Inquiry into the impact of climate change on Queensland agricultural production

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INQUIRY INTO THE IMPACT OF CLIMATE CHANGE ON QUEENSLAND AGRICULTURAL PRODUCTION

State Development and Regional Industries Committee

CSIRO Submission

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Executive summary

Australia is a relatively food secure country with experience in managing diverse risks. Our agricultural sector has a successful history of responding to a variable climate, managing marginal environmental and volatile operating conditions. CSIRO has a long history of delivering world class research and development in the areas of agricultural systems, climate science, human and animal health, and environmental sustainability.

CSIRO is working towards preparing Australia for a more volatile future where climate change and other global change processes interact. Australia has the opportunity to proactively implement local and national solutions that are cognisant of, and adapt to, changing local and global contexts.

In discussion with industry partners, state, federal and local governments and through many years of operating in the agricultural sectors in Australia, the following themes may be of interest to the committee, grouped by the two terms of reference.

Terms of Reference 1. Impacts of climate change and climate variability

- Anthropogenic climate change has had, and will continue to have significant impacts, on agriculture in Queensland.
- Climate data and projections can give general insights into impacts and risks, but to understand potential impacts on different commodities, data needs to be tailored to different production systems.
- Chronic changes in temperature regimes will restrict the suitability of production for some agricultural industries, while creating new opportunities for others. Drought and rainfall extremes will continue to present major challenges.
- Managing extremes in temperature and rainfall are critical risks to agriculture and will affect crop production, quality and livestock welfare. Warmer temperatures and altered weather patterns across most of Queensland will lead to shifts in growing seasons, increased heat stress, and changes in pest and disease dynamics. Differences in regional climate trends, species and varietal sensitivities and management approaches mean that industries will see differing levels of impacts.
- A changing climate has the potential to influence the distribution and behaviour of agri-pests affecting both agricultural productivity and sustainability. This includes changing the potential risk from both endemic and exotic threats, and the benefits derived from ecosystem services like biological control.
- Modelling suggests that climate change may reduce average farm profits under 2050 climate scenarios.
- The impact of climate change on water resources will impact further development of agriculture, and the issue of competing water use between agricultural versus industrial and municipal use will require consideration.
- Supply chains have been impacted by climate change through infrastructure damage and input uncertainty and as the frequency and severity of extreme events rise, greater infrastructure investment will be required to adapt to a more extreme climate, particularly to address vulnerabilities in logistics, storage, and worker conditions.

Terms of Reference 2. Opportunities for the Queensland Government to create and support resilience, adaptation and mitigation measures

- Effective climate adaptation requires climate information systems developed around nationally consistent and robust scenarios, modelling, assessment, and delivery approaches.
- There is significant need for comprehensive online information systems that encompass various aspects of climate change impacts and adaptation, providing less fragmented and more unified view of future climate risk.
- Adaptation responses to climate change can help to optimise production and will be increasingly coupled to market and policy driven changes to reduce carbon emissions and impacts on natural capital. These responses require consideration of system-wide solutions and the perspectives and requirements of all stakeholders within the sector.
- The uptake of climate smart agriculture practices will require a significant upskilling within the sector to navigate the emerging changes in farming systems, market opportunities and the growing digitisation of Australian agriculture.
- The systematic assessment of direct and indirect climate risks to agricultural supply chains is limited. Adaptation along the supply chain needs to be considered in light of their ability to address climate risks, as well as their secondary impacts on other parts of the supply chain.
- Queensland communities are seeking just transitions to prosperous, sustainable futures with low emissions goals. Research supports locally led, regionally coordinated and state-facilitated strategies to enable these transitions.
- Understanding impacts of climate change on variations in pest pressures and ecosystem services will enable effective mitigations of biosecurity risks and enable enhanced access to agricultural markets.

Harnessing innovation and integrating diverse knowledge systems will help address climate change needs as part of a holistic risk management approach for Queensland's food systems. The time for preparing the agricultural sector for future climate change is now: Business-as-usual and incremental adaptations to Australia's agri-food system will be insufficient for managing the changing risk landscape, shifts in policy and market drivers and sustainability challenges.

We acknowledge that this is a complex and challenging landscape and we look forward to contributing to a collaborative whole-of-systems approach to build a thriving and resilient agricultural sector.

Introduction

CSIRO welcomes the opportunity to provide input to the Queensland Parliamentary Inquiry into the impact of climate change on Queensland agricultural production.

CSIRO's mission-driven multidisciplinary science focuses on the issues that matter the most: for our quality of life, for the economy and for our environment. One key theme is the development and delivery of innovative science and technology to build a profitable, productive, trusted, and sustainable agri-food and fibre sector for the future. Our research in Climate Smart Agriculture for example develops sustainable solutions for cropping, livestock, aquaculture, and horticulture industries, and spans on-farm resilience, supply chains and communities.

Of note are some of CSIRO's Missions: an initiative to coalesce our research and development around some of Australia's largest challenges. The Drought Resilience Mission is a program of large-scale, impact focussed, collaborative initiatives with a goal of reducing the impact of Australian droughts by 30% by 2030. It is operating at three inter-connected levels to deliver on-farm innovation, regional resilience and development, and policy enablers and outreach in order to build resilience in Australia's agricultural industries, communities, and environments.

The Toward Net Zero Mission hopes to provide Australian industry, agriculture and regional communities with the tools to achieve net zero emissions and realise the opportunities of a low carbon economy. Working with the Queensland Government, the Mission developed the *Low Emissions Pathways for Queensland Agrifood* report which informed the QLD Government's Low Emission Agriculture Roadmap 2022-2032.

The Catalysing Australia's Biosecurity Mission, in collaboration with the Australian Department of Agriculture, Fisheries and Forestry, aims to directly address the pressures that trade, tourism and climate change are all putting pressure on our biosecurity system. In line with the National Biosecurity Strategy it aims to deliver innovative technologies, digital systems and capabilities that addresses the growing threats and impacts of pests, weeds, and diseases.

The Trusted Agrifoods Exports Mission aims to grow Australia's agrifood exports by $10 billion this decade by assisting Australian agricultural exports to access profitable markets based on biosecurity and sustainability credentials.

The Ag2050 Scenario-Based Road mapping project is a disruptive, multi-year program of work in partnership with the Commonwealth Department of Agriculture Forestry and Fisheries (DAFF) that will target non-incremental change of Australia's farming systems and provide an evidence-based picture of what Australia's farming systems could, should and need to look like in 2050 to be productive, resilient and sustainable. This includes better insights into the impact of Climate Change on agricultural productivity, and the development of shared understanding of critical industry system innovations required to meet desired future scenarios.

CSIRO's goal is to deliver solutions and innovations in line with nationwide aspirations, including to grow Australia's agriculture exports, to increase the uptake of digital technologies, to find solutions to ease the pressures of drought and water shortages, to navigate social licence issues and to capture value from enhanced sustainability.

CSIRO's Response to the Terms of Reference

CSIRO seeks to address the Terms of Reference by providing an overview of relevant research, learnings and opportunities gained through our decades of work in this area.

The following sections address the two Terms of Reference outlined in the inquiry.

These ToR are addressed in the context of both physical impacts and the opportunities arising from transitional risks. Physical risks are those associated with the direct impact of climate change, and transitional risks are those associated with impacts of repositioning markets, policies, and technology for a low-carbon economy.

1. TOR 1: Impacts of climate change and climate variability on Queensland agricultural production and the existing and potential future risks of climate change on the sector.

