Agriculture and land

AGRICULTURE AND LAND

Sector summary

The agriculture and land sector is well placed to continue to grow and underpin Australia's food security, deliver significant economic value and support healthy ecosystems, while at the same time making a vital contribution to Australia's transition to net zero emissions by providing a significant source of carbon removals.

Agricultural emissions are expected to remain stable around current levels to 2035 and then reduce modestly to 2050. This trend would result from a scale up of existing practices and technologies and new low emissions technologies becoming commercially viable in the sector from the 2030's through the 2040's. Some of these technologies include:

- feed supplements
- slow-release or nitrification inhibiting coated fertilisers
- improved herd and pasture management
- manure management, and
- vehicles and machinery powered by renewable fuel sources or electricity.

Combined emissions of Australia's agriculture and land sector produced a net sink of 3 Mt CO_2-e in 2022, with agriculture contributing 85 Mt CO_2-e in emissions and land contributing an 88 Mt CO_2-e sink.

Emissions from enteric fermentation from livestock are the main source of sector emissions, and are expected to remain high until around 2035. In the absence of a technology breakthrough on livestock emissions, or a major shift in production due to changing dietary preferences, the sector will likely need to rely on continued improvements in farming practices (herd and pasture management), as well as sequestration through land-based carbon removals, to balance livestock emissions and thereby contribute to whole of economy net zero emissions by 2050.

Increased land-based removals, including through reforestation, will be needed if emissions do not reduce significantly in energy-intensive sectors elsewhere in the economy. There is an opportunity to increase these removals by:

- establishing new forests for timber, carbon sequestration, agroforestry and environmental plantings, and
- protecting existing forests and other native vegetation from deforestation and degradation.

The sector will need to reconcile multiple pressures on land resources to maintain food security, protect and conserve biodiversity, store carbon, support infrastructure and increasingly produce biofuel feedstock. Land-based removals are exposed to the risks of climate change and these risks are expected to increase in the future.

AL.1 Sector state of play

The agriculture and land sector produces most of the food and fibre consumed and used in Australia. The sector underpins Australia's food security, contributes to the economy and is critical to the management of natural resources.

The total value of agricultural, fisheries and forestry production grew by 46 per cent from 2003-04 to 2022-23, reaching $100 billion in real terms (ABARES, 2024b) across the three industries. The agriculture industry is highly export-oriented, with 72 per cent of the total value of agricultural production, and 78 per cent of beef and veal production, being exported (ABARES, 2024b). Grains, meats and industrial crops (i.e. crops not for direct consumption or requiring further processing like oilseeds and fibres) made up 28 per cent, 20 per cent and 12 per cent of Australia's total agricultural exports respectively (ABARES, 2024a). The sector produces 90 per cent of food and beverages consumed domestically (ABARES, 2020).

The Australian agriculture industry is aiming to grow its economic value, with a target of reaching $100 billion by 2030 (NFF, 2019). Favourable growing conditions saw agricultural production reach $71 billion in value in 2021-22 (ABS, 2022). The sector accounted for 2 per cent of Australia's value-added GDP in 2022-23 (see Appendix B).

In 2022-23, the agriculture and land sector employed 299,000 workers (see Appendix B) with 81 per cent of workers living in regional or rural areas (ABARES, 2023). Across the workforce, 31 per cent of workers identified as female (Appendix B), 1.8 per cent as Indigenous and 13 per cent as culturally and linguistically diverse (ABARES, 2023). It is an aging workforce with a median age of 50 years (compared to 40 years for the general Australian workforce), with only 25 per cent of the workforce being under 35 years old (ABARES, 2023). Existing challenges for the workforce include labour shortages across most occupations, for both unskilled and skilled work (requiring post-school qualifications) (Skills Insight, 2023). Agriculture's peak food industries bodies calculated a labour shortage of at least 172,000 workers across the agriculture and food supply chain during 2022 and 2023 (NFF, 2023a). According to these peak bodies, labour shortages are increasing the costs of production, leading to higher prices for consumers (NFF, 2023a).

