validation

There was good agreement between simulated and observed values for ungrazed pasture yield at Wagin and Kojonup, with R^2 values of 0.6042 and 0.558, respectively (Pasture simulations Appendix 2). The fit between simulated and observed values at Merredin was adequate. Overall, GrassGro™ provided credible simulations for pasture production at Merredin, Wagin and Kojonup, indicating that it can offer useful insights into the impact of future climate at these locations.

3.1.2.2 Impact of a future climate on ungrazed pasture yields

Table 6 presents the impact of future climate on ungrazed yields. As expected, preliminary simulations suggest that pasture yields will decrease in 2030 and 2050 at all three locations, with the largest loss occurring at Merredin and the smallest at Kojonup. The yield range also decreases, with poor growing seasons particularly concerning at Merredin note the lowest values in the range in pasture yield for all climate scenarios for Merredin in Table 6. However, at higher rainfall sites (Wagin and Kojonup), yield losses are partly offset by higher atmospheric CO_2 levels and increased temperatures, which can enhance pasture growth rates for part of the season. For instance, at Kojonup in 2030 under RCP 8.5, the best seasons could provide small increases in yield (Table 6 range in pasture yield).

Table 6. Simulated ungrazed pasture yields (kg DM/ha/year) at Merredin, Wagin and Kojonup for the current climate 2000-2021 and future climate projections in 2030 and 2050 under RCP 4.5 and RCP 8.5.

Site	Climate	Average pasture yield (kg DM/ha/year)	Range in pasture yield (kg DM/ha/year)
Merredin	Current	3206	1714–4542
	2030 RCP 4.5	2177	811–3288
	2030 RCP 8.5	2511	1034–3707
	2050 RCP 4.5	2004	827–3152
	2050 RCP 8.5	1708	204–3217
Wagin	Current	7201	4447–10629
	2030 RCP 4.5	6494	4207–9116
	2030 RCP 8.5	6546	4196–9877
	2050 RCP 4.5	6501	4284–9102
	2050 RCP 8.5	6504	4066–9241
Kojonup	Current	8756	5529–12842
	2030 RCP 4.5	8058	5137–12141
	2030 RCP 8.5	8636	5624–13413
	2050 RCP 4.5	8102	4938–12900
	2050 RCP 8.5	8626	5501–11899

3.1.2.3 Impact of a future climate on a dual-purpose Merino enterprise

This section examines three key variables for a simulated dual-purpose Merino enterprise: pasture yield, minimum herbage mass (an indicator of potential soil erosion) and the amount of supplement fed to ewes, indicating the extent to which pasture fails to meet production targets. It is important to note that this analysis does not address potential reductions in livestock drinking water supply or some aspects of heat stress on plants and livestock that might occur under extreme climatic events in the future.

Merredin

The model shows a strong correlation between ungrazed and grazed pasture yields and indicates a substantial decline in yield by 2050 under both RCP 4.5 and RCP 8.5 scenarios. Increased stocking rates reduce yields modestly, compensated by a significant increase in supplementary feeding triggered by ewe condition scores. Sheep should be removed once the minimum herbage mass reaches 800 kg DM/ha to minimise soil erosion. The model suggests that soil erosion is a risk even under the current climate (Fig. 5). By 2050, the soil erosion risk is likely to increase substantially in pasture paddocks in the low rainfall zone of the eastern wheatbelt (Table 6). Assuming a district average stocking rate of 2 DSE/ha (dry sheep equivalent), the model suggests Merredin sheep producers need to feed around 100 kg of grain per ewe to optimise production. Without adaptation and the corresponding loss in pasture yield, this could increase to around 180 kg of grain per head by 2050 (RCP 8.5), which is unlikely to be profitable. Conversely adaptation with no increase in supplement would require producers to recover a loss of around 1600 kg DM/ha/yr.

Wagin

As at Merredin, there is good agreement between grazed and ungrazed pasture yields, with the model indicating a more modest yield decline by 2050 under both RCP pathways. The risk of soil erosion with stocking rates below 10 DSE/ha remains low. Assuming current stocking rates in Wagin average 10 DSE/ha and remain at this rate into the future, a higher risk of soil erosion will need to be addressed by 2050. At a stocking rate of 10 DSE/ha, the model suggests producers currently need to feed each ewe around 40 kg of lupins, potentially increasing to 70 kg per ewe by 2050 (RCP 8.5).

Kojonup

Compared to Merredin and Wagin, the predicted loss of pasture yield at Kojonup due to future climate is very modest (Fig. 10 Appendix 2) possibly due to some pasture species benefiting from the projected warmer winter conditions and higher atmospheric CO_2. The relationship between stocking rate and pasture yield at Kojonup is relatively flat for all climate scenarios, suggesting that pastures in this environment can remain highly productive. Assuming a district average stocking rate of around 12 DSE/ha, the soil erosion risk at Kojonup from now until 2050 is minimal. The model predicts that at around 12 DSE/ha, sheep producers currently feed just over 20 kg of lupins per ewe per year, which without adaptation may increase to approximately 40 kg per ewe by 2050 (RCP 8.5) as a result of the loss in pasture yield

3.1.2.4 Discussion

Preliminary GrassGro™ simulations indicate that by 2050, all three locations—Merredin, Wagin and Kojonup—will likely experience reduced pasture productivity and increased seasonal variability. However, the extent of these impacts varies by location. At Kojonup, the simulations suggest that the loss in pasture productivity may be relatively minor implying that sheep producers can adapt with current technologies. At Wagin the projected decrease in pasture yield is more significant, despite this, adaptation to the projected 2050 climate is highly feasible. Without a change in management the simulations suggest that the low rainfall region typical of Merredin is possibly facing a significant loss of pasture productivity and an increase in land degradation. Furthermore, adaptation will be challenging and most likely involve technology not currently available. However, prior to 2050 it is likely that sheep production within the current farming system will remain viable in the low rainfall zone for some time assuming that producers adopt current pasture technology that will for a time arrest the loss of yield. Potential feedbase adaptations at all three locations include an increase in soil fertility, adoption of drought and heat tolerant temperate species, especially for Merredin, introduction of summer-active forages and forage crops to fill feed gaps.

3.1.3 APSIM™ simulating the impact of climate change on crop yields

3.1.3.1 APSIM™ background

This section investigates the impact of future climate change on crop yields across different rainfall zones in WA (Merredin, Wagin and Kojonup). The APSIM™ simulation model was used to obtain wheat yields for current and future scenarios for these locations.

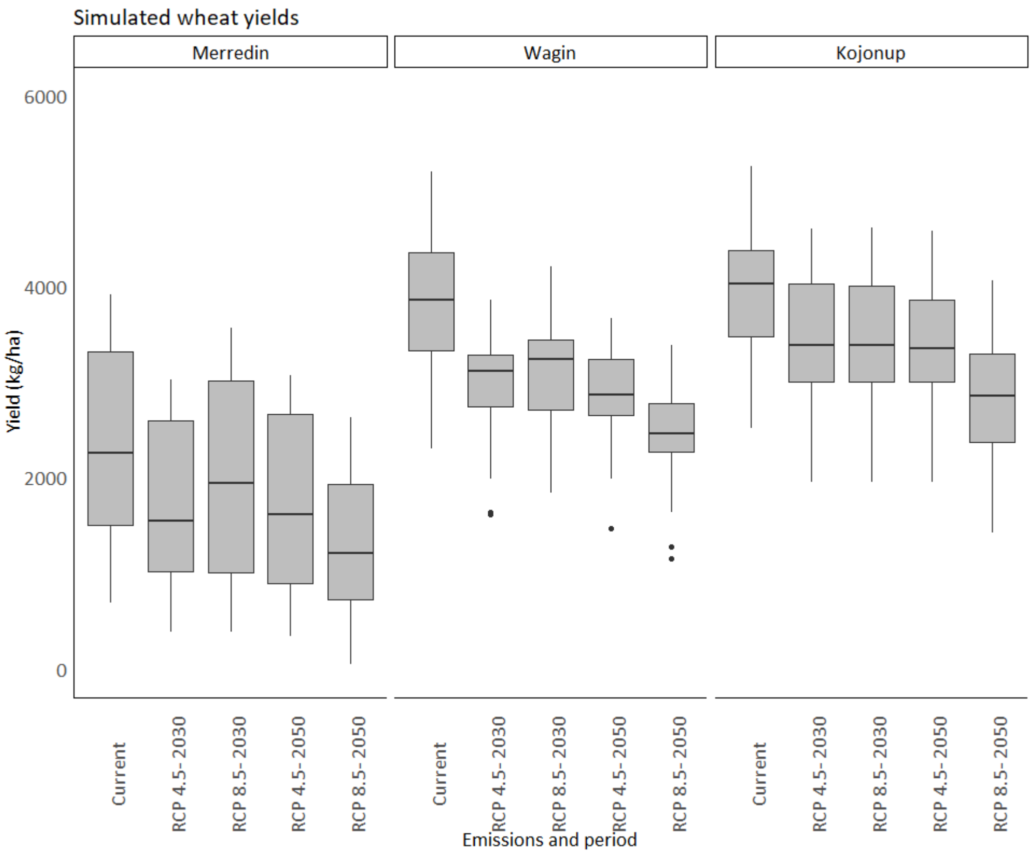
3.1.3.2 Model overview

This study used APSIM™ to simulate wheat production for 20 years using daily climate data, capturing water-limited potential yield for the three locations under current climate and future scenarios. Water-limited potential yield is the potential crop yield limited by temperature and rainfall, assuming non-limiting N and a pest - and disease-free crop, referred to here as "simulated yield" or "yield". Sowing operations followed specific rules dictating a sowing window and a rainfall threshold to determine the first sowing opportunity. In Merredin, the sowing window spanned 15 April to 15 June, while in Wagin and Kojonup, it ranged from 15 May to 15 June. Crops were sown on the first day within the sowing window after recording 15 mm of rainfall over three days. The wheat cultivar "Scepter" was used consistently across all years and locations, with fertiliser N applied adequately to prevent N limitation. A soil with good water holding capacity, featuring a water holding capacity of 127 mm between the drainage upper and lower limits, with root depth restricted to 120 cm. Soil water moisture was reset annually on 1 January, assuming full utilisation of available soil water by the previous crop. This approach ensured the independence of each simulation year, allowing for the isolation of climate impacts on crop yields.

3.1.3.3 Results

Figure 5 presents box plots representing simulated wheat yields for Merredin, Wagin and Kojonup during the current historical period (2001–2021 and for the 2030 and 2050 periods under medium (RCP 4.5) and high (RCP 8.5) emission scenarios. In these plots, the central line represents the median (50th percentile), the shaded area indicates the interquartile range (25th to 75th percentiles), and the lines outside the box indicate the minimum and maximum yields over the 20 years. Across all locations, the simulations suggest a negative impact of future climate on wheat yields (Fig. 5), highlighting the need for further research to explore adaptive measures. Strategies such as cultivar selection and adjusting sowing dates could help mitigate the adverse effects of declining rainfall and increasing temperatures on crop productivity.

Figure 5. Simulated boxplot wheat yields (kg/ha) (median, with lower to upper quartiles shaded) in Merredin, Wagin and Kojonup for the historical current period (2001–2021) and future climate projections in 2030 and 2050 under RCP 4.5 and RCP 8.5.



3.2 Economic analysis of profitability impacts of modelled climate change

3.2.1.1. Farming systems

Farming practices vary significantly across and within the study locations due to differences in farmer preferences, risk tolerance, abiotic and biotic factors, and socioeconomic conditions. Mixed cropping systems—typically split equally between sheep and cropping—are prevalent in WA's southern high-rainfall grain belt regions, where growing seasons are longer but prone to frost and waterlogging (Planfarm 2016-2020). In Kojonup and Wagin, land use systems vary, with some paddocks dedicated to livestock or cropping for extended periods, while others alternate between cropping and pasture. Hence, three land use sequence (LUS) types were chosen in Kojonup and Wagin: continuous cropping, continuous pasture, and a 50:50 cropping and pasture rotation. In contrast, Merredin's farming systems are crop-dominated, with small or marginal paddocks dedicated to sheep due to shorter growing seasons, hot and dry summers, and lower sheep profitability (Planfarm 2016-2020). Sheep are used primarily for grazing stubble post-harvest and weed management. Consequently, three LUS types were selected for Merredin: continuous cropping, continuous pasture, and pasture grown every fourth year after three crop rotations.