Key messages

1. **Anthropogenic climate change has had, and will continue to have significant impacts, on agriculture in Queensland.**

Climate

2. **Chronic changes in temperature regimes will restrict the suitability of production for some agricultural industries, while creating new opportunities for others.**
3. **Trends in annual rainfall patterns vary across Queensland, with some regions showing declines in rain and others increases. However, variability of rainfall is likely to be exacerbated by a warming climate.**
4. **Managing extremes in temperature and rainfall are critical risks to agriculture and will affect crop production, quality and livestock welfare.**
5. **Climate data and projections can give general insights into impacts and risks, but to understand potential impacts on different commodities, data needs to be tailored to different production systems.**

Production

6. **Across most of Queensland warmer temperatures and altered weather patterns will lead to shifts in growing seasons, increased heat stress, and changes in pest and disease dynamics. Differences in regional climate changes, species and varietal sensitivities and management approaches mean that industries will see differing levels of impacts.**
7. **Drought and rainfall extremes will continue to present major challenges for the northern livestock industry. These will be exacerbated by increasing temperatures, greater evaporation and potential changes in feed quality.**
8. **Heat stress will become increasingly more important to manage to ensure livestock impacts such as low reproductive success, reductions in milk yield and quality and livestock mortality.**
9. **Broadacre crops are most sensitive to rainfall across both the winter and summer growing seasons. Shifts in timing and rainfall amount are likely to place increasing pressure on crop productivity. The combined influence of heat stress will exacerbate production risk, while exposure to frost is likely to decline.**

Key messages (cont.)

10. **Temperature induced impacts will affect both perennial and annual horticultural crops causing shifts in suitable growing windows or make regions unsuitable for certain industries. Extremes in temperature and rainfall are likely to continue to pose threats.**
11. **The greatest direct impact of climate change on sugar cane production is likely to be the projected change in the amount, frequency, and intensity of future rainfall. Impacts of climate variability and change are likely to be seen across the entire value chain from farming and harvesting, transport, milling and marketing.**
12. **Climate change may have both positive and negative effects on cotton production including whole of system water use efficiency.**
13. **A significant challenge in irrigated production systems has been the increasingly drier climate in cotton growing regions and shrinking water resources caused by Australia's variable and changing climate. The impact of climate change on water resources will impact further development of agriculture, and the issue of competing water use between irrigation with industrial and municipal use will require consideration as to how this limited resource will be best divided amongst the various stakeholders.**

Profitability

14. **Climate change has the potential to make conditions tougher for Australian farmers with reductions in average farm profit possible under 2050 climate scenarios. These anticipated pressures on farm profitability come on the back of changes in total factor productivity across agricultural sectors in Queensland.**

Biosecurity Risk

15. **Pests, weeds, and diseases already have a significant impact on Queensland's agriculture and a changing climate has the potential to influence the distribution and behaviour of agri-pests affecting both agricultural productivity and sustainability. This includes changing the potential risk from both endemic and exotic threats, and the benefits derived from ecosystem services like biological control.**

Supply chains

16. **Extreme events along with gradual trends associated with climate change have impacted supply chains primarily through infrastructure damage and input uncertainty. However, indirect impacts are also felt throughout the chain, often resulting in the inability to continue business over a short or prolonged period. Increased investment in infrastructure will be required to adapt to a more extreme climate, particularly to address vulnerabilities in logistics, storage, and worker conditions.**

Anthropogenic climate change has had, and will continue to have significant impacts, on agriculture in Queensland.

Queensland has experienced significant climate variability in Australia and therefore is well positioned to take advantage of already significant understanding of climate risk management threats and opportunities. However climate change means that past experiences are becoming an insufficient guide for risk management strategies in the future. Key impacts of climate change on Queensland agriculture include temperature extremes, drought and water scarcity, changing growing seasons, increased pest and disease pressures, reduced productivity, soil degradation and erosion, the viability and wellbeing of rural communities, and ecosystem health. In collaboration with farmers, industry bodies, agribusiness and consultants and national and Queensland state and local governments, CSIRO's Climate Smart Agriculture research is developing sustainable and innovative agricultural practices to enhance food security and agricultural resilience in the context of a changing climate. These include improving climate-resilient crop varieties, pest management, efficient irrigation practices, sustainable land management, improved early warning systems, and income diversification.

The specific nature of the impacts and risks discussed below vary in their specific extent due to regional differences, local practices, and the trajectory of future climate change.

1.1 What climate science is telling us about climate change and variability.

Key Message: Chronic changes in temperature regimes will restrict the suitability of production for some agricultural industries, while creating new opportunities for others.

All of Queensland has warmed since 1910. Average annual temperature has increased by 1.5 °C since 1910 (CSIRO & BoM, 2022) and likely around 1.7 °C (CSIRO & BoM, 2022) between 1850-90 and 2011-2020, the period over which the world warmed by around 1.1 °C (CSIRO & BoM, 2022; Grose et al., 2023). Queensland will continue to get hotter into the future: under a high emissions scenario (RCP8.5), Queensland can expect an average annual temperature increase of around 1.3-2.5 °C (central estimate of 1.9 °C). Large and sustained reductions in global greenhouse gas emissions (RCP2.6) reduce projected warming to around 0.7-1.7 °C (central estimate of 1.2 °C). As well as changes in mean annual temperatures, agriculture is dependent on the frequency of temperature events: for example the number of hot days (>35 °C) will increase from approximately 2 days per year in Brisbane to approximately 8, and from approximately 4 to 14 days per year in Toowoomba under this high scenario. There is *very high confidence* in further projected warming in Queensland based on the assessment of the full range of evidence (IPCC 2021).

Key Message: Trends in annual rainfall patterns vary across Queensland, with some regions showing declines in rain and others increases. However, variability of rainfall is likely to be exacerbated by a warming climate.

In general, since 1900 summer (wet season) rainfall has increased over most of Queensland, while winter (dry season) rainfall has declined. As a whole, Queensland is likely to become drier in the May-October period. Average annual rainfall change is unclear in the monsoon region, with significant change possible. Both wetter and drier futures should therefore be considered (CSIRO & Meteorology, 2023).

Key Message: Managing extremes in temperature and rainfall are critical risks to agriculture and will affect crop production, quality and livestock welfare.

A warmer climate means increasing frequency of heat waves (even in winter) and impacts to a range of agricultural systems. There is also evidence for increases in short-duration rainfall events (CSIRO & BoM, 2022). There is also high confidence of such trends in increased rainfall intensity in future projections for Queensland (CSIRO & BoM, 2022).

The number of days with dangerous weather conditions for bushfires has increased in nearly all locations across the state. Projections for mid-century suggest Queensland can expect longer fire seasons, with around 40% more very high fire danger days (Climate Change in Australia 2023).

The number of severe landfalling tropical cyclones near and south of Cairns has declined since the late 19th Century. The number of tropical cyclones is projected to decrease by about 8% for this region of Australia. In addition, in the future, east coast lows are projected to decrease by up to 20% under a high emissions scenario, primarily due to a reduction during winter. However, current evidence suggests that the proportion of storms in the highest categories is projected to increase, and that the impact of storms is also likely to increase due to higher rainfall rates and arriving on a higher sea level (IPCC 2021).

Key Message: Climate data and projections can give general insights into impacts and risks, but to understand potential impacts on different commodities, data needs to be tailored to different production systems.

Agricultural impacts from climate are borne out of changes in a combination of different drivers such as growing season rainfall and high temperatures. Consequently, as part of the federal Government's *Climate Services in Agriculture* program funded by DAFFs *Future Drought Fund*, CSIRO in partnership with BoM together with farmers has created a tool, *My Climate View* (https://myclimateview.com.au).The tool presents location-specific and commodity-specific climate information designed to support longer-term agribusiness and risk mitigation planning across Australia.

These efforts build on established programs to deliver the latest information on historical and projected trends in climate. CSIRO's Climate Science Centre and the Bureau of Meteorology (BoM) collaboratively produce the biennial *State of the Climate* report (CSIRO & BoM, 2022), and in partnership with many other research organisations have developed The *Climate Change in Australia* platform[1].