The agriculture and land sector contributes both significant sources and sinks of greenhouse gas emissions. The biggest sources of the sector's emissions are associated with livestock production through enteric fermentation and manure, and deforestation to maintain pastures (Table AL.1). Agricultural soils are the second largest source of emissions in the agriculture sector. Emissions from agricultural soils include those from fertiliser, crop residues, animal wastes deposited by grazing animals on pasture and mineralisation due to loss of soil carbon. Other sources of emissions stem from fuel use in agricultural vehicles and machinery. The storage of carbon in woody biomass and vegetation, and in soils, represents a substantial carbon sink in the sector.

Climate change impacts on the agriculture and land sector are already being experienced and are projected to increase, presenting a growing challenge for the sector. Changes in climate have impacted the productivity and profitability of Australian cropping farms, particularly in south-western Australia and south-eastern Australia from higher temperatures and lower winter rainfall (Hughes et al., 2017, 2019, 2022). Increased heat stress can reduce the milk yield, milking frequency and rumination time in dairy cows (Talukder et al., 2023), and in livestock heat stress can reduce feed intake, growth, weight gain, and reproduction (Lees et al., 2019). Droughts result in increased costs, decreased production and lower income for livestock producers (MLA, 2024a). ABARES' modelling shows that hotter and drier conditions in northern Australia are projected to impact livestock profitability through reduced herd numbers and increased fodder expenses (Hughes et al., 2022). As climate impacts are projected to increase over time, farmers will require significant adaptation responses to maintain productivity and profitability (Hughes & Gooday, 2021).

Table AL.1: Emissions and sinks in the agriculture and land sector (2022)

	Mt CO_2-e	Subsector share (%)
Agriculture		
Enteric fermentation[a]	55	64%
Agricultural soils (including fertiliser and urea application)	13	16%
Manure management	7	8%
Fuel use and other	10	11%
Net total – Agriculture	85	
Land		
Deforestation[b]	8	8%
Existing forests	-15	-14%
Reforestation	-50	-48%
Croplands	-12	-11%
Grasslands	-17	-16%
Other land use, land-use change and forestry (LULUCF)	-3	-3%
Net total – Land	-88	
Net total – Agriculture and land	-3	

[a] Subsectoral agriculture emissions proportions are expressed as a percentage of total agriculture emissions for 2021-22.
[b] Subsectoral land emissions proportions are expressed as a percentage of land sector carbon stocks (sources and sinks) for 2021-22. A negative emissions value indicates a carbon sink. A negative subsector share indicates the proportion of the associated emissions value relative to the total land sector carbon stocks.

Net emissions from the agriculture and land sector have steadily decreased since 2005. This has been driven by declines in sheep and dairy cattle numbers and reductions in deforestation (ABARES, 2024a; DCCEEW, 2023). More recently, net emissions decreases have been influenced by recent La Niña conditions that caused vegetation to rapidly grow and recover from drought impacts in preceding years (DCCEEW, 2023).

AL.2 Existing and prospective technologies

Safeguarding Australia's food and fibre production is critical for food security and economic growth. Technologies that reduce agricultural emissions and simultaneously achieve productivity benefits are a priority for the sector. Food production and land management is interlinked with many other societal and environmental issues, beyond productivity. This includes competing demands on land and the potential for flow-on impacts for people, communities and ecosystems (see AL.3 Barriers, opportunities and enablers). As such, careful planning by communities, businesses and government is essential to realise the full potential of benefits and avoid unintended consequences within the Australian agriculture and land sector.

Within existing production systems, there are limited existing technology solutions to reduce agricultural emissions in large volumes. The land component of the sector is currently a net sink with significant potential for additional land-based carbon removal (CSIRO, 2022a). Emissions reductions and long-term decarbonising of the agriculture and land sector will require a suite of technologies.