3.2.1.2 Results and discussion

Gross margins (GM) provide a straightforward measure of the costs and benefits of different farm system components. Preliminary analyses indicate that climate change will significantly impact the GM of cropping enterprises more than sheep enterprises without adaptation measures in all three locations. Cropping yields are highly dependent on rainfall, with most costs incurred upfront. During hot and dry seasons, farmers have limited options to reduce operation costs, primarily adjusting N application and a few other factors, decreasing yields and income and substantially lowering the gross margin. Conversely, the impact of climate change on sheep enterprises is less pronounced because sheep can be finished on grain or destocked if pasture production decreases, stabilising income depending on lamb/mutton and wool prices while increasing production costs. The price of sheep commodities tends to impact the gross margin of sheep more than the climate. By 2050 under RCP 4.5, the gross margin in Kojonup decreased by 16%, 2% and 23% for the crop:pasture rotation, continuous pasture and continuous cropping, respectively (Fig. 1a–c Economic analysis Appendix 3). Moreover, the gross margin's coefficient of variation (CV) increased from 30% to 39% for crop:pasture rotation and from 31% to 42% for continuous cropping while remaining unchanged for continuous pasture.

The impact of climate change is projected to be more severe in Wagin than in Kojonup, with GM losses by 2050 ranging from 17–45 % /ha under RCP 4.5 and from 16-59 %/ha under RCP 8.5 over 20 years, depending on land use practices (Fig. 2a–c Appendix 3). Moreover, the gross margins CV increased from 34% to 58% for crop: pasture rotation, from 39% to 70% for continuous cropping, and from 51% to 56% for continuous pastures from the current climate to 2050 under RCP 4.5, indicating a greater impact of climate change on cropping than pasture in Wagin and Kojonup.

In Merredin, similar trends were observed. Continuous pasture had a gross margin of $27/ha and CV of 149% under the current scenario (note: the model does not consider stubble feeding, which can impact the GM of sheep enterprises in Merredin. This impact is however small.) (Fig. 3c Appendix 3). The modelling indicates that the GM of continuous cropping (Table 1 Appendix 3) will decrease by 53% by 2050, with variability more than doubling from 62% to 138% under RCP 4.5.

Pasture enterprises had lower gross margins in all locations than cropping. According to Kharel *et al*. (2022), Farmanco's industry benchmarks (Ward 2022), and data from Kingwell *et al*. (2018), cropping has significantly higher fixed costs per hectare than sheep in higher rainfall regions. However, the sheep enterprise's GM in Merredin is barely positive under current climate conditions due to high supplementary feeding costs (Fig. 3c Appendix 3). Even with small fixed costs, the sheep enterprise is not profitable under future scenarios without adaptation. Nonetheless, factors like stubble grazing have not been accounted for, and sheep provide other benefits in low rainfall regions, such as weed management and reduced gross margin variability.

GHG emission accounting was conducted for each land use practice, revealing higher emissions in systems involving sheep, with stocking rates significantly influencing emissions across all locations. For example, Kojonup had the highest stocking rates under continuous pasture, followed by Wagin and Merredin. Similarly, Kojonup had higher emissions in cropping systems due to the higher yields requiring more N application.

3.2.2 Australian Farming Optimisation (AFO) at Kojonup and Merredin

The Australian Farming Optimisation (AFO) model (Young *et al.* 2023) is a comprehensive whole-farm bio-economic optimisation model to simulate year-to-year variations and various tactical management options. This model examines the impact of a drying climate on farm profitability and optimal management strategies. By using AFO, we can overcome many limitations of previous analyses, providing more realistic and accurate insights into the impact of a drying climate in Kojonup and Merredin on farm profitability and optimal management. Wagin was not included in this analysis as the purpose was to contrast the high and low rainfall regions. This analysis will also determine whether further economic evaluations under the predicted 2050 climate scenarios will be beneficial.

3.2.2.1 General results and discussion for Kojonup

This preliminary analysis aimed to provide general economic insights into the impacts of climate change. Unlike previous studies that often considered the effects on sheep enterprises in isolation, AFO allows simultaneous consideration of all elements of a typical farming system.

In the current Kojonup climate, there is a 34% chance that a given year will be a drought (decile 3 or lower). Under these circumstances, profit is expected to decrease by ~$52,000 (6%) annually. However, sensitivity analysis showed that the timing of reduced rainfall plays a crucial role. For example, an increase in the frequency of late rainfall breaks has a more significant adverse effect than an increase in poor spring seasons. Therefore, examining changes in rainfall distribution would provide valuable information for predicting future outcomes.

A 6% reduction in profit leaves the modelled farm with $805,000 operating surplus (profit before interest, tax and drawings). Thus, farmers in Kojonup can remain viable even under a drying climate, but optimal farm management strategies will need to adjust based on how the climate dries and other changes in the farming system. Tactical adjustments in management between years remain essential due to significant weather variations.

The study indicated that farm profitability and management in Kojonup vary depending on climate drying patterns and market price fluctuations. This suggests that other production efficiencies, such as improvements in crop yields per millimetre of rainfall or adoption of new technologies, will interact with climate change. A more detailed prediction of the 2050 climate would provide a more accurate assessment to aid industry preparation. However, a meaningful analysis would also need to consider changes in other aspects of the farm system.

The drying climate will impact farm profitability and optimal management in Kojonup. However, given its less extreme climate, low rainfall years will have a smaller impact in Kojonup than in other regions in the wheatbelt.

3.2.2.2 General results and discussion for Merredin

Understanding the impact of a drying climate on mixed farming systems in the LRZ is crucial. However, due to differences in farming systems between regions, extrapolating results from the Kojonup analysis to other regions is challenging. Therefore, replicating the analysis for LRZ, specifically Merredin, was a project priority. Thus, the weather variation component of the AFO model was calibrated to this region (AFO calibration LRZ Appendix 4), and GHG emissions were also included in this analysis.

The specific objectives were to (1) identify how a drying climate in Merredin will affect farm profitability, (2) identify how a drying climate in Merredin will affect farm GHG emissions, (3) quantify key management changes that farmers can implement to adapt to a drying climate, and (4) identify future steps to ensure farming remains viable in Merredin.

In the current Merredin climate, there is a 23% chance that a given year will be a drought (decile 3 or lower). If the climate continues to dry at a similar rate to the last 50 years, the probability of drought could increase by 40%, to 48%. Under these circumstances it is estimated that profit would reduce by $91,000 (46 %) per year (Table 7 AFO Appendix 8). Examining changes in rainfall distribution is also crucial for understanding future outcomes. Management adjustments, such as reducing stocking rate and increasing pasture area, can partly offset the adverse economic impacts by 18%. Producers must balance management between mitigating losses in unfavourable years and exploiting favourable years. High stocking rates may be profitable in good years but costly in poor years. As the probability of drought increases, focusing more on reducing losses in poor years rather than exploiting favourable years is optimal. This also highlights to importance of a flexible farm system allowing for tactical management changes, such as altering stocking rate.

Technology and production efficiency improvements were assumed to remain consistent with today's levels. Advancements, such as increasing grain and pasture yields with less rainfall beyond current levels could help offset the impacts of a drying climate. A 10% increase in drought years can be offset by a 5% increase in crop yields and a 7.5% increase in pasture growth. Moreover, a 4–5% price increase in sheep and crop enterprise would offset the economic impacts of 10% more drought years.

Increasing the probability of dry summers has a larger adverse effect than dry springs on profitability. For instance, an increase in the frequency of dry summers (Table 15 Appendix 8) reduces the optimal stocking rate compared with an increase in dry springs. The timing of rainfall events was shown to be an important consideration when examining a future drier climate. Reduced summer rainfall significantly impacts early-season pasture production, a critical factor in determining feed availability for livestock. Reduced spring growth also decreases dry pasture availability, but this is not as critical because sheep can graze stubble at this time. These results emphasise the need for specificity when discussing and analysing future climate conditions. Rather than focusing solely on total growing season rainfall, it is crucial to consider the timing and distribution of rainfall events.

A drier climate reduces production per hectare and slightly reduces crop area, decreasing total farm emissions by 132 t/year (5%) (Table 13 AFO Appendix 8). However, emissions intensity slightly increases, indicating a negative outcome for the GHG challenge. Different accounting methods (National Greenhouse Gas Inventory and Blaxter and Clapperton) revealed significant variations in predicted livestock methane emissions. Given methane emissions contribute significantly to whole-farm emissions, further work is required to improve the accuracy of predicting methane production from livestock.

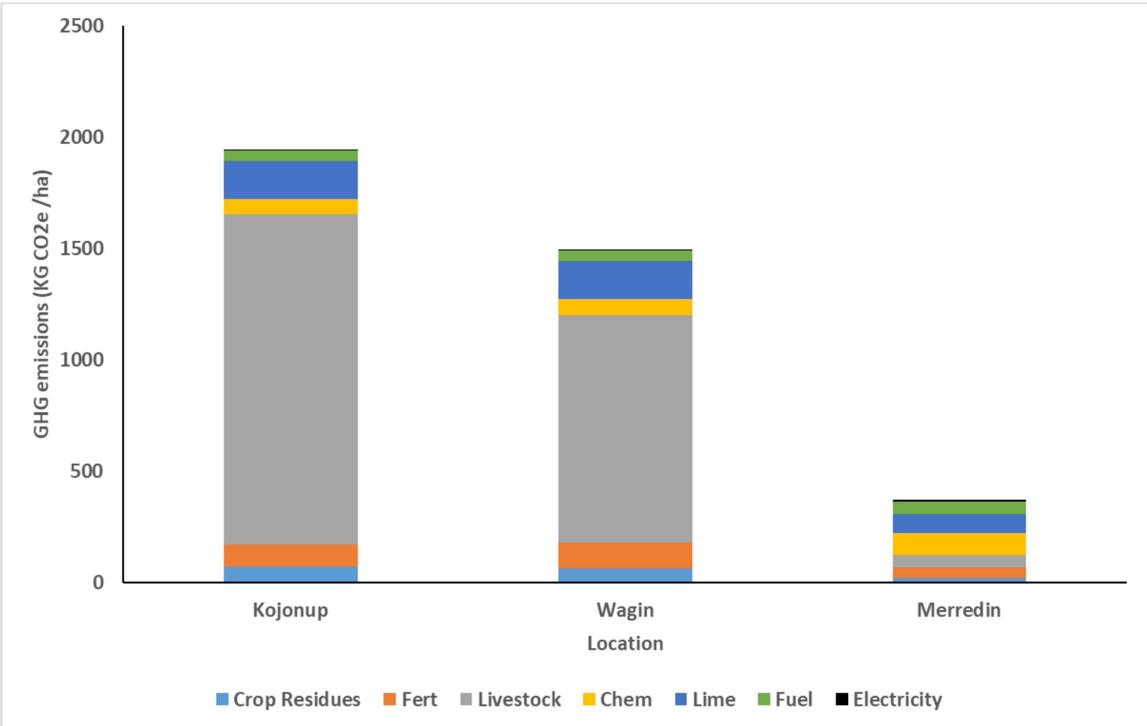
3.3 Enterprise GHG and intensity benchmarking at each location

The project assessed emission intensity at each study location. However, obtaining a comprehensive "benchmark" requires multiple data sets, which currently do not exist. There is a notable lack of studies on emissions and emission intensity in livestock specific to farms in WA, particularly in the study region. Existing studies include Kharel *et al.* (2022), which examined livestock emissions as part of crop rotations in Merredin, Kojonup, and Narrogin (near Wagin) but did not explore emission intensity and relied on modelled data rather than actual farm data. Wiedemann *et al*. (2022) studied statewide livestock emissions for baseline and reporting purposes. Finally, Gebbels *et al.* (2022) looked at productivity change and its impact on methane intensity.

3.3.1 Results and discussion

In Kojonup and Wagin, livestock were the largest emitters of GHGs (Fig. 6). Higher stocking rates in these areas mean sheep contribute significantly to emissions, unlike in Merredin, where lower stocking rates result in less contribution from sheep. Fig. 6 illustrates the average emissions from different sources at the three study locations. In Kojonup, a crop rotation of wheat, canola and two pasture cycles generate around 1950 kg CO_2e/ha per year, primarily from livestock emissions followed by lime application. Fertiliser usage contributes only 5% of total emissions due to N fixation during the pasture phase substituting for N fertiliser. Wagin shows similar patterns, but 8% of emissions arise from fertiliser due to lower pasture productivity necessitating increased N inputs.

Figure 6. Annual emission breakdown (kg/CO_2e/ha/yr) for three locations under different land use sequences: Kojonup: WCPP, Wagin: WCPP, and Merredin: CWWP; W: Wheat, C: Canola, P: Pasture.



Merredin, with significantly fewer sheep and a smaller pasture component (25%) in its cropping rotation, has much lower emissions (factor of 10) than Kojonup. Lower crop production and fertiliser use further reduce farming emissions in Merredin compared to Kojonup and Wagin. Table 7 shows emission intensity for different commodities under various crop rotations. Emission intensity for grains is similar across all locations, aligning well with values reported by Curnow (2022). Emission intensity for wheat and canola is lower when livestock is included in the system due to N fixation during the pasture phase, reducing the need for fertiliser. Canola benefits more from fixed N as it follows the pasture, resulting in a more significant difference in emission intensity between 100% and partial cropping systems than wheat.