1.2 Impacts on production

Key Message: Across most of Queensland, warmer temperatures and altered weather patterns will lead to shifts in growing seasons, increased heat stress, and changes in pest and disease dynamics. Differences in regional climate changes, species and varietal sensitivities and management approaches mean that industries will see differing levels of impacts.

Queensland has a considerably diverse range of agriculture, the composition of which changes over time. It covers 88% of Queensland's land and in terms of contributing to the state economy in 2021-22, livestock's value is $8.7b, cropping $4.9b, and horticulture $4.2b.

Exposure to climate change and variability presents various challenges at various scales from individual enterprises, the sector, dependent communities, and the greater supply chain. The impacts of climate change on production systems are multifaceted and highly complex due to interacting elements of biophysical systems and how they are managed. Although there is uncertainty in the future climate projections, especially for annual and seasonal rainfall, the likely impacts on various production systems have been assessed through combinations of statistical and simulation modelling and participatory research with producers and researchers. CSIRO has been at the forefront of developing detailed farm simulation tools such as pasture growth models (e.g. GrassGro, (Moore et al., 1997; Moore et al., 2004) and crop growth models such as the Agricultural Production Systems Simulator, APSIM (Holzworth et al., 2014; Keating et al., 2003) and are well documented (for example (Cobon et al., 2017; Williams, 2016). It is therefore not the intent of this submission to detail all possible impacts. Here we focus on some key commodities and industries to provide an assessment of key trends and potential changes to production.

Key Message <u>Livestock systems</u>: Drought and rainfall extremes will continue to present major challenges for the northern livestock industry. These will be exacerbated by increasing temperatures, greater evaporation and potential changes in feed quality.

Longer and more frequent droughts will decrease pasture production, and therefore livestock carrying capacity and animal production, and cause significant change in plant and animal species composition (Cobon et al., 2009; McKeon et al., 2009). Examining decadal rainfall patterns at St George, extended dry periods of 20 to 30 years are associated with extensive droughts, degradation events, reduced profits, and greater debt and human hardship (Cobon et al., 2017).

Increase in short duration rainfall events and rainfall extremes will increase flood risk and impact livestock survival, pasture availability and ability to muster and transport livestock to markets.

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[1] https://www.climatechangeinaustralia.gov.au/en/changing-climate/state-climate-statements/queensland/

Carbon dioxide concentrations will continue to increase above pre-industrial levels, stimulating an in increase in the efficiency of plant water and nitrogen use (Stokes et al. 2008). The well-known carbon-dioxide 'fertilisation' effect can sometimes enhance growth when water and nutrients aren't limiting. However future increases in growth of pastures are likely to be offset by a reduction in overall pasture quality (lower protein and lower digestibility (Stokes et al. 2011). These second order effects will not play out consistently across the sector due to the variability in nutrient and water availability. For example, in areas in far north Queensland where nitrogen is limiting, increased carbon-dioxide concentrations reduced nitrogen concentrations in the forage will increase the risk of lower live weight gain of livestock. An increase in minimum temperatures over winter will increase pasture growth. However, the specific nature of species change is complicated with higher temperatures may make tropical C4 pasture species more competitive at the expense of more nutritious C3 grasses.

Under circumstances where pasture growth does increase, it may promote greater wildfire risk, highlighting the importance of prescribed burning (Stokes et al 2011).

Key Message Livestock systems: Heat stress will become increasingly more important to manage to ensure livestock impacts such as low reproductive success, reductions in milk yield and quality and livestock mortality.

Heat stress has differential impacts on livestock based on breed and management. For sheep, high temperatures (e.g. days above 32 °C) during the joining period can reduce reproductive success through changes in fertility. For much of Queensland's sheep producing regions, heat stress during the joining process will increase and require strategic planning around joining and lambing programs to help avoid heat-induced declines in reproduction. For beef and dairy cattle, heat stress is a function of temperature, relative humidity, solar radiation and air movement and can affect calf rates, milk production and ultimately cause death. Based on combined measures of temperature and relative humidity (Temperature-Humidity index) used to infer moderate stress levels for dairy cattle, there is strong confidence that all regions across Queensland will experience a greater incidence of stress.

Key Message Cropping systems: Broadacre crops are most sensitive to rainfall across both the winter and summer growing seasons. Shifts in timing and rainfall amount are likely to place increasing pressure on crop productivity. The combined influence of heat stress will exacerbate production risk, while exposure to frost is likely to decline.

Queensland's broadacre crops include cereal, oilseed, and legume crops. Wheat and sorghum are the most commonly grown winter and summer crops respectively. For some southern Queensland cropping regions there has been declines in summer rainfall (November to March), while northern regions have shown no significant trend for either growing season. Whilst the climate projections for growing season rainfall indicate no clear direction of change, drought duration and intensity are likely to add to year-to-year variability in production. This may reduce the occurrence of highly profitable 'wet' years and opportunities to grow both winter and summer crops in a given cycle.

There is high confidence in an increase in late winter season heat stress on crops across the entire cropping belt of Queensland. High temperatures during flowering and grain fill reduce yield directly and have follow on effects on grain quality. The occurrence of heat stress earlier in the season i.e. late winter/early spring represents a critical challenge for cropping systems. Furthermore, the interactive effects of heat and water stress are poorly understood but are likely to exacerbate yield declines into the future.

Frost conditions tend to increase during seasons with lower rainfall, however over decadal time-scales, frost risk will decline with increasing minimum temperatures. This may reduce crop damage during flowering and grain fill and avoid localised crop losses from frost events.

Key Message <u>Horticulture</u>: Temperature induced impacts will affect both perennial and annual horticultural crops causing shifts in suitable growing windows or make regions unsuitable for certain industries. Extremes in temperature and rainfall are likely to continue to pose threats.

In general climate change is expected to impact heavily on the horticulture industry due to the high proportion of temperature-sensitive crops and high irrigation requirements (Putland, 2014). Increases in both minimum and maximum temperatures will alter the length and timing of the growing season particularly in short-lived crops such as lettuce and Brassicas. For some regions, shifts in temperature regimes may make some regions unsuitable for certain crop species or varieties e.g. tomato production in the Lockyer Valley.

For mangos, increasing minimum temperatures are already affecting flowering patterns in the northern most growing regions i.e. Darwin region (Clonan et al., 2020), and will eventually impinge on production in across Queensland’s mango growing regions.

In the tropics higher minimum temperatures will increase growth of winter fruit and vegetable crops in regions that are not close to the top end of their temperature regimes. Higher minimum temperatures and lower frost frequency may increase the climate-suitability of subtropical crops such as avocado (Deuter et al., 2011).

Heat waves, high intensity rainfall events and flood, will continue to pose significant threats to horticulture. The incidence of extreme events are likely to increase and may impact on crop quality and yield but also affect ability to harvest and transport produce.

Key Message <u>Sugarcane</u>: the greatest direct impact of climate change on sugarcane production is likely to be the projected change in the amount, frequency, and intensity of future rainfall. Impacts of climate variability and change are likely to be seen across the entire value chain from farming and harvesting, transport, milling and marketing.

Sugarcane is grown in three distinct climate regions in Queensland: the wet tropics of the far north, the dry tropics, and the subtropics of Bundaberg. 60% of this production requires irrigation (Inman-Bamber, 2007). In general, an increase in temperatures in cool regions may be favourable for plant growth, but in warm regions may be detrimental. In terms of rainfall change, plant growth will increase or decrease as rainfall increases or decreases. Overall the greatest direct impact of climate change on sugarcane production is likely to be the projected change in the amount, frequency, and intensity of future rainfall (Stokes & Howden, 2010). In the coastal regions where sugarcane is grown, the projected changes in rainfall over the next couple of decades are unclear due to the masking effect of natural variability however in winter-spring there is a greater risk of effective rainfall decreasing (or showing little change), and increase evaporative demand due to increased temperatures (CSIRO & Meteorology, 2023; Stokes & Howden, 2010). In addition, an increase in temperatures and CO_2 are likely to result in faster crop development, an increase in yield, and a longer growing season (Williams, 2016).