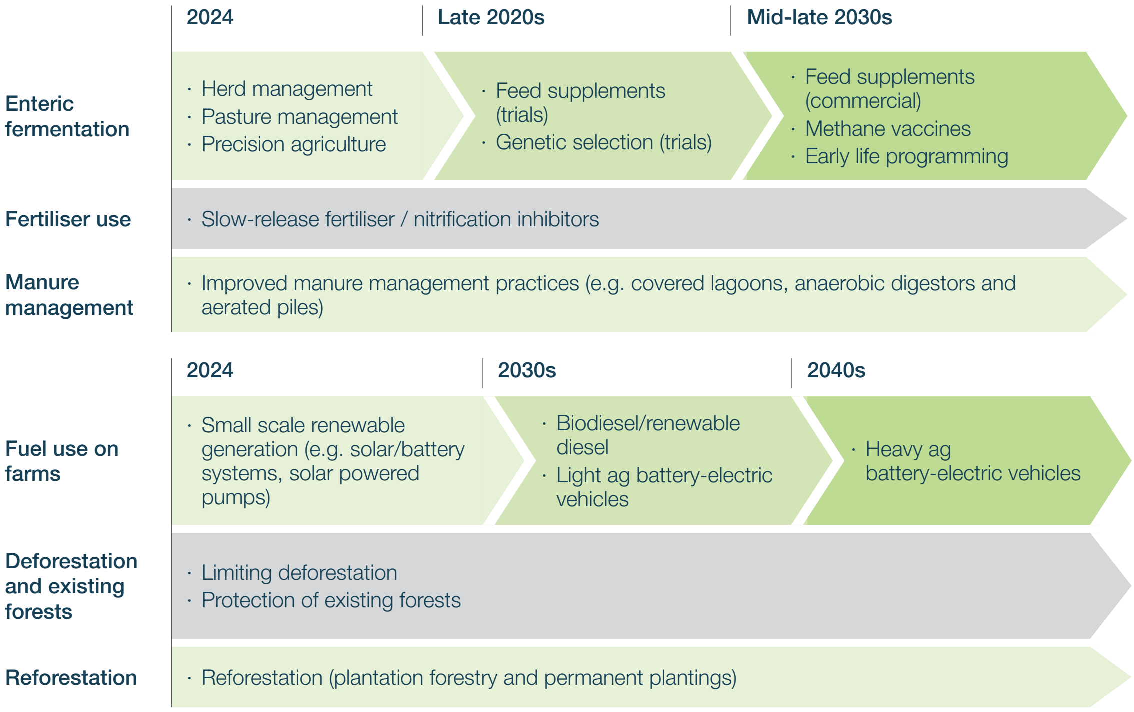
Key technologies are identified in Table AL.2 below and a possible technology deployment pathway is shown in Figure AL.1. These are presented in order of abatement potential for agriculture and land, respectively and are discussed further below.

Table AL.2: Key technologies and practices

Emissions subsector	Percent of sector emissions	Technology	Readiness	Barriers to adoption
Enteric fermentation	64% of agriculture emissions	Feed supplements	· Commercially available but further R&D required. Scale up of production of *Asparagopsis* would be required to allow for widespread adoption. · 3-NOP is commercially available and research suggests no negative effects on animal productivity (Alemu et al., 2021; De Almeida et al., 2022).	· Cost · Tech maturity · Uncertainty of productivity benefits · Scale of production · Current lack of effective delivery mechanism for pasture-based cattle and sheep
Fertiliser	7% of agriculture emissions	Slow-release and nitrification inhibitor coated fertilisers	· Commercially available	· Cost
Manure management	8% of agriculture emissions	Improved manure management practices	· Commercially available	· Cost · Awareness and capacity
Fuel use on farms	7% of agriculture emissions	Replacement of fossil fuels with renewable fuel sources or renewable electricity	· Various (commercial to developing)	· Cost · Availability · Lack of awareness of benefits · Slow equipment turnover
Deforestation[a]	2% of national emissions	Limiting deforestation / Protection of existing forests	· Well-established	· Competing land uses · Limited financial incentives
Existing forests	-3% of national emissions			
Reforestation	-10% of national emissions	Reforestation: Plantation forestry and permanent plantings	· Well-established	· Cost · Competing land uses · Land and water requirements · Supply chain limitations · Social impact · Regulatory burden