Livestock emission intensity varies across locations, with the lowest intensity in Kojonup and the highest in Merredin. This discrepancy can be attributed to the higher enterprise efficiency in Kojonup, enabling quicker lamb turn-off compared to Merredin. Several factors contribute to these differences. Firstly, sheep emissions negatively correlate with dry matter digestibility (DMD) (Hart *et al*. 2009), with Kojonup and Wagin exhibiting higher DMD levels than Merredin. Secondly, lower weight gain in Merredin means lambs stay on the farm longer to reach sale weight, increasing emission intensity. Additionally, lower lambing rates in Merredin result in marginally lower emissions from ewes, but fewer lambs sold increases the emission intensity. Notably, changes in crop rotations had minimal impact on emission intensity across livestock rotations. Livestock emission intensity modelled during this exercise was almost one-third lower than the intensity from Katanning Research Facility (KRF) (Curnow, 2022) and slightly lower than Wiedemann *et al.* 2016b as cited in Curnow (2022). The meat and wool emission intensities provide in this report however was higher than those reported in Harrison *et al.* (2014) and Cottle *et al.* (2016).

Table 7. Annual emission intensity for commodities sold in Kojonup, Wagin and Merredin under different cropping scenarios.

Emission Intensity	Cropping %	Kojonup	Wagin	Merredin
Wheat (kg CO2e/t)	100%	239	272	252
	50%	197	236	241
	0%	0	0	0
Canola (kg CO2e/t)	100%	444	525	571
	50%	366	456	547
	0%	0	0	0
Meat (kg CO2e/kg)*	100%	0	0	0
	50%	6.1	6.3	7.5
	0%	6.1	6.2	7.8
Wool (kg CO2e/kg)	100%	0	0	0
	50%	26.2	27.6	34.5
	0%	26.5	27.2	35.7
*includes both lambs and ewes				

Table 8 displays the total emissions per hectare per annum for various enterprises across the study locations. Wagin had slightly higher emissions for wheat than Kojonup; however, the reverse was true for canola. This difference is due to similar modelled wheat yields in both locations but lower N inputs in Kojonup due to higher soil organic carbon. Conversely, the higher modelled yield for canola in

Kojonup required increased N inputs, leading to higher emissions. Additionally, Merredin had half the total emissions compared to Wagin and Kojonup.

Emissions decreased across all locations under a 50% cropping scenario due to reduced total fertiliser demand facilitated by N fixation from pasture legumes. However, livestock emissions in Wagin slightly increased under 50% cropping compared to 100% livestock. This increase can be attributed to the need for better pasture management under the 50% cropping scenario. Stocking rates positively influenced location-specific livestock emissions. Figs 2–4 (Enterprise GHG intensity Appendix 5) illustrate GHG emissions for different crop rotations under various climate scenarios.

Table 8. Total emissions per annum for enterprises in Kojonup, Wagin and Merredin under different cropping scenarios.

Total emissions	Cropping (%)	Kojonup	Wagin	Merredin
Wheat (kg CO_2e/ha)	100%	798	885	493
	50%*	673	778	457
	0%	0	0	0
Canola (kg CO_2e/ha)	100%	1071	908	428
	50%*	926	823	427
	0%	0	0	0
Livestock	100%	0	0	0
	50%*	3204	2291	308
	0%	3238	2256	319
*75% cropping for Merredin				

3.3.2 Further research

There are a number of studies on emissions and emission intensity in livestock farming (Alcock and Hegarty, 2006; Alcock and Hegarty, 2011; Cottle *et al*. 2016) but few within WA (Gebbels *et al*. 2022), particularly in these study regions Unlike grain industry benchmarking, emission benchmarking for livestock requires extensive research due to the significant influence of livestock weight, feed intake, crude protein (CP), and dry matter digestibility of the feed on emissions. While producers are well-acquainted with their farming systems, they typically do not record detailed data beyond the sale weight of lambs and ewes.

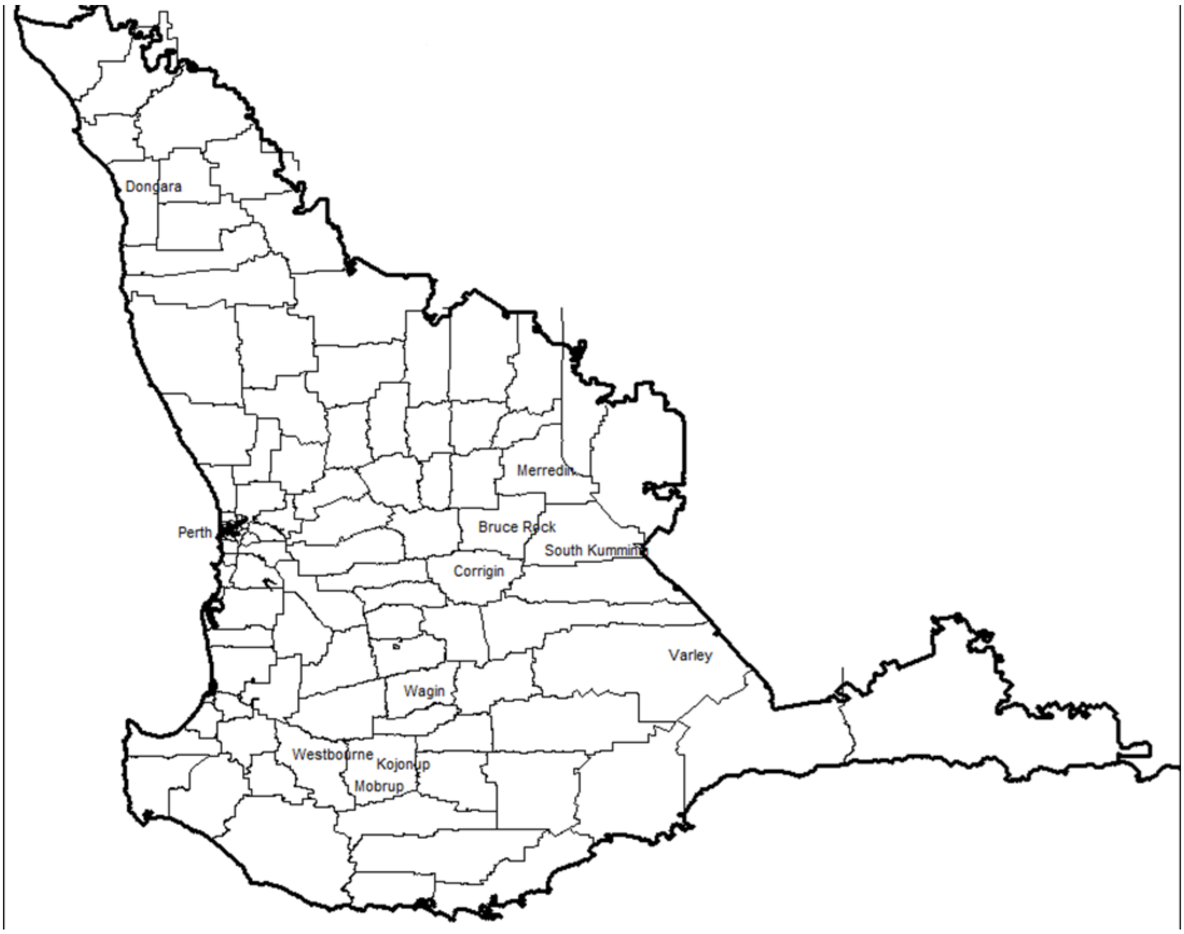
One approach to address this gap is a new project proposed by DPIRD to establish a baseline for comparing various livestock production systems and contributing to carbon accounting in WA's southeastern wheatbelt. This project will provide insights into the average and variability of gas emissions from ewes and their lambs over 12 months in a Mediterranean grazing system on a commercial farm in WA. The project will also benchmark the variability in emissions from current grazing systems and pasture species mixtures for the first time as part of the Zero Net Emissions CRC initiative, which will help evaluate the benefits of incorporating new anti-methanogenic legumes into the feed base. Another approach is to model farms in each location to calculate emission intensity, as done in the FutureSheep project. While modelling simulates farms under specific scenarios, making it challenging to account for variations, aggregating data from various studies could provide useful benchmarking figures for the future. Higher CP levels in animal diets correlate with higher emissions (Schrade *et al*. 2023), yet CP is crucial for liveweight gain (Roberts 2022). Therefore, research is needed to determine the marginal diminishing return of CP for growth and emissions. Identifying the optimum CP level that maximises growth while minimising emissions could reduce the emission intensity of livestock products. Moreover, pasture type significantly affects livestock emissions (Fraser 2015). Although subclover-based annual pastures are predominant in WA, producers often experiment with various pasture species.

3.4 Case studies

3.4.1 Introduction and site background

We conducted eight targeted grower case studies (Fig. 7) focusing also on the social science aspects of adapting livestock systems to future climate challenges. Two properties (Dongara and Varley) were included outside the three target regions as producers had recently renovated their pastures with a focus on shade and shelter. The underlying concept of these case studies was fostering two-way communication between producers and researchers, ensuring that on-farm climatic issues were discussed in a practical, effective, and focused manner. In addition, GrassGro™ was used to simulate changes to pasture yield in 2050 at these case study sites, and the results provided to each of the producers. The results are presented in farm case studies (Case studies Appendix 10) and are consistent with the findings presented in section 4.1.2. This study parallels the NEXUS project undertaken in the eastern states.

Figure 7. Locations of the eight case studies relative to Perth, Merredin and Kojonup: The were located at Bruce Rock, South Kumminin, Westbourne, Mobrup, Wagin, Varley, Corrigin and Dongara.



3.4.2 Feedback from interviews LRZ

In low rainfall zones (LRZ), seasonal variability and the risk of drought, which results in water and pasture feed scarcity for sheep production, were identified as limiting factors impacting producers' decisions on stocking rates. Producers recognised climate change as manifesting through more variable rainfall, late breaks, and reduced winter rainfall. One producer was removing all but two of their largest dams due to lack of inflow. They emphasised the need for more acid-tolerant and drought-tolerant pastures, particularly at the seedling stage "so they can sow the pastures and relax". Moreover, there is a demand for earlier-maturing aerial cultivars (e.g. pink and yellow serradella) that remain productive and persistent through shorter, hotter, and drier seasons. New pasture species are needed to support higher stocking rates, produce more wool and/or enable quicker lamb turn-off, which may help reduce GHG intensity. Oats and vetch, particularly in serradella mixes or late feed options, were noted to perform well. Producers expressed the need for innovative farming, stating that "growing legumes with deep roots has been a must" and emphasised planning during good years rather than reacting to bad seasons. Several producers highlighted the success of vetch, describing it as robust and easy to manage, akin to cereal crops. Biserrula was also performing well, with interest in new cultivars, and there was a call for legumes that are tolerant to herbicide residues.

Producers continuously adapt to various challenges by modifying their crops, sowing times (including summer sowing of hardseeded legumes), pasture species (increasing serradella use) and acquiring new equipment. They have also taken measures like planting trees along creek lines and hilltops for carbon sequestration, shade and shelter, constructing more dams and roaded catchments, storing more hay, grain and silage than a decade ago, and increasing the amount of hay, lupins and mineral supplements they feed to sheep. One producer noted keeping enough feed for two years of drought "was essential". Deep ripping of paddocks in the LRZ was also described as "a game changer" for increasing crop and pasture productivity.

Some producers are adopting confinement feeding or feedlotting, while others are interested but face barriers such as the initial construction costs and a need for more support and extension services. Shelter for sheep, disease management, and accurate feed rations were identified as areas requiring further assistance. Confinement feeding can also positively impact mental health by providing a sense of control, with one producer stating that "it takes away the worry about the start of the season" and another mentioned the "high stress of late breaks and no feed". Some producers now maintain closed Merino flocks with breeding objectives focused on the quick maturity of wether lambs, better mothering types and dual-purpose sheep.

Lamb producers are seeking to capture high prices for out-of-season lambs but are looking for alternative, less expensive, and less labour-intensive feed sources for summer and autumn. One producer noted an increased use of lick feeders, grain rations and pellets over summer in the past 10–15 years and expressed a desire for "multi-species pastures where something is always thriving regardless of the season". There is interest in drought-tolerant perennial pastures to ensure a year-round feed supply that can use more out-of-season rainfall, such as saltbush or perennial grasses. Producers also welcome more information on alternative feed base options and more support for pasture agronomy, especially on herbicides and information on nodulation assessment.

Producers are exploring novel options and tactical within-year management in response to weather and price conditions, such as not joining ewes for all or part of their flock for a year. Given that not mating ewes affects self-replacement and lamb supply for processors, producers need a detailed economic analysis to guide their decision-making and establish trigger points. Some producers have already purchased additional properties in more reliable rainfall zones as a "drought-proofing" strategy for their farming systems. Examples from our case study interviews include a producer in the LRZ moving to HRZ with more reliable rainfall. Some producers north of Esperance have bought land in Kojonup and manage livestock operations across both properties. Diversifying by farming in multiple locations can help producers mitigate risk in the face of climate change.