Analysis using the APSIM model of sugarcane comparing future projections of production in north Queensland with that of southern Queensland indicates that by 2030 the cooler southern regions are more likely to have greater yield losses than the north due to increased water stress (Park et al., 2007). Any impacts of climate variability and change on production are likely to be seen across the entire value chain from the farming and harvesting, transport, milling and marketing as described in (Park et al., 2007).

Key Message <u>Cotton</u>: Climate change may have both positive and negative effects on cotton production including whole of system water use efficiency.

Climate change may have both positive and negative effects on cotton production. Increased CO_2 may increase yield in well-watered crops, and higher temperatures will extend the length of growing season (especially in current short season areas) (Bange et al 2010). However, higher temperatures also have the potential to cause significantly lower yields and increase evaporation and thereby reduced whole of system water use efficiency. Higher atmospheric CO_2 and higher temperatures may create a more favourable environment for growing cotton if there is available water (Williams et al., 2018; Williams et al., 2015). However, the availability of water in the future is highly uncertain (see Irrigated systems below).

Key Message <u>Irrigated systems</u>: A significant challenge in irrigated production systems has been the increasingly drier climate in cotton growing regions and shrinking water resources caused by Australia's variable and changing climate. The impact of climate change on water resources will impact further development of agriculture, and the issue of competing water use between irrigation with industrial and municipal use will require consideration as to how this limited resource will be best divided amongst the various stakeholders.

High-input irrigated crops such as cotton and sugarcane face many of the same future challenges as other broad acre crops (Brodrick & Bange, 2019). Currently the predominant irrigated crops in Queensland are cotton and sugarcane which consume 41% of Queensland's water supplies (Qld Government 2018), with primary industries comprising 62% of all water extractions. A very significant challenge in broadacre irrigated production has been the increasingly drier conditions in cotton growing regions and shrinking water resources (Jones 2010) caused by Australia's variable and changing climate (Humphreys et al. 2006, Bange et al. 2016). Current and future crop management practices will continue to evolve from, those which were developed assuming reasonable access to water, to those that need to operate under constrained water availability.

For irrigated crops, future water availability and irrigation management capabilities play a major role in enabling producers to maintain economically viable operations in variable climates. However, water use for irrigation will continue to compete with industrial and municipal use due to dwindling ground and surface water supplies in many areas. Policy makers will need to decide how this limited resource will be best divided amongst the various stakeholders: a major challenge in light of future climate change predictions (Brodrick & Bange, 2019). To meet these challenges there will be a greater need to incorporate other aspects of production efficiencies into the analysis of modern irrigated cropping systems (e.g. fuel/energy use or carbon emissions per unit of lint produced) in addition to existing production use efficiencies (e.g. water and N).

The impact of climate change on water resources will impact further development of agriculture. It is perceived that if water infrastructure is further developed then there is scope for expanding agricultural enterprises (Qld Govt 2018), such as the expansion of the grazing and cotton industries in North Queensland. Currently less than 2% of the water used for agriculture comes from recycled water sources, with 80% of water coming from extractive sources (groundwater and surface water schemes) (ABS, 2022).

1.3 Impact on profitability

Key Message: Climate change has the potential to make conditions tougher for Australian farmers with reductions in average farm profit possible under 2050 climate scenarios. These anticipated pressures on farm profitability come on the back of changes in total factor productivity across agricultural sectors in Queensland.

While future projections are subject to much uncertainty, results reported from the FarmPredict model (a statistical model of Australian cropping and livestock farms) indicate that beef farms in northern Australia show significant reductions in average farm profit under the Future 2050 scenarios (−22.1 to −3.0% under RCP4.5 and −54.5 to −16.3% under RCP8.5) (Hughes et al., 2022). These changes are driven by projected declines in winter and summer rainfall along with increases in maximum temperatures. Although such statistical models do not account for longer-term adaptation, it was concluded that even with strong adaptation responses, climate change could still reduce Australian farmers' international competitiveness depending on the climate change impacts and productivity trends in other nations.

These projected pressures on farm profitability come on the back of historical changes in estimated Total Factor Productivity (TFP) in Queensland. ABARES estimated an average decline in TFP over the past 30 years of -0.1%pa for the beef industry in QLD, and -0.7%pa when climate adjusted productivity estimates were made; these climate adjusted productivity estimates mainly measure underlying technological change and are a better reflection of 'true' industry productivity performance over time (Australian Agricultural Productivity - Broadacre and Dairy Estimates - DAFF (agriculture.gov.au)). In comparison the estimated TFP changes for the cropping industry in QLD was 0.4%pa (unadjusted) and 0.8% pa climate adjusted TFP.

Drought, a key impact of climate change on Queensland agriculture, also impact agricultural profitability. Evidence from Australia, synthesised by CSIRO's Drought Resilience Mission researchers, shows drought's impact on agriculture is complex (Fleming-Muñoz et al., 2023). Profitability can be impacted via changes to agricultural productivity, output and input prices, and access or availability of financial assistance. Further, profitability impacts are a product of decisions made in response to drought, such as choice of input mix, or the efficiency of machinery/intermediate input use and costs associated with these decisions (e.g., switching from surface water to groundwater). The distributional impacts of drought on profitability are also variable. Farmers able to benefit include those with fodder or water to sell at higher local prices, while those unable to produce due to drought or those who have to pay higher prices for water or other inputs will experience greater costs (Fleming-Muñoz et al., 2023).

Land sector carbon abatement projects (changing management to reduce emissions or sequester carbon in soils or vegetation) have been promoted as strategies to support farm profitability by diversifying farm income. Queensland hosts 395 land sector carbon abatement projects registered with the Clean Energy Regulator (at May 2023, (Regulator, 2023)). The cost of abatement produced by these projects is variable across agricultural sectors, abatement methods and locations in Queensland and Australia. The profitability impacts of these projects reflect the input costs and productivity impacts of the abatement project, the price of carbon abatement paid in voluntary markets and under government contracts, and the opportunity costs associated with changing land management practices (Dumbrell et al., 2017; Meier et al., 2023). CSIRO research focussing on identifying least cost abatement options for grain farms (using approved and potential methods for carbon abatement) indicates the potential for positive operating profits and gross margins as well as negative farm operating profits of up to more than AU$300 per metric tonne of carbon dioxide equivalent of abatement in the Darling Downs, Queensland (Dumbrell et al. 2017). This indicates the potential financial compensation required to achieve land sector carbon abatement and maintain farm profitability.

1.4 Impact on Biosecurity Risk in agriculture

Key Message: Pests, weeds, and diseases already have a significant impact on Queensland's agriculture and a changing climate has the potential to influence the distribution and behaviour of agri-pests affecting both agricultural productivity and sustainability. This includes changing the potential risk from both endemic and exotic threats, and the benefits derived from ecosystem services like biological control.

Pests, weeds, and diseases ("agri-pests") already have a significant impact on Queensland's agriculture (Knudsen and Muller 2017). A changing climate will influence the distribution and behaviour of pests, weeds, and diseases affecting agricultural productivity and sustainability. Increased temperatures and changes in rainfall could have multiple impacts on agri-pests including changing the geographical suitability of both exotic and already established agri-pests as well as changing the population dynamics and size (e.g. Queensland Fruit Fly can now overwinter in southern regions).