[a] Subsectoral land sector emissions proportions are a percentage of Australia's total emissions for 2021-22 (excluding LULUCF).

Figure AL.1: Prospective decarbonisation pathways for agriculture and land sector activities



AL.2.1 Feed supplements

Feed supplements can reduce emissions from enteric fermentation and show strong potential for abatement in the medium to long term. However, more research is required to firm up technical efficacy, and further efforts are needed to resolve commercialisation and implementation barriers. With the need to address supply, cost and delivery mechanisms to livestock, the authority's research indicates the technology is currently not likely to achieve extensive commercial use until the mid-to late 2030's.

The effectiveness of feed supplements can be variable, depending on dosage rates and delivery approaches. A recent study from Meat and Livestock Australia found that the inclusion of Asparagopsis-oil in cattle diets did not result in declines in methane emissions intensity when considered with declines in liveweight that counter-balanced emissions reductions (Cowley et al., 2023). Other studies have shown more promising results, with methane reduction potentials ranging from 59 to 98 per cent (Ridoutt et al., 2022). 3-NOP feed supplements have been shown to reduce emissions by 8 to 30 per cent (Black et al., 2021).

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The effective mitigation potential of feed supplements is currently limited. Most supplements are required to be delivered with feed on a regular basis, applicable in feedlot and dairy cattle production (Ridoutt et al., 2022). As a point of comparison, Australian cattle only spend a relatively short portion of their lifespan in feedlots compared to intensive cattle production systems in the US (Drouillard, 2018).

Cattle raised in pasture-based grazing systems for beef contribute approximately 60 per cent of the total emissions from enteric fermentation. The majority of grazing cattle production is located in large open rangelands in northern Australia (McGowan et al., 2020). Feed supplements can be delivered to feedlot and dairy cattle on a regular basis, however this is not currently possible in rangeland pasture systems where individual animals may not be seen for multiple years. There are currently no commercially viable solutions in the near to medium term to reduce emissions from grazing cattle herds. This is a key barrier to widespread uptake of this technology in Australian beef production (Ridoutt et al., 2022).

The estimated marginal abatement cost for delivery of feed supplements to beef cattle in feedlots, sheep on pasture and pasture fed cattle is estimated to be \$57/t CO_2-e, \$121/t CO_2-e and \$188/t CO_2-e respectively (EY, 2021). While feedlot and dairy production can feasibly adopt feed additives to reduce emissions, there remains significant uncertainty on the efficacy and cost. The authority has heard from stakeholders that the current cost of feed supplements can be up to \$2 per animal per day. At lower costs, uptake of supplements, and therefore reduction in emissions, is likely to occur sooner. New ACCU scheme methodologies could be used to encourage adoption of feed supplements.

Changes in domestic consumption towards lower emissions protein sources, including chicken and pork, may have limited impact on total beef production in Australia in the near term, with approximately 78 per cent of beef meat produced being exported (ABARES, 2024b). However, access to and the requirements of international markets and supply chains will continue to strongly influence production systems in Australia. Tools such as the EU's Carbon Border Adjustment Mechanism (CBAM) could introduce requirements for lower emissions products and may influence the requirements of other trading markets in the future. However, agricultural commodities are not currently included in the products required to buy carbon certificates under the CBAM. The shifts in food consumption and alternative, lower emissions protein sources are discussed further below.