3.4.3 Feedback from MRZ and HRZ interviews

Producers in the MRZ and HRZ have implemented various practices to adapt to climate change, including improvements in soil, pasture and water management and infrastructure enhancements. The primary triggers for these changes were often the lack of early feed and insufficient winter rainfall to fill dams. One producer noted that they had not observed significant climate changes on their farm but were preparing for “a drier climate”. Traditional subclover pastures also face challenges in terms of persistence and productivity (Fig. 8).

Producers are enhancing their on-farm Merino breeding programs and would like to see more investment in the development of sheep with higher feed conversion efficiency. Looking ahead, some producers aim to purchase more land nearby to ensure long-term business viability and are increasing their pasture cropping. This integrated approach combines cropping and grazing into a single land management unit to provide early feed and increase water storage capacity. There is also a strong desire for more accessible climate information and improved weather analysis from DPIRD and the Bureau of Meteorology (BOM). Developing new early feed options (pastures or crops) was also a high priority for these producers.

The infrastructure plans often include more sheds and fencing and investing in more roaded or plastic catchments to capture more rainfall. All producers plan on increasing their dam sizes, with one also installing more bores on their properties. However, a decline in winter rainfall will likely make it a challenge for new groundwater sources. One producer mentioned that desalination was “would be a game changer” but was too expensive due to the infrastructure costs associated with moving water around and disposing of the brine. However, the cost of desalination plants is decreasing (Barron *et al*. 2021). In the near future it could be more economical to produce desalinated water at the point of consumption rather than piping water around the farm. Combining desalination with affordable solar electricity would further reduce the cost of high-quality water for livestock or irrigation. This would make the intensification of farming systems, (feedlotting and confinement feeding), more viable by providing a secure water source independent of rainfall. There is also the non-financial benefit that it adds value to the producer with certainty of water supply.

There are annual pastures species that can tolerate low to moderate levels of saline water and these species grown with supplemental irrigation from desalination could add valuable early and late feed in the season or cut for hay or silage and would be transformative. Not only can a desalination aid drought-proofing the sheep system but enables huge flexibility in the nature of sheep production (e.g. when best to turn off and finish lambs).

Desalinated water can also be used to aid crop and pasture spraying operations and adds additional “peace of mind” value to the farming system. A project on how best to access and use saline groundwater resources is a strategic project of potential worth for sheep industry and establishing the breakeven levels of costs, prices and production gains is worthwhile to aid future research.

Figure 8. Establishing serradella pasture into a degraded subclover paddock in the MRZ.

3.4.4 Changes and adaptations in the last five years

- Sowing different pasture species mixes, including forage cereals for early feed
- Using tillage radish for increased winter feed
- Buying land nearby or in other regions to diversify and secure farming operations
- Growing more deep-rooted legumes and using spray topping in good years for conservation
- Using grazing cereals for early winter feed and sorghum for summer feed
- Planting more perennials, and saltbush for feed and carbon sequestration
- Using confinement feeding early and feedlotting at the end of the season
- Liming paddocks, using soil-wetting agents, clay delving to improve crop and pasture yields
- Using aerial mapping for water to increase water storage
- Relying more on BOM and DPIRD weather forecasting for decision-making
- Improving sheep genetics, delaying lambing and trialling shedding sheep
- Conserving more feed and grain to prepare for adverse conditions
- Constructing more dams and subsurface drainage from waterlogged areas to fill the dams
- Planting shade /shelter for livestock and trees for additional carbon sequestration benefits
- Applying gibberellic acid to increase pasture growth rates and making them easier to graze
- Improving pasture nutrition through better fertilisation practices
- Building more hay sheds and grain silos to protect feed supplies.

3.4.5 Producers on adapting to climate change

Some producers have yet to formally plan their climate adaptation beyond the next 3–5 years. This hesitation was due to "a lack of information" on possible mitigation responses rather than climate change scepticism. Farm adaptations were sometimes referred to as preparing for a "changing climate" or "new rainfall patterns". Below are some examples of these adaptations.

Annual legumes
In adapting to a drying climate, producers face several challenges and barriers, including the absence of clear guidelines on suitable pastures and how to sow and manage them. Producers highlighted the challenge of establishing new aerial legume species as "failure means we are reluctant to try again". They emphasised the need for a shift in mindset among producers, advocating for more support mechanisms to encourage retrying in case of initial failure. Extension services were deemed crucial to "grasp the new legume technology" and "increase adoption".

Confidence issues also hinder the adoption of new species, as producers struggle to gain certainty in how the system would work and "how to just get started". Moreover, the lack of additional chemical weed options for some legumes poses significant challenges, as producers often rely on trial and error, learning from "each other on rates and chemistry but making expensive mistakes".

The importance of demonstration trials was underscored, with producers emphasising the need for practical examples, ideally, around 10 ha using farm sized equipment. However, producers lament the perceived lack of knowledgeable DPIRD staff and those private pasture agronomists familiar with these aerial legume species, and suggested this is hindering their widespread adoption. Effective grazing management was deemed essential "especially when establishing the new stand", necessitating attention to seed inoculation, establishment techniques, seed production and farming systems tailored to the emerging climate. Integrating new species into online models was suggested to assist producers in making proactive decisions within the farming season.

Despite these challenges, producers highlight success stories with legumes like French and yellow serradella (Figs. 9 and 10), which can be established over large areas at minimal cost and producers can harvest and save their own seed. These legumes can be sown using twin or summer sowing options without clashing with cropping programs, offering benefits such as high productivity, high-quality feed for livestock, early flowering, high hardseeded characteristics, and adaptation to lower rainfall and acidic soils compared to traditional subclover cultivars. Producers rely on various information sources, including other case studies, social media, local agronomists, fact sheets, and webinars from DPIRD, MLA, and Grower Group Alliance (GGA). These resources play a vital role in increasing the adoption of new species and enhancing knowledge of climate change adaptations in farming practices.

Figure 9. Aerial legumes like pink and yellow serradella across WA's low to medium rainfall regions are highly productive and provide high-quality livestock feed.

Figure 10. New low to medium rainfall zone pasture options like yellow serradella can be grown on acidic, sandy soils with 300–600 mm annual rainfall (photo courtesy of Graham Barrett-Lennard).

Other adaptations producers discussed
Producers desired reliable information that "educates about the longer-term climate challenges". They emphasised the need for more accurate weather predictions (>7 days) to support farm management decisions such as sowing and N application for crops. They advocated for farm-scale trials to validate practices (Fig. 11), with producer demonstration sites considered valuable tools for addressing challenges because you can "see it and figure out any local problems as they arise". However, sustaining these initiatives requires more than two to three years of funding support.

Figure 11. Large field trials of summer-sown serradella highlighting the early feed compared to the same legume cultivar with a traditional autumn sowing time.

In the WA sheep industry context, producers displayed optimism about its long-term future. They aim to increase margins, reduce land usage for sheep, and adopt confinement feeding to allocate more land for cropping. Even if confinement feeding is not used every year, producers expressed a desire for the necessary infrastructure to be in place when needed. They emphasised the importance of identifying and implementing feeding strategies, along with the use of anti-methanogenic agents, to mitigate GHG emissions associated with livestock production. Lamb producers actively seek alternative feed options that are more cost-effective than pellets or grain feeding by hand, such as grazing cereals, brassicas, shrubs, or perennials. Producers recognised other potential benefits of confinement feeding, including saving energy reserves in sheep, labour efficiency of feeding, increased leaf area in ungrazed pastures, reduced erosion and producer stress.

3.4.6 Discussion

The livestock producers we engaged with overwhelmingly acknowledged the need to adapt to climate change. In seven of the eight case studies, producers expressed their commitment to continue with sheep farming. However, one producer plans to reduce their flock size to lease out areas for wind turbines, invest in tree planting for carbon offsets to fund feedbase and infrastructure improvements, and eventually reintroduce sheep. Producers are interested in early and late feeding systems and exploring novel feed options such as dual-purpose crops, perennials and shrubs. In the LRZ, significant triggers for change include the declining persistence of subclover pastures, the desire to store more biological N in the soil, the pursuit of higher-yielding crops, the need to reduce reliance on inorganic N fertiliser, and the imperative to conserve more feed for multiple consecutive poor seasons.

A notable knowledge gap exists among producers, consultants and researchers regarding soil N availability following a legume pasture phase. Without precise guidelines, producers often apply more N fertiliser than necessary, fearing they might miss out on maximising crop yield, thereby inadvertently increasing their GHG emissions.

Confinement feeding is an emerging strategy to cope with a drying climate and shorter growing seasons. While it offers flexibility in lamb turn-off dates, the perceived lack of economic benefits and concerns about potential livestock health and disease risks hinder its broader adoption.

Many producers are increasing or planning to increase their water storage capacity, improving catchments, constructing more dams, undertaking hydrological surveys, using aerial mapping and accessing underground water sources. Producers also recognise heat stress in livestock as both a production and welfare concern, with adverse effects on reproduction, even under current climatic conditions (van Wettere 2021).

3.4.7 Conclusion

The overarching strategy proposed by producers involves investing in more infrastructure, such as sheds and dams, grain silos, acquiring land in other regions to mitigate risk, intensifying systems through practices like confinement feeding and feedlotting, and adopting measures like sowing more aerial pastures, planting trees for shade and shelter, and introducing new sheep genetics or breeds. However, these changes are primarily incremental, with no large-scale land-use shifts implemented on farms.

Producers are acutely aware of climate change, noting increased rainfall variability, reduced runoff into dams, and diminished feed base persistence and productivity. The LRZ is particularly vulnerable without adaptation and will likely experience reductions in stocking rates due to declining pasture and crop production. In the short term, combining new technology, operations and management will be needed to offset the increasingly negative effects of climate change. Solutions include using mixtures of forage rye/barley, oats/vetch and tillage radish to fill the early feed gap and boost pasture yield and employing tactics like summer or twin sowing of annual legumes to establish new pasture legumes and provide valuable early feed.

In the medium term, there is a need for new cultivars/species of high-yielding annual legumes, forages and grasses for fodder production that possess greater heat and drought tolerance, particularly across the LRZ and MRZ. These new cultivars are essential to sustain livestock and crop production in areas already facing financial stress. Even slight increases in the severity or frequency of extreme weather events could overwhelm these mixed cropping and livestock enterprises, which will likely provide early warning signs of climate change impacts. In the long term, the drier parts of the landscape may no longer be suitable for traditional crops. Instead, these areas might transition into more sustainable rangeland systems with lower stocking rates and inputs. This shift would require significant adaptation but over the longer term, could offer a more viable solution for managing land and livestock under increasingly arid conditions.

The economic benefits of feedlotting and confinement feeding in anticipation of the projected drier and hotter climate should be modelled rigorously to inform decision-making and funding priorities. There is also a call to develop pasture systems and cultivars suitable for conservation within intensive systems and encourage producers to conserve more on-farm feed. As the climate in the LRZ becomes increasingly challenging, livestock production will need to adapt, such as reducing the cropping area and sowing more adapted pastures, reducing stocking rate or sheep numbers

Other priority issues highlighted by the industry include the need for:

- More technical support and training during transitions to new pasture or forage species
- Expansion of producer-ready packages like the “Lifetime Ewe Management” program to include sheep nutrition for intensive feeding systems
- Training in common livestock disease identification
- Addressing barriers and opportunities in intensified farming systems
- Addressing financial constraints hindering climate change adaptation
- Increased knowledge among agronomists regarding aerial legumes
- Improved capture and storage of rainfed water
- Improved pasture productivity after drier starts to the season
- Identifying cheaper sources of supplementary feeding.

3.5 Impact on processor supply chains under future scenarios

3.5.1 Introduction and supply chain overview

One of the project’s aims is to improve our understanding of the potential impact of climate change on the WA sheep supply chain, particularly the long-term supply of quality sheep. Approximately 80% of the sheep processed in WA are exported to overseas markets, with the remaining 20% consumed domestically (Maharjan *et al*. 2023). Sixteen abattoirs process sheep in WA, nine of which are export accredited. For this report, four of the major accredited export abattoirs—Fletchers International (Albany), Minerva Foods (Tammin), V&V Walsh (Bunbury) and WAMMCO (Western Australian Meat Marketing Co-Operative) in Katanning—were engaged.

Generally, WA saleyard prices are lower than those in the eastern states due to less competition among buyers and a greater reliance on export markets. Throughput is a key economic driver for an abattoir, as they are capital-intensive businesses operating on lower margins and high throughput (Hermann *et al.* 2017). Climate change has made future supply forecasting less reliable, potentially leading to a loss in processing capacity, reduced competition and could apply downward pressure on livestock prices. The WA sheep industry has some unique features compared to the eastern states, such as more seasonality in supply and a higher proportion of Merino or Merino-cross lambs, reflecting the traditional importance and profitability of the wool industry in WA. The Merino is also suited to the current Mediterranean environment, with dry seasonal conditions for at least six months of the year. Sheep are produced over a large area, so the industry depends on a well-functioning logistics and transport sector to facilitate the smooth flow of products between different stages of the supply chain. The effective functioning of the supply chains will become increasingly important with the additional challenge of climate change.