Resulting indirect impacts include direct productivity losses, increasing the cost of pest, weed and disease management (CSIRO 2008), change to market access both regionally and internationally will affect both exports and imports. Agri-pest occurrence in some areas may increase as a result of increased habitability of cultivated areas, decreased habitability elsewhere in the landscape due to drought/heat thereby enhancing the suitability of cultivated areas, translocation due to poor observance of control protocols during disaster response episodes (e.g. fire, floods), and decreased effectiveness of chemical controls, for example chemicals can be less effective at high temperatures and plants under stress may be less resilient to chemicals (e.g. Bt cotton). Climate change also has the potential to variably influence ecosystem services derived from beneficial biological control of pests in Queensland's agricultural systems (Harms et al., 2021; Thomson et al., 2010). Where negatively impacted, this can add economic costs for pest, weed and disease mitigation to Queensland's agriculture.

The impact of pests, weeds and diseases on natural environments will have also have implications for agricultural productivity in terms of ecosystem services.

The specifics of climate change impacts on biosecurity can vary depending on the region, the specific pests and diseases involved, and the local ecological and agricultural context.

1.5 Impacts on supply chains

Key Message. Extreme events along with gradual trends associated with climate change have impacted supply chains primarily through infrastructure damage and input uncertainty. However, indirect impacts are also felt throughout the chain, often resulting in the inability to continue business over a short or prolonged period. Increased investment in infrastructure will be required to adapt to a more extreme climate, particularly to address vulnerabilities in logistics, storage, and worker conditions.

Queensland agriculture relies on regional diversity in order to continue to supply domestic and international markets with a wide range of agriculture products. Equally, it relies on its supply chains to get products from farm to market. Yet, these supply chains are increasingly exposed to the direct and indirect impacts of climate change. To date, there has been limited research on the impacts of climate change on Queensland supply chains; the majority of the focus has been on extreme events, in particular, flood events (MacMahon et al., 2015; Smith et al., 2016; Wisetjindawat et al., 2017). Here we summarise key supply chain areas impacted by climate change, both in the form of extreme events and gradual change, as well as other similar threats that disrupt supply chains in a similar manner.

Infrastructure

Queensland has experienced significant infrastructure losses from extreme climate events, in particular road and rail damage from major rainfall events. It is estimated that extreme events over the two-year period between April 2010 to April 2012 resulted in road network damages in excess of AU$7 billion, excluding impact on local governments (Pritchard, 2013). In 2017, flooding and landslides from heavy rainfall from Tropical Cyclone Debbie resulted in record flood levels damaging mining rail infrastructure and subsequently closing ports as a safety precaution (Lim-Camacho et al., 2021). Downstream of the supply chain, impacts on storage and retail infrastructure were also felt, with warehouses and stores closed for prolonged periods. Overall, the impacts of climate change on agricultural supply chains are business continuity and financial risks, as they limit operations and require significant investment to repair and recover from.

Input uncertainty

Australia is a net importer of fertilisers, and any disruption to global trade can impact on the availability and price of agricultural inputs domestically, including those caused by climate events (Savary et al., 2020). In considering future impacts of climate on agricultural inputs, it is pertinent to evaluate impacts of other events, including the COVID-19 pandemic. The lack of availability of shipping containers because of port closures limited global trade, causing imports to decline

(Notteboom et al., 2021). Likewise, limited seasonal labour availability also impacted on farm operations (Godde et al., 2021), with significant impacts on Queensland horticultural industries. These events, made acute by the COVID-19 pandemic, can also be caused by climate events.

In considering the relationship between supply chains and climate change, it is important to note that impact is not uni-directional. For example, increased agricultural productivity and movement of goods may have an impact on ecosystem resources, potentially exacerbating the impacts of climate change (Ortiz et al., 2021). In addition, as the urgency to limit climate change heightens, emissions reduction efforts, both from within supply chains and external to it, will also impact on supply chain operations and corporate governance (The Climate Leaders Coalition, 2022).

2 TOR2: Opportunities for the Queensland Government to create and support resilience, adaptation and mitigation measures in preparing the agricultural sector for future climate change.

Key Messages:

1. **Effective climate adaptation requires climate information systems developed around nationally consistent and robust scenarios, modelling, assessment, and delivery approaches.**
2. **Previous strategies to manage climate variability may be insufficient to decrease risk in Queensland agriculture into the future. Adaptation responses to climate change can help to optimise production and will be increasingly coupled to market and policy driven changes to reduce carbon emissions and impacts on natural capital.**
3. **A key component of adaptation is long-term planning. This requires a consideration of system-wide solutions and the perspectives and requirements of all stakeholders within the sector.**
4. **The uptake of climate smart agriculture practices will require a significant upskilling within the sector to navigate the emerging changes in farming systems, market opportunities and the growing digitisation of Australian agriculture.**
5. **There is significant need for comprehensive online information systems that encompass various aspects of climate change impacts and adaptation, providing less fragmented and more unified view of future climate risk.**
6. **The systematic assessment of direct and indirect climate risks to agricultural supply chains is limited. Adaptation along the supply chain needs to be considered in light of their ability to address climate risks, as well as their secondary impacts on other parts of the supply chain.**
7. **Queensland communities are seeking just transitions to prosperous, sustainable futures with low carbon goals. Research supports locally led, regionally coordinated and state-facilitated strategies and enable these transitions.**
8. **Understanding impacts of climate change on variations in pest pressures and ecosystem services will enable effective mitigations of biosecurity risks and enable enhanced access to agricultural markets.**
9. **Successful transition to low emissions agriculture needs innovative governance to ensure maximum adoption across agricultural sectors.**
10. **Disasters and recovery increase GHG emissions, and maladaptive actions can be reduced through capacity building, adaptive planning and collective governance.**

2.1 Opportunities to improve climate science and address key gaps

Key Message. Effective climate adaptation requires climate information systems developed around nationally consistent and robust scenarios, modelling, assessment, and delivery approaches.

Climate change analysis should make use of the latest climate assessments and modelling to inform the current and future climate risk space in a framework consistent with best-practice guidelines, including:

- Produce analysis and planning consistent with the latest scientific literature and scientific assessment of climate change (e.g., IPCC Sixth Assessment Report). Include an assessment of various lines of evidence and assess likely changes as well as risks in the extremes.
- Make use of the latest high-quality observation and reanalysis datasets (e.g., Australian Gridded Climate Dataset AGCD update, ERA5 and BARRA2 Reanalysis) and understand any differences in datasets (e.g., SILO versus AGCD).
- Make use of newest generation of climate modelling at the global scale (the CMIP6 model ensemble) and the multi-model ensemble of regional climate modelling produced in Australia in response to the Bushfire Royal Commission recommendations and following: the 'NextGen Projections' report (Karoly et al., 2021), the new Climate Projections Roadmap for Australia[2] and the National Partnership for Climate Projections[3]. This ensemble includes the *Queensland Future Climate* modelling as a key component, as well as other contributions for a more comprehensive set of modelling (Grose et al., 2023).
- At the least, the full range of modelling should be presented as context before detailed data and information from *Queensland Future Climate* is given. Aim for national consistency in choices to present information (e.g., future scenarios, time periods, global warming levels), with comparability to the National Climate Risk Assessment (NCRA), new IFRB Financial Reporting S2 Standards, other federal and state assessments and guidelines, major hydrological projects (e.g., Murray Darling Basin work).
- Work with and leverage work done in other states and federally, such as *Climate Services for Agriculture* (CSA) to ensure comparability and to minimise duplication.
- Include a major focus on extreme events, hazards and compound extremes, where the biggest damages and impacts are felt, including consistency and leverage with federal programs such as the *Australian Climate Service* (ACS) wherever possible.

Communications

- A key focus on climate change assessment and projections that is scientifically credible, as well as information that is salient, legitimate and actionable, with a focus on co-design and other best-practice aspects of climate services.
- Utilise good practice techniques for presenting information that build trust and credibility, as well as convey the ranges of possibilities robustly. Utilise social science research on communication wherever possible.