AL.2.2 Slow-release or nitrification inhibitor coated fertilisers

Use of nitrification inhibitors can more than halve the nitrous oxide emissions produced by fertiliser applied to land (Grace et al., 2023; Meng et al., 2021). Fertilisers coated in nitrification inhibitors are commercially available but are more expensive than conventional fertilisers (Fertilizer Australia, 2023). This is likely limiting widespread adoption. The near-term marginal abatement cost of these stabilised fertilisers is estimated to be \$37/t CO_2-e (Energetics, 2019). Fertiliser coatings based on biopolymers are available that also limit risks associated with microplastics in agricultural soils and waterways (Islam et al., 2023; Witt et al., 2024).

Continued efforts to improve fertiliser use efficiency, such as through precision agriculture, could help to achieve further emission reductions, positive environmental outcomes and cost savings for farmers.

AL.2.3 Manure management practices

There are commercially available options for managing emissions from livestock manure such as anaerobic digesters, covered lagoons, aerated stockpiles and composting. These treatments directly reduce methane emissions and can enable the production of by-products that can substitute for energy from fossil fuels and chemical fertilisers.

Manure management technologies that contain and capture methane and use it as a fuel are reported to be cost negative when factoring in revenue from energy and other products (Energetics, 2019). Near-term marginal abatement costs for manure management are estimated to provide a net economic gain ranging from \$12/t CO_2-e for composting to \$250/t CO_2-e for large-scale production of biogas (Energetics, 2019; EY, 2021). Uptake of these technologies is limited by capital costs, space, the availability of concentrated, collectable manure and the relatively small size of Australia's biogas industry (Energetics, 2019). Recycling manure and other on-farm residues has the added benefit of reducing on-farm loss and waste, a key feature of a lower emission circular economy production system (Energetics, 2019).

AL.2.4 Replacement of fossil fuels in agricultural vehicles and machinery

Fossil fuel emissions from the use of diesel in agricultural vehicles and machinery comprise 7 per cent of agricultural emissions. Renewable fuels like biofuels and renewable diesel are commercially available and can replace diesel in existing vehicles but can cost 1.5 to 3 times more than petroleum fuels (Acclimate Partners, 2022). Renewable fuels will likely be the only significant option for near term decarbonisation of agricultural vehicles and machinery (Acclimate Partners, 2022; Gjerek et al., 2021). Uptake of these fuels in Australia is limited as domestic production and availability is modest and costs are high (Acclimate Partners, 2022; Gjerek et al., 2021).

The near-term marginal abatement cost for electric tractors and heavy vehicles is estimated to be \$113 and \$222/t CO_2-e, respectively (EY, 2021). It is possible that the uptake of electrified agricultural machinery may increase following the transport and mining sectors' overall trends toward the development and deployment of electrified heavy vehicles around the mid-2030s. The marginal cost of hydrogen farm vehicles in 2030 is estimated to be above \$370/t CO_2-e (Energetics, 2019).

The use of solar PV systems on farms is reported to have a near-term marginal abatement cost of -\$42/t CO_2-e (EY, 2021). There are also other existing opportunities to reduce fuel use on farms, such as through replacement of diesel water pumps with solar powered pumps. Solar powered pumps produce no emissions and have low operational and maintenance costs (Aliyu et al., 2018), with an estimated marginal abatement cost of -\$27/t CO_2-e (Energetics, 2019).

AL.2.5 Additional agriculture technologies

Beyond the key technologies listed above, there are other opportunities to reduce emissions from agriculture and store carbon in the land.

Technologies that address ruminant methane emissions are unlikely to be ready for extensive commercial use in the near term, but commercial readiness in dairy and feedlot applications is progressing. To achieve near term emissions reductions, agricultural producers may need to focus primarily on pursuing the broadest and most efficient uptake of current technologies and practices to increase productivity for given inputs (e.g. fuel and fertiliser) and therefore reduce the emissions intensity of production.