3.5.2 Processor concerns and strategies

All four of WA's meat processors interviewed expressed concerns about climate change and GHG emissions, albeit at different levels and with varied timelines. All processors agreed that methane mitigation and reducing their carbon footprint were important business factors. Planning horizons varied, but the most organised processors discussed their existing strategies for using solar-generated power, buying carbon offset farms and planting trees for CO_2 sequestration. One processor plans to implement a carbon accounting program over the next 3–5 years, while another is undertaking feasibility studies on monitoring their GHG emissions. Treatment of onsite wastewater was a priority issue for some, indicating a need to address this in the medium to long term.

Environmental, social and governance (ESG) factors were noted as important for all processors, although they were also at different stages of implementation. Several processors observed that both domestically and internationally, financial institutions have been addressing ESG within their business models as a key factor in approving finance. Addressing ESG compliance in the short term is crucial for maintaining competitiveness, which will also require compliance from livestock producers.

Robotics and automation present opportunities to reduce reliance on labour for some tasks, but the cost of implementation is very high, and processors need certainty of supply to achieve a return on their investment. Power, energy and water are all significant costs and, in some cases, may limit short-term expansion. Some processors as mentioned are already investigating solar power generation and recycling. They would like to see clearer guidance on the industry future of live sheep export policies to help producers and industry plan for future flock sizes with more confidence. The uncertainty in this area (prior to the Federal government announcement May 11, 2024) makes planning difficult for other participants in the supply chain, such as transport companies, who may be more reluctant to invest in new equipment.

3.5.3 Reduced flock size: impact of not joining as a dry season response

The recommendation by some agricultural consultants in 2023/24 to "not join ewes" in response to current market prices and dry seasonal conditions has gained momentum among producers. The MLA Sheep Producer Intentions Survey (October 2023) forecasts the WA lamb drop for 2024 at 3.93 M, down from 5.06 M in 2023 (based on 379 respondents). If this trend eventuates, it will have long-term ramifications beyond just 2024, affecting the WA flock's ability to maintain sheep numbers (Changing joining rates Appendix 6). This response may become more frequent, especially in the LRZ, due a hotter and drier climate or low sheep prices in the future.

The underlying issue for processors is the uncertainty of sheep meat supply, which could impact their ability to guarantee supply to domestic and export customers and creates uncertainty about investing in new infrastructure (e.g. robotics). A significant decline in sheep supply will have serious effects along the whole supply chain, including the wool industry. Some producers in the HRZ also indicated they are not joining ewes, highlighting that the issue is not solely about feed base availability but also market uncertainty, low prices for lambs and sheep in 2023 and the lack of processing space.

Changes in rainfall patterns will affect runoff and water availability for sheep, leading to challenges in providing sufficient drinking water. The water needed for livestock varies depending on the local climate, with hotter conditions leading to increased consumption (Ward and McKague 2019). Heat stress in livestock has been acknowledged as a production and welfare issue for several decades, including adverse effects on reproduction. Heat stress can significantly impair sheep reproduction in the field, even under current climatic conditions (van Wettere 2021).

Livestock are often transported long distances by road to sale yards and processors. In the future, livestock transport businesses and sale yards will likely be affected by increasing hot days and the reputational risk regarding animal welfare (see Table 3). We conducted future climate projections for a sale yard site to help plan mitigation strategies to reduce animal heat stress. Under RCP 4.5, the climate is projected to reach 50°C and above from December to February by 2050, indicating the need for additional cooling and temperature sensors to monitor heat stress in livestock. The hotter days projected for 2050 may result in additional restrictions on sheep transport, such as the time of day they can be moved, maximum temperature limits at receiving yards, and or the duration of transport. Uncertainty around the WA flock size adds to the complexity of planning for such improved facilities.

3.5.4 Turning off lambs

The traditional peak of spring lamb turn-off has flattened, resulting in a more balanced supply of lambs between the spring flush and the first quarter (January to March). This change has led to a less seasonal supply of sheep for processing, greatly improving asset utilisation. According to the MLA Sheep Producer Intentions Survey (MLA 2023), 54% of expected lamb sales are expected to occur in the first six months of 2024 in WA, compared to the spring of 2023. Adult sheep slaughter, however, remains highly seasonal and spring based. Western Australia still has the highest proportion of Merino in the flock compared to other states, with 56% of lambs on hand being Merino this year in WA, compared to 37% nationally.

3.5.5 Meeting welfare and consumer expectations

The social licence of the livestock sector worldwide is challenged increasingly by rising consumer awareness of climate change and its potential impacts on livestock. Concerns regarding animal welfare and the environment also influence financial institutions. There is a growing expectation for transparency throughout the food supply chain, with many consumers demanding information on food provenance. ESG credentials will become increasingly important for processors to maintain and grow premium markets overseas. Markets for sustainable production are emerging in Europe and some parts of the Middle East but not yet in the USA. Changes in consumer preferences, regulations and overseas trade agreements influenced by climate change can affect the demand for sheep products and prices. For instance, the increasing global adoption of ESG integration in investment markets presents risks and opportunities for the WA red meat processing and livestock industry.

3.5.6 Discussion

Processors would prefer to see a more even supply of sheep and lambs throughout the year, facilitated by greater use of supplementary feeding and alternative lambing dates through feedlotting. While lamb supply is now more evenly split between the spring flush and the first quarter (Jan–Mar), it is uncertain if this trend will continue.

Modelling suggests that continued drying and warming trends could significantly change agriculture in the east and northeast (without feedbase or technological adaptations). Currently, the cereal sheep zone (CSZ) supports nearly 50% of the sheep flock in WA. However, the proportion of sheep on farms in the LRZ will likely decrease as these systems are unlikely to support current stocking (SR) rates under a drying climate and declining feed base. If new pasture technology, such as new annual and perennial species, shrubs, or forages or systems developed to align with projected future climate scenarios are made available and adopted, producers could maintain their current SR. Alternatively, they could expand their pasture areas while operating at lower SR, thereby sustaining their sheep numbers. Without adaptation, it is likely the supply of lambs to processors for domestic or international slaughter will decline. If the processing sector in WA contracts, sheep enterprise profitability could decline due to reduced competition, potentially decreasing sheep numbers further and creating more pressure on remaining processors.

Access to a skilled and reliable workforce is a major issue for all processors, often affecting daily processing capabilities and overall capacity. The effectiveness of system adaptations for processors and producers must be assessed not only on the profitability but also on GHG emissions and consumer demands. Some processors in WA may not meet the required ESG specifications that banking, lending, overseas super funds and insurance products may soon mandate, especially in the short to medium term (1–5 years).

3.5.7 Conclusions

Processors are vital for the sustainability of the sheep meat value chain. However, the changing climate may lead to a decline in sheep numbers, particularly in the LRZ and impacts on the processing sector. For the WA sheep industry to remain viable and profitable by 2050 while meeting consumer expectations, changes in pasture species, sheep breeds and farming systems in some rainfall zones may be necessary. Key issues are summarised below.

- Developing livestock systems adapted to a future climate is challenging and will require **modifying existing systems and developing new technologies,** such as new pasture species with traits for drought and heat tolerance
- **Vertical integration** among commercial sheep and plant breeders, producers, feedlots and processors could provide **significant production advantages to address climate change**
- Frequent, intense, and prolonged dry seasons will make it challenging for producers **to maintain a supply of drinking water and feed for livestock**
- Need to meet consumer expectations for improved **animal welfare and ESG standards**
- There may be increased pressure on transporters to reduce fossil fuel consumption**, cool holding yards at processors and sale yards**, **restrict livestock transport timings to avoid heat stress**, and implement technology-based monitoring of animal welfare, all of which add to business costs
- All processors were **willing to work together** with DPIRD and industry and build stronger relationships across the supply chain to mitigate climate change impacts
- **Processors are looking for leadership from the government and industry on GHG mitigation,** emphasising the critical role of DPIRD and MLA in addressing climate change.
- **Government and industry enhance international trade opportunities and R&D activities** to innovate in productivity and efficiency along the supply chain
- **WA has a strong position to build on its reputation** as a reliable supplier of clean, safe and high-quality food to overseas markets. Thus, industry adaptation to future climate is crucial.

3.5.8 Recommendations

- **Encourage collaboration** among producers, policymakers and researchers to develop and implement effective adaptation strategies for sheep supply chains in WA's future climate

- Promote on-farm confinement feeding and feedlotting**, especially in the LRZ,** to ensure consistency in product quality and quantity for processors
- Design pasture systems suited to **conservation for confinement feeding and feedlotting** and encourage producers to conserve more feed on-farm, allowing for different turn-off dates for lambs to aid adaptation to future climates for producers and processors
- Conduct **a multi-year economic analysis** of the “not joining ewe” strategy to determine if it is a viable long-term tactic for producers, considering the long recovery period and the potential impact on red meat processors
- Develop a program to account for **GHG emissions across the entire processing supply chain**, and identify opportunities for emissions reduction
- Engage sheep producers across WA to understand **their contribution to the supply chain’s GHG emissions** and identify reduction opportunities
- Ensure that WA sheep meat producers have access to all global market opportunities by reducing emissions in response to the **emerging requirements of overseas customers.**

3.6. Industry, extension activities and collaboration

We have significantly raised awareness of the FutureSheep project through extensive engagement with the livestock and cropping industries. Our team attended eight field days and 16 industry events, including GRDC Crop Updates (twice) Woolarama (twice), Dowerin field day (twice), FutureSheep and Feed365 at Katanning and Corrigin AgZero field days. These events were also reported on social media platforms, further broadening our outreach. Additionally, we participated in the WA Farmers Federation annual general meeting (Fig. 12). In 2024, we strengthened our relationships with the Grower Group Alliance (GGA), Western Australian Livestock Research Council, and our established network of livestock producers and consultants. Our collaborative efforts extended to Farmers for Climate Action (FCA), Merredin and Districts Farm Improvement Group (MADFIG), Rural Edge, ASHEEP and Beef, AgZero30, Corrigan Farm Improvement group (CIFG), CSBP, ICON, AgricUltra Farm, and numerous individual producers from our network. We developed presentations and flyers on climate change and the FutureSheep project for delivery at conferences and field days (Figs 13 and 14). The FutureSheep flyer is also available online at the DPIRD website.

We also worked closely with DPIRD Developmental Officers and Research staff in regional locations and with the Western Australian Meat Industry Authority (WAMIA). The FutureSheep project has been featured in Farmers Weekly and various press releases, generating significant conversation within the pasture and livestock community. FutureSheep published a farm case study to examine the economics, carbon emissions and climate resilience of a mixed farming system near Kulin (Tolga farm Appendix 9). This case study was integrated into the FutureSheep project, helping to identify new research proposals for DPIRD and MLA.

Figure 12. The SheepLinks stand at the WA Farmers Federation conference (March 2023).

Figure 13. Paul Sanford presenting at the Feed365/FutureSheep field day in Katanning (April 2023).

Figure 14. Janet Conte at the SheepLinks and FutureSheep stand Newdegate field day (Sep 2022).

Meredith Guthrie met with Professor Brendan Cullen from the University of Melbourne and attended the "Forewarned is Forearmed" conference in Melbourne. She also attended Dr. Pandora Hope's lecture on the IPCC 6th assessment talk at the University of Melbourne and visited Dr Andrew Watkins at the BOM to discuss future climate projections under different GHG emission scenarios. Additionally, Meredith participated in a workshop with Professor Mark Howden (Vice Chair of the IPCC and Australian National University) on effective climate change responses in WA and an academic workshop (invite-only event) providing insights into the current tracking of future climate projections and GHG scenarios. Professor Mark Howden () visited Perth to discuss advancements in climate prediction tools, including those developed by the BOM, such as the Climate Services for Agriculture tool, which Meredith uses extensively to produce future projections for the Southwest Land Division. Meredith also posted an online climate talk (https://grdc.com.au/events/past-events/2022/march/grdc-grains-research-update-online-perth-day-6-soils-pulses?videoId=6304468840001) and presented at the GRDC updates in Bencubbin in March 2023 on "Monthly weather forecasting- the holy grail".

Paul Sanford and Kevin Foster attended the NEXUS meeting in Launceston in November 2022, where the FutureSheep team also presented online. Kevin Foster also attended the "My Climate View" training workshop in March 2024, organised by the BOM and CSIRO, and provided feedback on his experiences. In April 2024 Kevin Foster and Meredith Guthrie met with the CEO and board representatives of a livestock sales yard to present future climate projections for that site.