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[2] https://www.dcceew.gov.au/climate-change/publications/climate-projections-roadmap-for-australia

[3] https://www.dcceew.gov.au/climate-change/policy/climate-science/climate-science/climate-change-future

- Utilise FAIR principles (Findable, Accessible, Interoperable, Reusable) and transparency of all analyses.

Despite best efforts across different state and federal jurisdictions, agribusiness, consultants, research providers and government still struggle to access and incorporate consistent and comparable data and analysis for evaluating climate risk. There will be continued need to invest in national efforts that provide coordination and guidance to inform climate risk assessment across all areas of business and government. The growing requirements for reporting on climate and nature related financial disclosures is creating high levels of demand, particularly for climate exposed sectors such as agriculture. Governments can play a role in supporting greater transparency and equitable approaches to enable all areas of agriculture to access to trusted, robust and traceable information such as *Australian Climate Service* and the *National Partnership for Climate Projections.*

2.2 Opportunities through adaptation, adoption, and digital agriculture

Key message. Previous strategies to manage climate variability may be insufficient to decrease risk in Queensland agriculture into the future. Adaptation responses to climate change can help to optimise production and will be increasingly coupled to market and policy driven changes to reduce carbon emissions and impacts on natural capital.

Climate change is already occurring and present novel patterns of risk such as compound events and increasing frequency of extremes such as heat and flood. The impacts of a changing climate are complex because of interacting and opposing forces operating within the biophysical system (McKeon et al. 2009). Managing climate variability has historically been a foundational component of Queensland's agricultural sector and climate risk management strategies have been utilised for incremental adaptation to climate change. However, adaptation will not occur in isolation.

The transition to net zero and towards nature positive farming will see a greater focus on transformational changes within agriculture. The emerging markets for carbon and biodiversity represent a large opportunity for diversifying the revenue stream of farms whilst improving economic and climate resilience. This will require policy that can provide greater confidence to the agricultural sector when investing in new infrastructure and capability. Uncertainty in government policy and the longevity of policy is a significant barrier to adaptation (e.g.(Henry & Knudsen, 2019): it prevents participants at all stages of the value chain in engaging and investing in climate change adaptation and mitigation opportunities. Policy instruments to support climate change adaptation in agriculture include policies on: water management/trading/irrigation, drought relief, biosecurity, infrastructure, land stewardship, carbon sequestration, protection of prime agricultural land (NCCARF 2013). In addition to policy, governments can further support adaptation through strategically directed research in agricultural innovation such as: long-term breeding and trait development programs, whole of farm systems and experimentation studies, novel climate risk mitigation technologies, efficiency gains through circular economy practices and improving environmental credentials.

Across Queensland's primary industries adaptation is already occurring; the most frequent adaptations are on-farm management practices, and farm and agricultural business planning and management (Queensland AgSAP 2017). Less common adaptations, but recognised as essential, are regional, industry, and whole of supply chain-level adjustments incorporating processing, transport and marketing stages.

Genetic improvement, whether by conventional breeding or by applying biotechnology tools and technologies, also has the potential to develop cultivars with improved water use efficiency and heat tolerance which will further assist systems to be more resilient to climate change and climate variability.

Key message. A key component of adaptation is long-term planning. This requires a consideration of system-wide solutions and the perspectives and requirements of all stakeholders within the sector.

Long-term planning is essential to achieving workable solutions that allow Queensland agriculture to adapt to a climate constrained future. Irrigated agriculture serves as an important case study to demonstrate this point. For farmers reliant on water supplies for irrigation, building capacity for long-term planning, through improved long-term weather forecasting and drought planning was deemed critical according to a recent study by Jakku et al. 2022. This was considered critical in addition to more tactical responses to improve on-farm efficiency through agtech tools. Importantly this study identified that important next steps to enable adaptation to climate variability through prolonged droughts and weather extremes should also include system-wide solutions, such as changes to water allocation, water market and water trading processes, improving water supply and security, and better collaboration processes between governments, grower groups and other stakeholders in water planning.

Drought impacts financially but also takes a toll on social networks and communities, right when these are most needed to help farmers through tough times. Developing approaches to support morale and strengthen social connection can be as important as new technologies for achieving drought resilience.

Water use for irrigation will continue to compete with industrial and municipal use due to dwindling ground and surface water supplies in many areas. Policy makers will need to decide how this limited resource will be best divided amongst the various stakeholders (Brodrick and Bange 2019). Trade-offs across the food-water-energy nexus will need to be increasingly scrutinised. For example, a greater push for improvements in water use efficiency has led to demand for more sophisticated irrigation systems that may be more energy intensive.

Key Message. The uptake of climate smart agriculture practices will require a significant upskilling within the sector to navigate the emerging changes in farming systems, market opportunities and the growing digitisation of Australian agriculture.

Agriculture will continue to thrive if it can take advantage of shifting market opportunities around emissions reductions and offsets and its environmental credentials whilst building long-term climate resilience. Many of these changes require sustained capacity building within the agricultural sector; from research providers, agricultural extension and advisors, farmers and the associated value chain. Utilising the trend towards digitisation will be ubiquitous across all aspects of the sector. Digitisation of on-farm operations includes the use of technology to support efficiency through precision agriculture, as well as technology to help monitor, manage and plan, such as drones, models, automation, sensors, machine learning and big data, as examples (Wolfert et al., 2017). CSIRO's *WaterWise* technology is one example, which is the only water-use efficiency product for irrigated crops, such as cotton, tomatoes and sugarcane. It uses proximal sensing of crop water status combined with machine learning to predict future water needs in real-time. This innovation is one of many emerging tools that can help farmers optimise tactical decisions and production while improving their environmental footprint.

Innovation in digital agriculture needs to maintain a strong 'farmer first' focus that ensures the sector benefits from improved tools to maintain productivity, social licence to operate and market access, while still being environmentally and socially sustainable (Fleming et al., 2021). These efforts will be aided by strong support by government (including via RDC's) and a thriving innovation system that sees research providers partner closely with startup/business sector.

While tools exist to help farmers manage seasonal and decadal climate patterns, such as *Long Paddock, Farming Forecaster*[4], *Climate Guides*[5], and *Climate Services for Agriculture Program's My Climate View*[6], they often require support for farmers to interpret and apply. This means adoption is not a simple 'roll out' of technology, but a more complicated interplay of farmers/technology/advisors over time and in different forums (industry groups, one-on-one, on-farm demonstrations). In addition, as climate change impacts are variable and context specific, each farm context will require different levels of adaptation and change, which again requires farmers to take time to plan. Government funded programs which support planning and peer learning are effective ways to encourage adoption of farm practices to build resilience to climate change, especially if these programs include direct links to tailored climate projections, such as the work underway in the Farm Business Resilience Planning programs utilising *Climate Services for Agriculture Program's* extensive information resources.

Climate literacy is generally low in the Australian community – e.g. incorporating multiple sources of climate information, often provided in probabilistic terms, to inform an understanding of climate risk. This is also challenging because interpreting future trends based only on historic experience may be limited if climate changes outside past parameters (as is already being experienced in the severity and frequency of extreme events). A focus on risk can be a useful way to help farmers think about the uncertainty of impacts that preparing for future climate change requires (Hewitt & Stone, 2021). However, upskilling across the sector is urgently required to ensure different actors can navigate the complexity of undertaking climate risk assessment and where necessary, respond to risks in a timely and suitable manner.

Extension policies will continue to serve as crucial instruments of adoption, as trusted advisors and peer networks are required to support farmers. This requires longer term and more systemic

[4] https://www.farmingforecaster.com.au/

[5] http://www.bom.gov.au/climate/climate-guides/

[6] https://myclimateview.com.au/

views of how adoption occurs and investment in industry programs for learning, planning, demonstrations and accessing advice.

Key Message. There is significant need for comprehensive online information systems that encompass various aspects of climate change impacts and adaptation, providing less fragmented and more unified view of future climate risk.