Herd management practices could yield significant emission reductions within current farming approaches and result in productivity gains. These practices include improved health management, optimised joining strategies, removal of unproductive livestock, and improved genetics among other strategies (Almeida et al., 2021; Harrison et al., 2016).

Current practices in pasture management, such as selecting specific legume or grass species for pastures, can reduce livestock emissions by improving feed quality and the presence of anti-methanogenic compounds such as fats, oils and condensed tannins (Badgery et al., 2023). However, selecting pasture species with greater emissions reduction properties may also affect productivity (Badgery et al., 2023). The authority heard from stakeholders that improving pasture species is an effective near-term opportunity to reduce emissions and is likely to be lower cost and significantly easier to deliver to livestock than currently available feed additive strategies. Vaccines targeting ruminant methanogens or methane oxidising microorganisms could become viable technologies in the future (Finn et al., 2012; Jeyanathan et al., 2014; Soder & Brito, 2023).

Precision agriculture techniques that harness new developments in agricultural equipment, spatial mapping and measurement (e.g. nutrients, soil carbon, water or salinity) technologies can optimise productivity and sustainability (Shafi et al., 2019). The purpose of precision agriculture is to provide farmers with a better means to observe, understand and manage variability in their production systems. This can be done by tailoring inputs to optimise efficiency and yield and applying enhanced land management techniques, such as limiting soil compaction through controlled traffic farming for cropping production (GRDC, 2013). Further uptake of precision agriculture techniques can be realised across areas such as viticulture, broadacre cropping, dairy and sugar cane farming (CSIRO, 2021).

Increased uptake of intensive horticultural practices and technology can also improve the efficiency of production and use of inputs such as water and fertiliser (Zhou et al., 2021). These technologies can include controlled environment greenhouses, sunlight spectrum modification and artificial lighting, arid land glasshouses and vertical farming systems (Goddek et al., 2023; Goodman & Minner, 2019; QFF, 2015). Intensive agricultural production systems have the potential to reduce land use demand and consequently rates of land clearing and associated carbon emissions (Tollefson, 2010).

Farmers and other land managers are already undertaking activities to increase carbon drawdown and storage on their land. This includes through reforestation and retaining existing vegetation, which is discussed further below. There are also other agricultural practices already used by farmers that can be scaled up to increase the storage of carbon in soils and vegetation. These include low- or no-till cropping, stubble retention, adaptive multi-paddock grazing or the application of compost and manure (Biala et al., 2021; Jayaraman & Dalal, 2022; McDonald et al., 2023; Page et al., 2020). Application of biochar to soils also has the potential to improve soil carbon storage (Woolf et al., 2010).

Increasing soil carbon can also have important productivity, soil structure and water retention benefits (Soussana et al. 2019). However, soil carbon is highly influenced by soil type, season, weather and climate (Luo et al., 2019). Some studies have also found variable or negligible long-term impacts of some agricultural practices on soil carbon stocks (Luo et al. 2010; McDonald et al. 2023). Therefore, while increasing soil carbon is an opportunity to achieve carbon and non-carbon benefits, the scale and permanence of its potential impact as a climate solution is less certain than many other land-based carbon removal opportunities.

The use of fencing around farm dams can also reduce emissions and improve water quality by reducing the production of methane from organic decomposition from manure contamination (Malerba et al., 2022).

AL.2.6 Limiting deforestation and increasing reforestation

A critical aspect of decarbonising the agriculture and land sector is scaling up nature-based solutions that store biological carbon, particularly through limiting deforestation and increasing reforestation. Beyond forests, native vegetation more broadly provides land-based carbon removal as well as valuable habitat for biodiversity. While the data and analysis presented for the sector has a primary focus on forests, the authority considers that protecting native vegetation that falls outside the government's formal definition of forests is also a critical opportunity.