In August 2022, Janet Conte attended the Australian Evaluation Society International Evaluation Conference and a one-day workshop on "Creating impact through systems-led evaluation and design". Insights from these events were applied to the FutureSheep Project evaluation. The team engaged with a researcher from Curtin University on emerging supply chain issues due to climate change. Two project members attended the "Carbon Neutral Agriculture" training in Perth on 3–4 August 2023, provided by Richard Eckard from the University of Melbourne. This training covered the Primary Industries Climate Change Centre (PICCC) and GHG Accounting Framework (GAF) for livestock and cropping. Livestock producers and industry representatives heard the latest climate research from the FutureSheep team at the Katanning field day in April 2023 (Fig. 13). These activities were posted on Twitter and featured in several press releases in rural print media (and GGA featured the FutureSheep project in their newsletter (see below).

> **Future Sheep – Climate Adaptation: Ensuring a Sustainable WA sheep industry**
>
> "FutureSheep" is an MLA & DPIRD combined project assessing the impact of projected climate changes by 2030 and 2050 in WA to identify potential adaptation strategies. If you'd like to be involved in the 'partner farm' activity matching producers from one region to those in another who are already farming in an environment that has projected similarities to that of their land in 2050, contact Dr Kevin Foster via Kevin.Foster@dpird.wa.gov.au

Research supported by FutureSheep project was also featured in the following press releases: https://www.agric.wa.gov.au/news/media-releases/2023-grains-research-update-farming-systems-balance-key-profitable-low-0

https://grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2023/02/s6-karel-sud

3.6.1 Conferences proceedings, publications and social media

Paul Sanford and Imma Farre presented current and future pasture and cropping production scenarios for three sites at various conferences. DPIRD also sponsored the WA Farmers Federation Conference in Perth in March 2023. FutureSheep team members attended this event to promote the SheepLinks program, engage with producers and industry, and distribute supporting materials (Fig 12). In February 2023, Sud Kharel presented at the Grains Research Update (see links and image below), showcasing the first economic and emission analysis for a WA farm titled "Profitable low emission crop rotation?" Sud also presented at the 2024 Grains Research Update, with a paper titled "Emissions through the lens of productivity: how do nitrogen and lime affect both?"

https://groundcover.grdc.com.au/innovation/industry-insights/on-the-case-of-low-emission-crop-rotations

https://www.agric.wa.gov.au/print/node/1779

Balancing cropping and sheep is key to low emission profits

Sheep Central, February 27, 2023

Sud Kharel and Christophe d'Abbadie

BALANCING farming systems has been shown to be the key for profitable low emission crop production in Western Australia.

Broadacre farmers seeking to reduce emissions need not always compromise profitability or risk, according to a recent analysis profiled at the 2023 Grains Research Update in Perth today.

The analysis of where and how changes to farming systems can help growers reduce emissions was undertaken by the Department of Primary Industries and Regional Development and Meat and Livestock Australia's FutureSheep program.

The results of the analysis with the Economic Valuation of Alternative Land Use Sequence model show net margins can be improved by making changes to the ratio of pasture to crop in different Western Australian agricultural regions.

Kharel S, Foster KJ, Guthrie M, Kingwell R (2024) Farm business impacts of consecutive drought years under future climate scenarios in southwestern Australia. *Australian Farm Business Management Journal* (Accepted).

Plunkett B, Overheu T, Foster KJ, Kharel S, Roberts D (2023) Towards carbon-neutral dryland farming: Improving climate smart practices and profitability through reducing emissions and expanding soil carbon pools. *Australian Soils Conference* – Darwin, 25–30 June 2023.

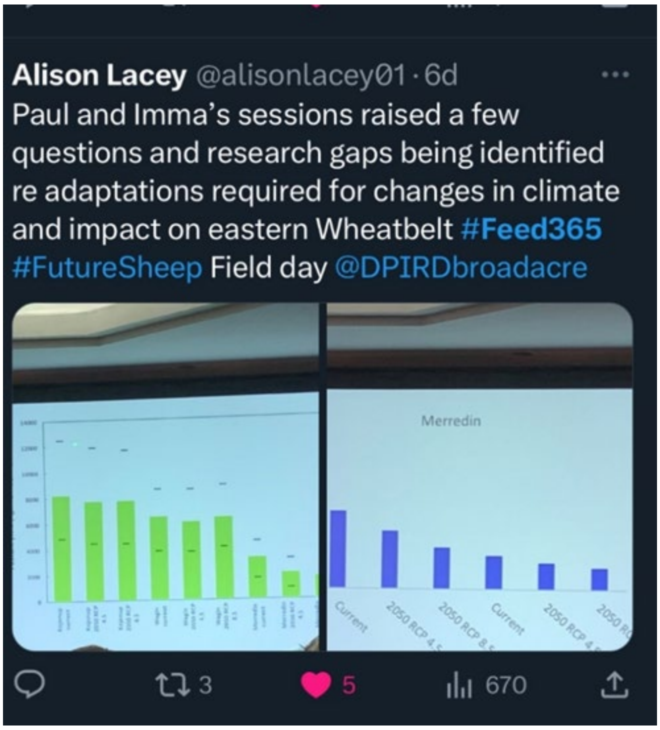
Plunkett B, Roberts R, Kharel S, Foster KJ, Overheu T, Savage B (2023) High performance of a low input, mixed western Australian farming system: public policy implications from the case of Tolga farm. *Sustainable Earth Reviews.* **6**:12.

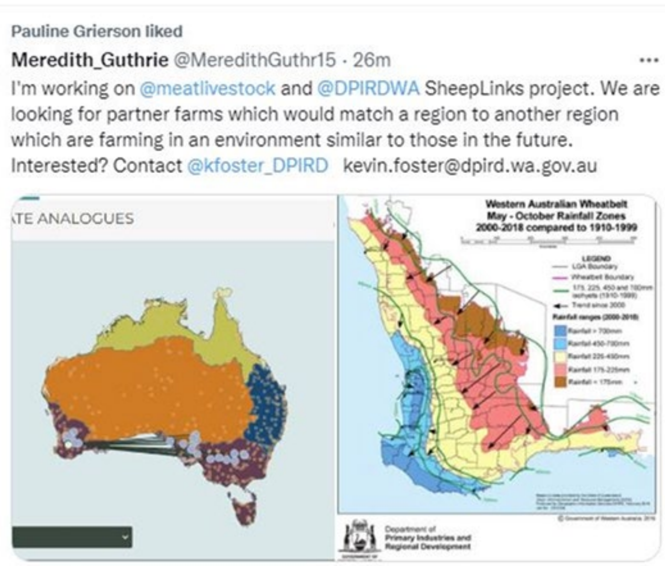
Sanford P, Guthrie M, Farre I, Kharel S, Revell C, Conte J, Foster K (2024) FutureSheep – What will pasture production look like in south-west Western Australia in 2050? *Australian Agronomy Conference.* Adaptive agronomy for a resilient future. 21-24 October 2024. Albany WA.

[Sheep reproduction and reducing methane emissions | Agriculture and Food]

Social media

Social media platforms played a vital role in extending our outreach and engagement. Regular posts on X (previously Twitter) resulted in direct engagement with producers and consultants. Facebook posts about field days and other activities helped us reach a wider audience beyond what traditional print media or field days could achieve alone.





3.6.3 University and student engagement

Engaging the younger generation of farmers and agronomists is crucial for preparing them to handle the projected climate changes for 2030 and 2050, as they will be responsible for advising or farming during that time. Meredith Guthrie delivered a lecture on climate and modelling to Master of Agricultural Science students at UWA in 2023 and 2024. Sud Kharel presented to students at Curtin University in April 2023 and 2024, covering topics on pasture, livestock and crop production and their economics under future climate projections. Janet Conte and Kevin Foster discussed designing and running a course at Murdoch University with Narrogin Agricultural College. Kevin Foster provided a series of climate and pasture lectures to Curtin agricultural students in August 2023.

3.6.4 Activities for ongoing MLA use

We have actively contributed to the body of research and knowledge on climate change and its impact on agriculture through several channels:

- Submitted two scientific publications to peer-reviewed journals with one published.
- Presented several conference papers.
- Developed presentations and flyers on climate change and the FutureSheep project for delivery field days.
- Created a dedicated FutureSheep page on the DPIRD website.
- Janet Contre is preparing an updated literature review as part of her PhD research on "Integrating climate thinking into agricultural decision-making", which will be made available to MLA along with our PowerPoint presentations.
- Established strong relationships with the GGA and expanded our livestock producer, consultant and processor network.
- Parametrised and validated the AFO model for low rainfall systems, providing the capacity for a range of future analyses beyond the FutureSheep project.
- Processors are now positive about working together in the future and focus on building stronger relationships across the supply chain to mitigate the impacts of climate change.

3.7 Impact of adoption activities and number of producers engaged

3.7.1 Background

The FutureSheep project aimed to identify the key barriers to climate change adaptation (CCA) in order to plan effective strategies for overcoming them. As part of this effort, a literature review was conducted to pinpoint the barriers to CCA in agriculture.

While there is a growing body of international and national literature on barriers to CCA, research specific to Western Australia is scarce. An exception is Kragt et al. (2013), who developed an interdisciplinary conceptual framework based on literature and expert interviews. This framework highlights various barriers to CCA, including the inherent uncertainty of climate change, the availability of viable adaptation strategies, the level of adaptive capacity (institutional, technological, financial, knowledge, or social), and the willingness to adopt (influenced by risks, values, goals, attitudes, and beliefs).

The results of the current literature review (to be published) confirmed this framework, identifying many different barriers to CCA in agriculture. The majority of barriers (and enablers) were related to adaptive capacity, with the most frequent being a lack of self-efficacy (the perception of one's own ability to undertake a practice) and financial concerns (including cost, uncertainty of returns, commodity prices, and financial markets). While there were several barriers related to willingness to adopt and the very nature of climate change, there was little mention of the availability of viable adaptation strategies. Barriers were found to be highly specific to the location, audience, and specific adaptive practices.

Therefore, empirical research is needed in WA to focus on the barriers to CCA specific to particular practices, target audiences, and locations. This research should distinguish between barriers to CCA planning and the adoption of adaptive practices. While previous research on factors affecting the adoption of new agricultural practices can inform this research (e.g., Pannell *et al*., 2006), the unique characteristics of CCA practices and their context must be considered. Workshops with the GGA and grower groups are recommended to identify perceived barriers to specific adaptive practices among grower group members.

3.7.2 Results and key findings

Extension activities have commenced, although more effort is needed to impact producer adaptation planning and adoption of adaptive practices. Intense engagement with producers and consultants occurred through the reference group, case studies and one-on-one interactions. Medium and introductory levels of engagement tended to merge, including a joint field day with the FEED365 project, attendance at field days and industry events, and communication through social and traditional media. This engagement raised awareness of climate change projections and their impact on sheep production among a large number of producers.

Feedback from the reference group and field day participants was positive and provided insights into producers' issues and the support required for adaptation.

It is too early to measure producer adoption of adaptive practices resulting from the project. However, based on case studies and surveys with reference group members and producers, recommendations can be made about extension and adoption processes. A case study with Emily Stretch (https://www.mla.com.au/news-and-events/industry-news/future-climates-no-stretch-with-resilient-strategies/) highlighted the importance of localised and personalised climate projections to enable adaptation planning and adoption of adaptive practices.

3.7.3 Events and participant numbers

Project team members recorded their engagement with different stakeholders. In summary, team members attended eight field days and 16 industry events, engaging over 1,300 producers at an introductory level, students (291), researchers (187) and other DPIRD staff (129) (Table 9). Individual meetings were also held with supply chain stakeholders, including red meat processors, and the WA Meat Industry Authority. Three formal reference group meetings were held, engaging nine producers and two consultants. Interviews were conducted with farmers from eight different businesses. Moreover, Kevin Foster had many one-to-one conversations with producers, processors and reference group members to seek and provide advice.

Table 9. Summary of engagement with stakeholders.

Category	Individual contacts
Producers – Introductory engagement	1,319
Students	291
Researchers	187
DPIRD and other institutions	129
Processors/supply chain representatives	30
Pasture and livestock consultants	24
Intense engagement (reference group and case studies)	23

Communication

- Articles in the Countryman, Sheep Central, MLA Feedback Magazine and Ovine Observer.
- Websites: DPIRD (www.agric.wa.gov.au/FutureSheep) and MLA (www.mla.com.au/news-and-events/events-and-workshops/feed365-and-futuresheep-field-day; www.mla.com.au/news-and-events/industry-news/future-climates-no-stretch-with-resilient-strategies)
- Social media posts.

Engagement with meat processors and supply chain

- Consulted with four WA meat processors, a sales yard and a Curtin University supply chain expert about the potential impacts of climate change on industry.
- Increased consultation with producers regarding adaptation options is ongoing, particularly in the Merredin region.