Climate-driven vulnerabilities in the global food system will continue to impact Queensland agriculture. Opportunities to reduce vulnerability and engage in adaptation strategies will be aided by access to robust and consistent climate information including: improved seasonal forecasts and future projections in combination with digital agronomy tools. Digital tools tailored to particular commodities such as *My Climate View* improve farmers' ability to plan, allocate resources and reduce risk.

Historically, the development, integration and commercialisation of bespoke digital agriculture solutions has been slow, inflexible, hard to scale and expensive. This has limited the capacity to distribute agriculture decision support tools for the benefit of multiple decision makers and producers. The challenge we face now is that we can no longer risk the time and money to continue to create solutions in isolation without the infrastructure to support: (a) leveraging scientific knowledge (Public and Private); (b) developing platforms to support economies of scale; (c) developing a marketplace upon which we can commercialise our solutions for now and the future. The CSIRO led *Frost and Heat Management Analytics* project funded by the GRDC is creating a marketplace for commercial partners to easily access products via API that can provide enhanced delivery of climate information for key hazards affecting the cropping sector. Innovation in both the science and delivery of its outputs are supporting visibility, adoption and innovation of solutions for parties across the value chain, including grain growers, advisers, insurers, plant breeders and co-investors.

In addition, producers, advisors, and extension staff find the ever-increasing complex source of data and decision support tools becoming more challenging to access and a barrier to utilisation. A more consolidated offering across the emerging market of climate and environmental reporting is deemed preferable to reduce the need for countless platforms and dissemination points especially given the increasing requirements of emissions reporting and other sustainability credentialling (Battaglia, 2022).

2.3 Opportunities to manage the impact on supply chains

Key Message. The systematic assessment of direct and indirect climate risks to agricultural supply chains is limited. Adaptation along the supply chain needs to be considered in light of their ability to address climate risks, as well as their secondary impacts on other parts of the supply chain.

An adapted supply chain is one that can sustain and grow its competitive advantage in a changing climate (Lim-Camacho et al., 2016). Adaptation action in supply chains is part of supply chain management, and is therefore dependent on capability, decision processes and governance. While supply chain adaptation has been raised as an important aspect of adaptation for the agriculture and food sectors, efforts to inform this through evidence-based research has been limited. Focus has still been on adaptation of production, and to a limited extent, the impacts of climate on supply chains.

Shared risk and collective governance

Supply chain adaptation includes actions across the whole chain – from input providers to consumers – and the consideration of what these actions mean for others. One of the biggest challenges to supply chain adaptation is shared risk management (Lim-Camacho et al., 2017). Recovery from Cyclone Debbie, while not directly focused on the agricultural sector, demonstrated the importance of shared investment. Escalating climate risks has also increased concerns around how risks are managed, thus the need to collectively govern action along the supply chain (Muller, 2017). Prior studies in adaptation in Queensland agricultural produce has shown that respondents tend to manage risks in an individualised way. However, recovery from extreme events have shown that a collective approach is required, involving a wider set of actors including government and consumers (Muller, 2017). This collective approach was investigated in Queensland, in the context of collaborative responses to the Queensland floods, recommending collaboration, communication, engagement and governance as key policy and practice levers for enhancing adaptive capacity (Kinnear et al., 2013).

Building resilience

All food and agricultural supply chains will experience diminished resilience and increased vulnerability as a result of climate change, whether that is through direct impacts, or indirect effects. Studies have shown that complex chains – those with more options available to move product from production to consumer – have higher resilience than simpler chains (Lim-Camacho et al., 2017). Understanding the structure of chains has been the focus of research in supply chain resilience (García-Flores et al., 2022), but there is also some attention paid to understanding human and social capital aspects of resilience as they apply to economic activity, including supply chains. Knowledge management and assimilation, as they pertain to understanding plausible futures and experience from past events, has been found to be critical in building the capacity to minimise exposure and enhance risk management opportunities in agri-food companies (Ali et al., 2023). Ricketts, et al. (2022) also found that the quality of supply chain relationships also served to support the resilience of Australian food supply chains, particularly those involved in global supply chains as they benefitted from 'tailwinds' or advanced notification of events.

From supply chains to food systems

There have been many calls to 'shorten' supply chains by relying on local food production sources, and the resilience of both chains have been investigated in the context of Queensland's flood events (Smith et al., 2016). The definition of short vs long chains is context dependent, and caution needs to be placed in favouring the former, because winners are often resource rich and less vulnerable populations. Queensland is still dependent on long food chains and geographically concentrated but distant food production and consumption zones, with vulnerable populations often dependent on food supplies from distant sources.

2.4 Opportunities to transition to sustainable futures and increase community resilience.

Key Message. Queensland communities are seeking just transitions to prosperous, sustainable futures with low carbon goals. Research supports locally led, regionally coordinated and state-facilitated strategies and enable these transitions.

Regional Queensland communities with economies and social capital rooted in agricultural production are seeking to transition to prosperous, low emissions, sustainable futures while mitigating the impacts of and adapting to climate change.

An understanding of co-dependencies around energy, water, biophysical conditions and socio-economic drivers will support community resilience and transition pathways to adapt to climate change and capture opportunities. This understanding will also support climate-driven spatial, and commodity shifts in agricultural production occur where it is feasible and socially accepted such that it can achieve necessary scale (Brodrick and Bange, 2019). Paddock and farm-scale adaptation and mitigation strategies will also have regional impacts, including co-benefits. Likewise, regional adaptation and mitigation strategies can support farm-scale transition pathways by, for example, supporting a skilled workforce and fostering local innovation (CSIRO, JCU, USQ and TEG 2019). A holistic approach to resilience and transition, addressing the many factors affecting the agricultural industry's response to climate change, and investments in this transition can improve outcomes. Continued support for place-based multiple or bundled regional benefits through targeted natural capital investments for climate change mitigation plus co-benefits (such as under the Queensland Government's *Land Restoration Fund* or agricultural extension programs) could also support this.

CSIRO research is already supporting regional resilience and transitions in Queensland. For example, *Queensland's Regional Resilience Strategies*[7] employ CSIRO's *Resilience Adaptation Pathways Transformation Approach* (Q-RAPTA) process as a resilience building approach tailor-made for the Queensland context. Further, CSIRO, with other institutions, designed a program of work for a pathways approach to the Queensland Climate Transition Strategy '*Pathways to a clean*

[7] See https://www.qra.qld.gov.au/regional-resilience-strategies

growth economy,' a strategy that focuses on the risks associated with environmental, social and economic changes (CSIRO, JCU, USQ and TEG 2019).

Ongoing programs of work, including CSIRO's Towards Net Zero Mission and Valuing Sustainability Future Science Platform seek to provide an evidence base that enables communities to plan for and transition to low carbon futures while supporting outcomes for the environment more broadly (e.g. biodiversity) and people. The Towards Net Zero Mission is capturing and sharing lessons from transitions in communities either driven by industrial transformation or looking to capture collective advantage by the net zero transition by responding to new market mechanisms for insetting emissions and establishing governance arrangements to support shared value creation. Further, the Valuing Sustainability Future Science Platform moves CSIRO beyond being a science delivery agency in the sustainability space, to being an integral partner and broker of legitimate and credible future pathways for sustainability options and transitions (Leith et al. 2021). In keeping with this, a Valuing Sustainability Future Science Platform project is working in partnership with the Queensland Government Department of Environment and Science and Department of Agriculture and Fisheries to consider the regional level social impacts of investments in natural capital.

2.5 Opportunity to manage biosecurity risks and impacts

Key Message. Understanding impacts of climate change on variations in pest pressures and ecosystem services will enable effective mitigations of biosecurity risks and enable enhanced access to agricultural markets.