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Limiting deforestation is a readily available opportunity to avoid emissions in the landscape. Australia's forests currently play a critical role in storing carbon, protecting biodiversity and providing a range of other ecosystem services (ABARES, 2018a). Limiting clearing of forests involves avoiding conversion of forests and other native vegetation into other uses. This can include forestry and land management practices that prevent degradation of carbon stocks and biodiversity in existing forests or land cleared of native vegetation. Analysis by CSIRO found that human induced regeneration of forests costs around $5/t CO_2-e and the cost of avoided deforestation is between $5 and $10/t CO_2-e (CSIRO, 2022a). More broadly, avoiding clearing of native vegetation, both within and outside forested landscapes, is an opportunity to increase land-based carbon removal.

Box AL.1: What are nature-based solutions?

Nature-based solutions are 'actions to protect, sustainably manage and restore natural and modified ecosystems in ways that address societal challenges effectively and adaptively, to provide both human wellbeing and biodiversity benefits' (IUCN, 2020). These solutions target challenges such as climate change, biodiversity loss, and water and food security, and are an opportunity to remove carbon from the atmosphere and store it in the landscape using natural sinks.

Submissions to the authority's Issues Paper supported a focus on nature-based solutions to achieve carbon removal as well as broader outcomes, such as biodiversity conservation, improved water quality and climate resilience (The Nature Conservancy, Better Futures Australia, Queensland Conservation Council submissions, 2024).

Increasing reforestation[1] is central to increasing Australia's land-based carbon removal. This can involve activities that establish large areas of new tree plantings, such as plantation forestry, agroforestry or farm forestry, and permanent plantings like carbon forestry and environmental plantings. CSIRO assessed the cost of plantation forestry is currently around $10 to $30/t CO_2-e and the cost of permanent plantings are currently around $20 to $30/t CO_2-e (CSIRO, 2022a). These costs are likely to be higher in the future as Australia is expected to require more abatement to achieve its net zero target. Reforestation can also include smaller scale revegetation projects, such as planting shelterbelts or restoring vegetation in marginal areas of agricultural land. Another practice involves allowing natural regeneration of ecosystems, though this has lower abatement potential in the near term than active planting (UNEP & IUCN, 2021). The vast majority of reforestation in Australia involves the conversion of grasslands to forest land (DCCEEW, 2024b). Other conversions such as croplands converted to forest land is a rare occurrence. It is likely that this is because the intensive management of croplands and improved pastures makes them valuable for agricultural production. This trend will likely continue and discussion of reforestation over the period to 2050 in this chapter should be read as the conversion of less intensively managed grasslands to forest.

How Australia meets demand for food, fibres and wood products while achieving climate and nature goals is an important consideration in informing land use choices. Balancing outcomes like carbon and biodiversity could involve balancing approaches that prioritise carbon through monoculture plantings and instead establishing mixed species plantings (Paul et al., 2016). It is also important to consider the water impacts of land use decisions, given current and growing pressures on water resources.

1 The Intergovernmental Panel on Climate Change describes reforestation as human-induced plantings on land that was previously forested, whereas afforestation involves planting on land that has not been previously forested for at least 50 years (Penman, 2003).

Competition for land and water resources and the potential to achieve multiple outcomes is discussed further in section AL.3 Barriers, opportunities and enablers.

Carbon stored in vegetation and soils via land-based removal is at risk of being released due to seasonal or climatic conditions, such as rainfall. This risk is exacerbated by the impacts of climate change, with the potential for more frequent and extreme bushfires, droughts and extreme weather events likely to impact the agriculture and land sector's rate of carbon removal and storage (Luo et al., 2019; Roxburgh, 2020; Viscarra Rossel et al., 2024).