3.7.4 Reference group

Feedback from the first meeting of reference group members included agreement that "the session gave me a better sense of the value of the FutureSheep project". Positive aspects included enough time to think and ask questions, understanding participants' backgrounds, facilitation and organisation, chat questions to facilitate instead of unmuting, and fast presentations. Areas for improvement included better understanding of the project's direction and more input from reference group members. Producers requested more information on alternative feed base options (or systems) to deal with future climate change impacts, GHG emissions and on-farm water options. Personalised future climate scenario graphs were offered to each reference group member to highlight potential impacts on their livestock business. The reference group discussions helped identify information needs and priorities for developing adaptation strategies.

Joint FEED365 and FutureSheep field day

The joint FEED365 and FutureSheep field day at Katanning Research Facility presented recent findings from both projects and toured FEED365 field trials. Table 10 presents the findings of the feedback survey on respondents' ratings of the day.

Table 10. Ratings of FEED365 and FutureSheep field day.

Questions	Average rating (/10)
Overall satisfaction with the day (*n*=49)	8.0
Content (*n*=49)	7.5
Presentation (*n*=49)	7.2
Relevance (*n*=49)	7.4
Value to your work/business (*n*=47)	7.4

3.7.5 Benefits to industry

How did any practice changes lead to the intended benefit?

The WA sheep industry benefits from the FutureSheep project through a clearer understanding of projected climate change impacts on the pasture feedbase, wheat yields, profitability, ESG, GHG, and supply chains. This information is vital for informing adaptation planning and prioritisation. While the project aimed to influence practice changes among producers, it became evident that adaptation practices would only be adopted after the project's completion. Promoting specific practices prematurely was deemed inappropriate without comprehensive results on climate projections, their impacts on pasture and sheep production across rainfall zones, and the identification of suitable adaptation strategies. Additionally, producers also require the necessary support and training before implementing these adaptation strategies. Nevertheless, the project yielded significant insights into the barriers to climate change adaptation and provided valuable guidance for future extension efforts.

3.7.6 Indications for practice change beyond the project's life

- Producer implementation of adaptation recommendations is expected to occur beyond the project's life. Evidence suggests that localised climate projections prompt adaptation planning and adoption of adaptive practices (Emily Stretch case study).
- Further extension of adaptation planning, and practices is planned for the final stages of the project in 2024 and post-project. GrassGro™ analysis in the future will focus on plant adaptations to future climate projections.

3.7.7 Recommendations

Recommendations for improvements and extension work in the final stage of the project were developed based on evaluation results and discussion with the project team. The evaluation report can be found in Appendix 1. Key results in relation to adoption activities, producer engagement and practice change are included below.

Adaptation options

1. Explore new pasture species. Early and late feeding systems, novel feed options early in the season, confinement feeding for different lamb turn-off dates, spatial diversification, within-year tactical management in response to unfolding weather and price conditions.

Extension

2. Continue extension activities. Collaborating with the GGA, related projects and programs (e.g. Farm Business Resilience program, Lifetime Ewe Management), consultants, webpages, online presentations and workshops with grower groups. Highlight future case studies showing producer adaptations to climate change
3. Recognise that adoption takes time and resources. Understand that adaptation is a gradual process requiring significant time and resources
4. Promote Adaptive Practices. Emphasize the economic and additional benefits of adaptive practices to encourage their adoption
5. Conduct empirical research on attitudes to climate change, climate change adaptation, and barriers to adaptation planning and adoption
6. Provide localised and personalised climate projections to encourage adaptation planning and pathways.

Assessing climate risks

7. Use a risk management approach, focusing on inter-related issues like the planned phase-out of lives export by sea and social licence, as emphasised by the IPCC and WA state government departments (e.g. Department of Water and Environmental Regulation)
8. Conduct a desktop analysis of international standards for climate change adaptation to assess adaptive capacity. Consider scale and methods for this assessment.

Overall project

9. Adopt a multi-disciplinary approach for climate change adaptation projects
10. Ensure appropriate funding for collaborators and clarify roles and responsibilities.

3.8 Literature review on adaptation

The literature review identified various barriers and enablers to climate change adaptation in agriculture. Most barriers (and enablers) relate to adaptive capacity, with key barriers including the lack of self-efficacy (i.e. producer's perception of their ability to undertake adaptive practices) and financial barriers (e.g. costs, uncertainty of returns, commodity prices and financial markets). Other barriers include willingness to adopt, the nature of climate change and, less frequently, the availability of viable adaptation strategies. Barriers are specific to the location, audience, and adaptive practice, necessitating empirical research tailored to specific practices, target audiences and locations in WA. Research should differentiate between barriers to climate change adaptation planning and barriers to the adoption of adaptive practices. Previous work on practice adoption is informative, but the unique characteristics of climate change adaptation practices and their contexts must be considered. Workshops with the GGA are recommended to identify perceived barriers to specific adaptive practices for grower group members.

Preliminary findings of surveys conducted with the project team, reference group and producers identified key barriers to climate change adaptation, including the 'uncertainty of climate change' and 'costs' involved (identified by all three groups) 'politics' and 'lack of time' (reference group members and producers). Producers' reluctance to accept the climate model projections may increase if their recent personal experiences of climate change contradict projected future changes in 2050.

3.8.1 ADOPT model on confinement feeding

A literature review, survey and trial of the Adoption and Diffusion Outcome Prediction Tool (ADOPT) for confinement feeding were conducted to identify barriers to climate change adaptation in agriculture (Confinement feeding Appendix 7). Barriers to climate change adaptation are obstacles that are difficult but possible to overcome (Gawith and Hodge 2018; Moser and Ekstrom 2010). However, biophysical and economic limits to adaptation may not be overcome (Kragt *et al*. 2013). The trial of ADOPT with confinement feeding in the LRZ predicted a peak level of adoption at 73% after nine years. Further trials should be conducted in the MRZ and HRZ to compare projections. The literature review, surveys and ADOPT trial consistently indicate that producers' key barriers to climate change adaptation are self-efficacy, financial barriers, willingness to adopt, and the uncertainty and nature of climate change.

3.9 General discussion

Over the past 50 years, WA has experienced decreased rainfall and more frequent droughts (Guthrie 2022). CSIRO Global Climate Model projections indicate further decreases in rainfall over the next 50 years. These changes pose significant challenges for the sheep industry, including shorter growing seasons, reduced stocking rates, reduced yields due to less reliable growing seasons, increased reliance on supplementary feeding, decreased runoff for dam-filling, and environmental concerns such as methane emissions. There are still gaps in our understanding of the potential environmental impacts of sheep the intensive feeding systems, such as possible groundwater contamination and runoff from confinement feeding. It is worthwhile to update best practice guidelines to address these concerns and particularly to demonstrate sustainability to our domestic and overseas markets.

The FutureSheep project used integrated assessments, models and case studies in key sheep-producing regions (Kojonup, Wagin and Merredin) to explore potential adaptations for projected hotter and drier climate scenarios by 2030 and 2050. One significant challenge identified is still the autumn feed gap, which is expected to widen with a drying climate. Addressing this gap requires new feedbase options or systems, such as incorporating shrubs, planting perennials, and sowing winter cereals, brassicas, forages or grasses for early feed. Adjusting lambing times to align with feed availability can also reduce reliance on costly supplementary feeding.

While numerous studies and models have investigated the response of crop and pasture species to drought stress, there has been little evaluation of seedling drought resistance, particularly in legumes. The slight increase in summer rainfall anticipated from January to March under the RCP 4.5 2050 scenario, for instance, is unlikely to yield significant benefits for perennial legume production. Nevertheless, in the HRZ where summer-active perennials are grown, the additional summer rainfall could produce extra growth and feed during that period. However, increased summer rainfall is sporadic, which could pose challenges in managing weed growth during the summer months. Moreover, the quality and quantity of annual pastures tend to diminish rapidly following summer rain events.

It is likely that with hotter, drier and more variable conditions under a changing future climate, the economic viability and sustainability of many farms with their current subclover feedbase will be tested further. Producers in the case studies have been exploring more resilient pastures that provide additional feed through summer and autumn and help lower the expensive cost of supplementary feeding. The low-cost seed from on-farm seed production of aerial legume species now like serradella (*Ornithopus* spp) are also being matched with low-cost establishment systems. These could be extended further to help lift current pasture productivity in the LRZ to achieve a more profitable, more sustainable, more resilient, diverse farming system both now and into the future. There are also likely other adaptation strategies adopted by producers for the long-term future of their livestock enterprises that were not captured by this project.

Some producers have already purchased additional properties in more reliable rainfall zones to “drought-proof” their businesses. However, some have not yet implemented climate adaptation responses due to a perceived lack of information than climate change scepticism. Breeding sheep resilient to varying feed supply within and between years would likely reduce costs in poor seasons and increase the role of livestock in managing climate change risks. Increasing sheep productivity (lambing percentages) through improved reproductive performance and reduced mortality can also reduce emissions per unit of product (emissions intensity). Much of these practices are available and well documented currently, but require significant extension support to drive ongoing adoption. Some information gaps do exist within industry regarding new pasture species and the appropriate agronomic practices.

Producers emphasised the importance of localised decision-making and research championed by other producers to increase adoption. Additional training for producers and consultants on agronomy skills with aerial pasture legumes is recommended. Guidelines should cover various aspects of pasture management and production issues, including seed inoculation, nodulation assessment, adaptation areas, establishment, companion species, forage production issues (e.g. disease or insect susceptibility), on farm seed production opportunities, nutrition, herbicides, and grazing management of aerial pastures and winter crops. Several existing reports and analyses could be consolidated into a single resource.

Biophysical and whole-farm systems modelling (AFO), in addition to climate change impact modelling for crops and pastures, is crucial for evaluating adaptation options identified by researchers, producers and consultants. The AFO results in the preliminary analysis also illustrate that classifying weather based on growing season rainfall is a sub-optimal method. Improved communication of weather and climatic conditions should adopt a system categorising years based on farm productivity and a farmer’s ability to adjust management.

Producers’ uncertainties about climate change diminished when climate modelling occurred at the farm scale. Computer modelling combined with producers’ climate records helped them proactively make on-farm decisions (Feedback magazine December 2023).

While climate change presents challenges, it also offers opportunities for innovation and adaptation. Intensive systems are emerging as key strategies. Once established, producers can have this infrastructure in place to use if needed. These systems can save energy reserves in sheep, improve labour efficiency, increase leaf area in ungrazed pastures, reduce erosion, and potentially lower GHG emissions through feeding strategies with anti-methanogenic agents. However, perceived costs, lack of economic benefits and disease management concerns for some producers hinder further adoption. Further research on economic benefits and improved pasture systems and species is needed. Producers and processors also need information on addressing any social licence concerns for intensified feeding systems.

Discussions with Ross Kingwell (DPIRD Chief Economist) highlighted the growing importance of domestic markets, especially the eastern states, due to Australia’s projected population increase from 26 M in September 2023 to 35 M by 2050. Moreover, domestic markets are willing to pay more for Australian commodities than overseas markets. In addition, the Australian dollar’s value impacts cropping more than livestock due to higher reliance on cropping inputs (machinery, fertiliser and chemicals).

The FutureSheep project will complement existing literature by collecting additional data within the project. Furthermore, Janet Conte's PhD research on "Integrating climate thinking into agricultural decision-making" will provide an updated literature review which will be a valuable resource for project and the broader industry. Participatory research approaches must be used to develop adaptation pathways in the sheep industry, as this will increase the rate of adoption and ensure research focus is commercially relevant. Understanding under what conditions and why farmers implement adaptation and mitigation practices, and identifying barriers to adoption, is essential for improving practice change, particularly in WA. Further market segmentation work is needed on farmers' decision-making processes to help identify and overcome these barriers.

4.0 Conclusions

Producers in WA have managed increased seasonal variability for decades, particularly in the eastern wheatbelt, with incremental changes to remain profitable. However, assuming uniform changes across an entire growing season in the future will likely understate the impacts of climate change. Future rainfall reductions might disproportionately affect the most sensitive periods, such as germination in autumn/winter and flowering in spring. The timing and pattern of rainfall are crucial, as well as the overall drying trend of the climate. Producers can respond to variable rainfall events by adjusting their strategic (overarching) management and making short-term tactical adjustments throughout the year to boost farm profits and/or mitigate losses. Renovating pastures in the eastern wheatbelt could improve biomass quantity and quality, creating larger dry season buffers within the production system. Future research should focus on identifying the most valuable within-season pathways for improvement.

The autumn feed gap remains a critical research focus, necessitating the design of species and systems better suited for early growth. AFO and GrassGro™ modelling indicated that drought at the start of the season significantly impacts pasture production more than spring drought at Kojonup and Merredin. Pasture mixes that include oats and vetch or barley and vetch can provide early feed (if sown dry), helping reduce supplementary feeding costs. Additionally, joining ewes later (i.e. one month) to lamb into green feed can further mitigate the reliance on supplementary feeding.

Integrating new annual pasture legumes into farming practices requires equipping producers and consultants with the necessary knowledge. Current hurdles to adoption include concerns about initial investment costs, establishment methods, suitable herbicides, and grazing management. Extension activities should highlight the role and economic benefits of new annual pasture legumes within emerging systems.