It is critical for Australia to develop adaptive strategies for biosecurity. Such strategies will include strengthening surveillance and early detection systems, improving scientific research on pest and disease dynamics under changing climate conditions, investing in established and novel technologies for integrated pest management, supporting Asia-Pacific neighbours with managing their pests which are often Australia's biosecurity threats, and collaborating with other countries to manage shared biosecurity risks.

As identified in the *Queensland Biosecurity Strategy*[8], *Australia's National Biosecurity Strategy*[9] and the CSIRO's *Australia's Biosecurity Future*[10] report, there is a need for technology-enabled transformations to mitigate biosecurity risks (current and in the context of climate change). Transformational opportunities include the digitisation and enhancing data sharing across supply chains and the human, agricultural, environmental and marine health sectors to ensure we identify and manage emerging risks (i.e. a One Health/One Biosecurity perspective; (Hulme, 2020). Sharing of data across agricultural production chain to anticipate and respond to biosecurity risks and mitigate impacts. This requires data systems that place a premium on accuracy, interoperability, access and privacy measures. The development of *Australian Agrifood Data*

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[8] https://www.daf.qld.gov.au/business-priorities/biosecurity/enhancing-capability-capacity/qld-biosecurity-strategy
[9] https://www.biosecurity.gov.au/about/national-biosecurity-committee/nbs
[10] https://www.csiro.au/en/work-with-us/services/consultancy-strategic-advice-services/csiro-futures/agriculture-and-food/biosecurity-futures

Exchange (AAFDX)[11] in partnership with industry through the CSIRO's Trusted Agrifood Exports Mission is an important first step in this context to enable Australia's primary producers to demonstrate and capture the value of biosecurity credentials. This will ensure optimal access to markets (domestic and international) for Queensland's agriculture.

Technologies that enable forecasting of biosecurity risks in a climate change context (e.g. *Biosecurity Commons*[12]) and those that enable rapid in-field diagnostics for early detection and response to pest, weed and disease threats will be crucial in the context of climate change. CSIRO's Catalysing Australia's Biosecurity Mission is supporting the development of such tools and technologies in partnership with the Commonwealth Department of Agriculture, Fisheries and Forestry and industry stakeholders. Supporting rapid innovation in this context may require embracing the concept of "biosecurity as a business", rather than sole reliance on "biosecurity as a service".

Other key ongoing CSIRO programs of research in support of Queensland and Australia's climate-change related biosecurity risks include (a) development of climate-resilient biological control solutions as part of integrated management systems (e.g. (Kriticos et al., 2021); (b) Asia-Pacific biosecurity partnerships to support regional neighbours with their endemic pests, weeds and diseases before they emerge as biosecurity threats for Australia (e.g. (Tay et al., 2022) ; (c) pre-symptomatic detection tools/technologies for diagnosing animal and plant disease[13]; (d) anticipating a chemically limited future for biosecurity management (e.g. Downes et al., 2021; Hunt et al., 2021) and (e) enhancement of digital tools for pest management interventions (e.g. (Parry, 2021) .

[11] https://www.integritysystems.com.au/ozdata
[12] https://www.biosecuritycommons.org.au/
[13] https://research.csiro.au/hostresponse/research/biomarkers-and-diagnostics/

2.6 Emissions reduction

Key Message. Successful transition to low emissions agriculture needs innovative governance to ensure maximum adoption across agricultural sectors.

Queensland has committed to net-zero by 2050, in keeping with Federal targets and the Paris Agreement (Department of Agriculture, 2023). Currently agriculture, land use and land use change contribute approximately 23% to the State's total Greenhouse Gas (GHG) emission profile (State Greenhouse Gas Inventory 2019). There are significant opportunities to reduce GHG emissions (e.g. (Macintosh et al., 2019). A suite of industry frameworks exist supporting a low-emissions agricultural sector with many industries (including cotton, sugarcane, red meat, dairy, pork, grains, wine) already identifying and committing to low-emission pathways(Department of Agriculture, 2023), and can be integrated with other industry natural resource management and production frameworks such as the Australian Agricultural Sustainability Framework. CSIRO has forecast a potential income of $40billion to the agricultural sector from carbon market opportunities (NFF, 2020)

However despite the dynamic and continuously evolving nature of agri-food systems, there has been, in general, little sector-wide on-ground GHG abatement, disproportionate uptake of innovations, technologies, and emission-reducing practices. There are many documented barriers impeding the full realisation of abatement opportunities, including low carbon price and associated policy uncertainty, a lack of trust in information providers and consequential poor awareness, and concerns about changes in the rules that govern participation and crediting. (Macintosh et al., 2019; NFF, 2020). Furthering these realisations, CSIRO's Toward Net Zero Mission[14] Regional Transition Team has investigated systemic resistances to transitions (Conti et al., 2021).

To this end CSIRO's Toward Net Zero Mission recently co-designed the *Queensland Low Emissions Agricultural Roadmap 2020-2032* (Battaglia, 2022) with the Queensland Department of Agriculture and Fisheries and its many stakeholders, contributing to the *Queensland Climate Action Plan*. Five key pathways are designed with a range of prospective activities and high priority actions, specifically: livestock emissions, cropping and horticulture emissions, on-farm energy opportunities, carbon farming and landscape management, and regions and supply chains. These actions are described in depth in the report, but a noteworthy finding is that the single largest contributor to emissions reduction was identified as the technologies and methods used for methane reduction in cattle. Specifically, CSIRO in partnership with Meat & Livestock Australia and James Cook University developed *FutureFeed*, a cost-effective seaweed feed ingredient which has significant mitigation plus productivity outcomes (Kinley et al., 2020; Li et al., 2018; Roque et al., 2019).

Without adoption of technologies and changes from existing modes of production, the absence of transformational change may result in significant negative social, economic, and environmental outcomes such as trade barriers, loss of markets, an unsustainable agricultural sector and reduced food security. The range of specific actions and other policy tools utilised by government (as for

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[14] https://www.csiro.au/en/about/challenges-missions/towards-net-zero

example recommended for Queensland by (Battaglia, 2022) have different impacts on the level of adaptation able to be achieved (Ulibarri et al., 2022). For example direct regulations, plans, and capacity building are associated with more transformational adaptation, whereas information delivery tools, decision support tools, economic levers (e.g. subsidies, taxes, insurances) and networks tend to operate on a smaller scale with targeted groups/subsectors (Ulibarri et al., 2022). The challenge is to develop and utilise policy tools that enable transformational adaptation of the agricultural sector while ensuring protection of the needs of rural and regional communities including under-represented indigenous groups.

Key Message. Disasters and recovery increase GHG emissions, and maladaptive actions can be reduced through capacity building, adaptive planning and collective governance.

Disasters, and the subsequent disaster recovery have been shown to increase GHG emissions, highlighting the importance of looking out for maladaptation (Foong et al., 2023; Schipper, 2020). Rebuilding infrastructure in areas where they are likely to be impacted again in the future is not only a costly effort, but also one that requires emissions-generating material and effort in order to complete. As we encounter a more volatile and extreme climate, extreme events will continue to damage critical infrastructure, and reducing vulnerability plays an important role in adaptation and mitigation. Shifting financial strategies from post-disaster approaches (force majeure contract clauses, insurance, recovery) to pre-disaster investment have been called for, particularly in light of major 'uninsurable' disasters such as the Black Saturday bushfires, the 2010-11 Queensland floods and Cyclone Yasi (de Vet et al., 2019).

There are examples of such efforts, and focus has been made on transformations such as the Helidon relocation, shifting Indonesia's capital and more recently, Thailand's awareness of the vulnerability that Bangkok faces with sea level rise. But what is not often mentioned is the capacity and capability to make decisions under uncertainty, and the collective adaptation governance required to make such decisions (Rissik et al., 2014). Understanding plausible futures, employing reflexive planning, and improving decision processes through enhanced information – whether they are around adaptation or mitigation – are win-win strategies to manage uncertainty.

3 References

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