Early lambers in the LRZ attempt to avoid the spring supply peak, but supplementary feeding remains expensive and early legume pasture feed is often lacking. Producers are seeking alternative feed options better suited to their drying environment, such as forage oats or mixtures of oats or barley with legumes. Adjustments to increase lamb survival by providing taller feed at lambing should also be considered and lambing into crops for improved nutrition and weather protection.

There is potential for processors to accept lambs at less traditional times, but challenges remain in managing sheep volumes later in the year and reducing animal heat stress during summer transport. Feedlotting and confinement feeding provide flexibility in adjusting the sale times for ewes and lambs.

The AFO modelling analysis for Kojonup identified multiple selling opportunities for ewes and lambs throughout the year. However, producers and processors need information on addressing social licence, animal health issues or feed budgeting rations for intensified feeding systems.

The simultaneous "not joining" ewes messages and the high turn-off in 2023 will exacerbate impacts on flocks, making it difficult for the state flock numbers to recover as long as these practices remain in place. This could have long-term ramifications for the sheep industry beyond 2024, impacting red meat processors and supporting industries. A contraction in the processing sector in WA would likely adversely affect sheep enterprise profitability, potentially decreasing sheep numbers further and creating more pressure on remaining processors.

Frequent, intense and prolonged heat in the future will challenge water supply maintenance for livestock and feed production in low rainfall zones. Some of the state's flock may need to transition from traditional Merino breeds to remain profitable in 2050. While a few producers have shifted to non-Merino breeds, including shedding breeds such as Dorpers, their proportion of sales remains small.

Currently, the cereal sheep zone supports nearly 50% of WA's sheep flock. Without adaptation, the proportion of sheep on these farms will likely decrease, as current systems cannot support larger flocks and stocking rates under a drier and hotter climate and a declining feedbase.

The modelling analysis using AFO, GrassGro™ and APSIM™ assumed that technology and production efficiency remain constant. While technological advancements are expected, this approach guides the magnitude of adaptation required, particularly in the LRZ.

Without adaptation, cropping and livestock enterprises at the dry margins of the wheatbelt could become less economically viable, leading to significant social and economic implications. Producers in lower rainfall locations with older cultivars may already be nearing declining rainfall thresholds, affecting their capacity to maintain minimum crop and pasture productivity.

Producers' long-term decisions, such as additional infrastructure investments or land purchases in other regions, will eventually be influenced by climate change once its impacts become clearer. Adjustments to the farming system in WA will be necessary to cope with future climate changes, requiring modifications of current systems and/or the development of new technologies. These adjustments will ensure WA maintains its reputation as a reliable supplier of high-quality sheep products to domestic and global markets. Despite these challenges from climate change, the WA sheep industry can thrive with strategic investment in research, extension and the implementation of adaptation strategies beyond 2050.

4.1 Recommendations

The following recommendations can be made:

1. **Knowledge and extension:** Equip growers and consultants with knowledge of the economic advantages, technical details and management practices for integrating new pasture/cultivars and forage crops into farming systems. Activities should explain the role and economic benefits of these new species within emerging systems.

2. **Case studies.** Conduct additional case studies on confinement feeding and best practice management and tools (ration feed, weight gain and cost calculators) for each livestock class.

3. **Lamb turn-off:** Adjust lamb turn-off times using feedlotting and confinement feeding to maximise the value received for the product, considering lamb liveweights and conditions at sale.

4. **Industry guidelines:** Develop guidelines for producers on site selection, design, shade and shelter, and ongoing sheep health management in intensive feeding systems, bundled into a producer-ready package like Lifetime Ewe Management or included in a phone application.

5. **Reduce GHG emissions:** Investigate management strategies or genetics for improving sheep conception and weaning rates to reduce enteric methane emissions from intensive and extensive grazing systems.

6. **Barriers to adaptation:** Address specific barriers faced by different producers in different rainfall zones regarding adaptive practices. Conduct a comprehensive cost-benefit analysis to assess adaptation strategies and research to understand barriers to adoption.

7. **Tactical management:** Utilising simple online model during the growing season to manage variable rainfall and increased temperatures.

8. **Farming system changes:** Prepare producers for changes in the farming systems to deal with climate change, including modifying current systems and developing new pasture species.

9. **New water resources**: How best to access and use saline groundwater resources for livestock and irrigation is a strategic project for the sheep industry and DPIRD.

10. **Strategic investments:** Seed industry and funders to adjust plant breeding goals now to ensure the industry's resilience and sustainability in the face of projected climate change in 2050.

4.2 Benefits to industry

The FutureSheep project has provided significant insights and tools for the sheep industry to navigate the challenges posed by climate change. Here are the key legacies and benefits:

- Identified the region's most susceptible to climate change, enabling the direction of extension resources and workshops to areas of greatest need. This targeted approach is crucial for effective adaptation strategies.
- The modelling results indicate "climate pressure" zones, highlighting regions where the need for adaptation is most urgent. This information is particularly valuable for processors who source their sheep supply from these impacted areas.
- Built stronger relationships across the supply chain, including with red meat processors.
- Processors now better understand the potential changes to their supply chains due to climate impacts, enabling them to ensure continued supply and market stability.
- Identified specific strategies to adapt and respond to climate change, particularly for the LRZ region of WA.
- Prioritise the need for more drought-tolerant annual pastures that mature earlier and possess increased seedling heat and drought tolerance and perennial species to use out-of-season rainfall to help mitigate feed shortages and enhance resilience.

- Parametrised and validated the AFO model for the LRZ, a significant achievement that adds value to the industry. This model now provides the capacity for a range of future analyses beyond the FutureSheep project.

4.3 Key messages

- With current technology adaptation, livestock and crop systems in the MRZ and HRZ will likely remain profitable in a future climate. However, the LRZ faces significant challenges and may experience economic downturns without new technological advancements.
- Revisiting and updating existing pasture packages and providing technical support are essential for producers transitioning to new systems.
- Mixtures of forage rye/barley, oats/vetch, triticale and tillage radish can fill early feed gaps, while serradella/vetch can provide later feed.
- Grazing crops in winter can also reduce the winter feed gap.
- AFO whole-farm modelling for the LRZ does not recommend a major shift to 100% cropping.
- Tactical changes in the cropping /livestock mix may be necessary depending on seasonal conditions, but a complete shift is not recommended.
- Easily accessible information is needed about newer pasture species with a reluctance from producers to retry if pasture establishment fails.
- Consultants and agronomists also requested more information on new aerial legume cultivars to make appropriate recommendations.
- New farming practices and technology must be viable to encourage adoption under current and future climatic conditions. Personalised climate projections can incentivise producers to implement changes.
- Confinement feeding and other intensive systems are emerging as key strategies for climate change adaptation.
- Water availability for sheep during summer is becoming a critical issue, requiring technologies to reduce evaporation or cheaper desalination units and solar systems.
- Barriers to climate change adaptation are specific to the audience, adaptive practice and location.
- Maintaining sheep slaughter volumes later in the year will remain a challenge due to potential heat stress during transport to or within sales yards.
- Spatial diversification (e.g. purchasing land in different zones) can help mitigate climate change effects and lower GHG emissions.
- Low input, low-risk sheep production systems in rangelands, with lamb finishing in western feedlots, could be a viable strategy.
- Properties in the LRZ with access to underground water are being considered for commercial feedlotting, highlighting the importance of integrated approaches to livestock production.

5 Future research

These funding priorities were developed based on input from computer modelling, producer feedback, grower groups, livestock consultants, and DPIRD staff. This process identified several critical knowledge and extension gaps that must be addressed to prepare adaptation strategies for the WA livestock industry. Short-term funding responses for building climate resilience.

5.1 Shorter term funding responses for building resilience

5.1.1 Biophysical, economic and climate modelling

- Improve modelling efforts by developing standard site descriptions (e.g. parameterisations of current soils, and climate) to better represent the LRZ
- Integrate advances in pasture agronomy and breeding (e.g. early cultivars of pink and yellow serradella) into the current simulation models
- Validate GrassGro™ and APSIM™ with trial data collected in the LRZ, including plant growth, nutritive value and sheep performance
- Address the cost concerns of confinement feeding early in the season through economic modelling around the value of deferring pastures in autumn
- Research the impact of different non-subclover pastures used in WA on methane emissions
- Conduct multi-year whole-farm economic modelling to assist producers in making informed decisions, particularly regarding the “not joining” strategy for ewes during dry seasons.
- Develop high-resolution global climate models (<5 sq km) to provide producers with more localised and relevant information, incentivising adaptation efforts.

5.1.2 Extension and knowledge sharing

- Bridge the knowledge gap on growing and managing pasture species better adapted to higher temperatures and drought than subclover. Develop extension programs to train producers and agronomists, particularly in the LRZ, on maximising the use of these pastures
- Improve quantification of nitrogen fixation by various legumes and its availability to subsequent cereal crops. This research could help producers reduce fertiliser N reliance and GHG emissions
- Survey MLA members to gather primary data on their sentiment towards climate change across different demographics and rainfall zones. This baseline data will help track progress and identify areas needing more focus
- Develop a phone application or online tool for future climate scenarios tailored to a producer’s property. This tool will help educate producers about long-term climate challenges and facilitate the adoption of adaptation strategies
- Increase extension on current technologies that will assist producers in maintaining or improving pasture productivity with the expected climate between now and 2050.

5.1.3 Forecasting

- Fund training courses to educate producers on the effective use of weather forecasting tools
- Examine how models could be used to predict future production within the growing season to assist producers in making better tactical decisions, such as reacting to specific rainfall trigger levels.
- Enhancing the accuracy of climate projections and improving medium-term to long-term weather forecasting are critical.

5.2 Investment options for building resilience over 3–5 years

- Conduct case studies in WA on feedlotting, confinement feeding and best practice management and tools (e.g. develop feed, weight gain and cost calculators) to increase adoption
- Evaluate the full costs and benefits of these adaptation responses to demonstrate their genuine advantages
- Expand the "Lifetime Ewe Management" (LTEM) training program to update feed budgeting and liveweight/condition score targets
- Include greater information on confinement feeding, feedlotting and sheep nutrition for different livestock classes within industry extension resources and supported learning packages
- Use detailed data from producer case studies for simulation modelling and industry benchmarks, serving as a powerful tool for others seeking low-cost, low-risk means to explore climate-ready scenarios for their farms.

5.3 Long-term investment

5.3.1 Feedbase and plant breeding

- Make long-term investments in developing new heat and drought-tolerant pasture species and earlier maturing cultivars of current species, particularly for the LRZ
- Develop cultivars with seedling drought tolerance to survive false breaks
- Explore more feed base options to optimise year-round feed supply, including dual-purpose crops, perennials and shrubs, to make the most of out-of-season rainfall
- Develop a Dalkeith subclover replacement with increased DM production, earlier maturity, resistance to false breaks, and enhanced drought tolerance compared to current cultivars.

5.3.2 Animal genetics

- Assessing Merino or other sheep breeds for heat tolerance to maintain fecundity, productivity and welfare expectations
- Select animals with greater energy reserves that can be mobilised during feed shortages and relate this to feed intake and other production traits.

5.4 Conclusion

Simulation modelling indicated that all study sites would experience a loss in pasture and crop yield by 2050 under a moderate greenhouse gas emission pathway (RCP 4.5). This is due to reduced rainfall, a shorter growing season, and increased temperatures. While the yield deficit was modest in the MRZ and HRZ, losses in the LRZ were projected to be substantial without adaptation.

Current pasture technology is likely sufficient for producers in medium to high rainfall zones to recover lost yield. However, in the LRZ, it will only provide a medium-term solution. To remain viable, new innovations will be required by 2050 highlighting the need for ongoing research and flexible policy frameworks to address these challenges.

Economic analysis revealed that without adaptation, climate change will reduce profit and increase its variability across all rainfall zones by 2050. The least change will occur at the highest rainfall sites, with the greatest impact at the lowest. The AFO LRZ modelling also shows the way the climate dries significantly impact profitability and influences the optimal management changes needed.

Discussions with producers identified critical knowledge and extension gaps crucial for preparing adaptation strategies for the WA livestock industry. The strategy of some producers to not join ewes as a dry season response has longer-term impacts beyond the implementation year. This includes the flock's ability to self-replace and the impact on lamb supply for processors.

Strategic investment for research, extension, and the implementation of adaptation strategies can build resilience into the sheep production system, enhancing its sustainability. Short-term investment responses should include improvements in biophysical and economic modelling, extension and knowledge-sharing initiatives, and enhanced weather forecasting capabilities. Further calibration of computer models for low rainfall regions with new aerial legume species would be a valuable R&D investment, providing capacity for future analyses beyond this project.

Medium and long-term funding priorities should focus on investments in the feedbase and plant breeding to ensure the industry's resilience and sustainability in the face of projected climate change.

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8 Appendix

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