AL.2.7 Expanding First Nations land management activities

First Nations people have been sustainably managing Australia's land, water and food resources through caring for Country for millennia (Janke et al., 2021). First Nations rights and interests in land are formally recognised over around 50 per cent of Australia's land mass – collectively referred to as the First Nations Estate (ABARES, 2022b). The activities of First Nations people in caring for Country currently takes many forms, including pastoral management, weed and feral animal control, cultural burning practices, threatened species management and revegetation (CSIRO, n.d.). These practices and activities positively contribute by reducing emissions and increasing land-based removal across First Nations lands. Opportunities to increase First Nations participation in the sector's workforce are discussed further in section AL.3 Barriers, opportunities and enablers. Much of Australia's renewable energy infrastructure will be located on lands where First Nations people have a legal right or interest (AEMO, 2024), presenting an opportunity for partnerships with First Nations communities (see section EE.3.4 on the electricity and energy sector pathway to net zero).

Demand for carbon dioxide removal is forecast to accelerate rapidly as Australia transitions to net zero (RepuTex Energy, 2023). Analysis in this report projects some sectors will have residual emissions by 2050 and may require offsets from sources of removal, including land-based removal, to achieve net zero emissions across the economy (see section NP.1). As identified in the authority's 2023 review of the ACCU scheme (CCA, 2023b), this represents a significant opportunity for First Nations individuals, businesses and communities to participate in and benefit from growing carbon markets.

The First Nations carbon farming industry has developed rapidly since 2006, to more than 39 First Nations-owned ACCU scheme projects generating 1.2 million tonnes of carbon equivalent abatement and $59 million in value each year (ICIN, 2024).

Savanna fire management currently represents the most significant share of First Nations-led ACCU scheme projects (ICIN, 2024). It is also a critical activity for reducing bushfire emissions, maintaining biodiversity, and storing carbon across Northern Australia (Gebbie et al., 2021). There are also a small number of First Nations-owned vegetation regeneration projects registered with the CER (ICIN, 2024).

The Indigenous Carbon Industry Network has highlighted opportunities to expand the scope of ACCU methods and projects available to First Nations peoples to practice on their lands (ICIN, 2022). There are opportunities to support greater access to caring for Country activities by First Nations people, which in turn can have positive social, cultural, economic and environmental outcomes.

AL.2.8 Other technologies and practices

AL.2.8.1 Blue carbon

Blue Carbon is the carbon captured by the world's ocean and coastal ecosystems. Coastal ecosystems generally store more carbon per hectare on average and remove carbon at a faster rate than terrestrial ecosystems (CSIRO, 2022a; UNEP & IUCN, 2021). Australia has relatively large volumes of blue carbon stocks and there are significant opportunities to restore blue carbon ecosystems that have been lost or degraded (Macreadie et al., 2021; Serrano et al., 2019). Actions such as the protection and restoration of mangrove, seagrass, saltmarsh and tidal ecosystems are an opportunity to increase blue carbon storage (McKinsey, 2022) while delivering a range of ecosystem services, such as enhancement of fisheries, water purification and coastal protection (Schindler Murray, 2023). First Nations peoples have legal or consent rights for over two thirds of Australia's coasts, presenting an opportunity for expanding First Nations leadership on blue carbon projects (ICIN, 2024).

AL.2.8.2 Shifts in food consumption patterns

Dietary preferences and consumption patterns in Australia and overseas are influenced by a range of factors, including economic conditions, culture, personal preference and health concerns (Australian Institute of Health and Welfare, 2012). The emissions impact of diets depends on a range of variables, including the type of protein consumed as well as food production and transport methods (Candy et al., 2019).

Shifts in consumption patterns that include lower emissions protein sources could represent another pathway to reducing emissions from meat production. Alternative proteins are plant-based and food-technology alternatives to animal protein.

They include food products made from plants (for example, grains, legumes and nuts), fungus (mushrooms), algae, insects, cell-cultured meat or protein from precision fermentation using yeast and other micro-organisms. Alternative proteins can be supplementary to red meat, particularly to ensure food security as global demand for protein grows (CSIRO, 2022b).

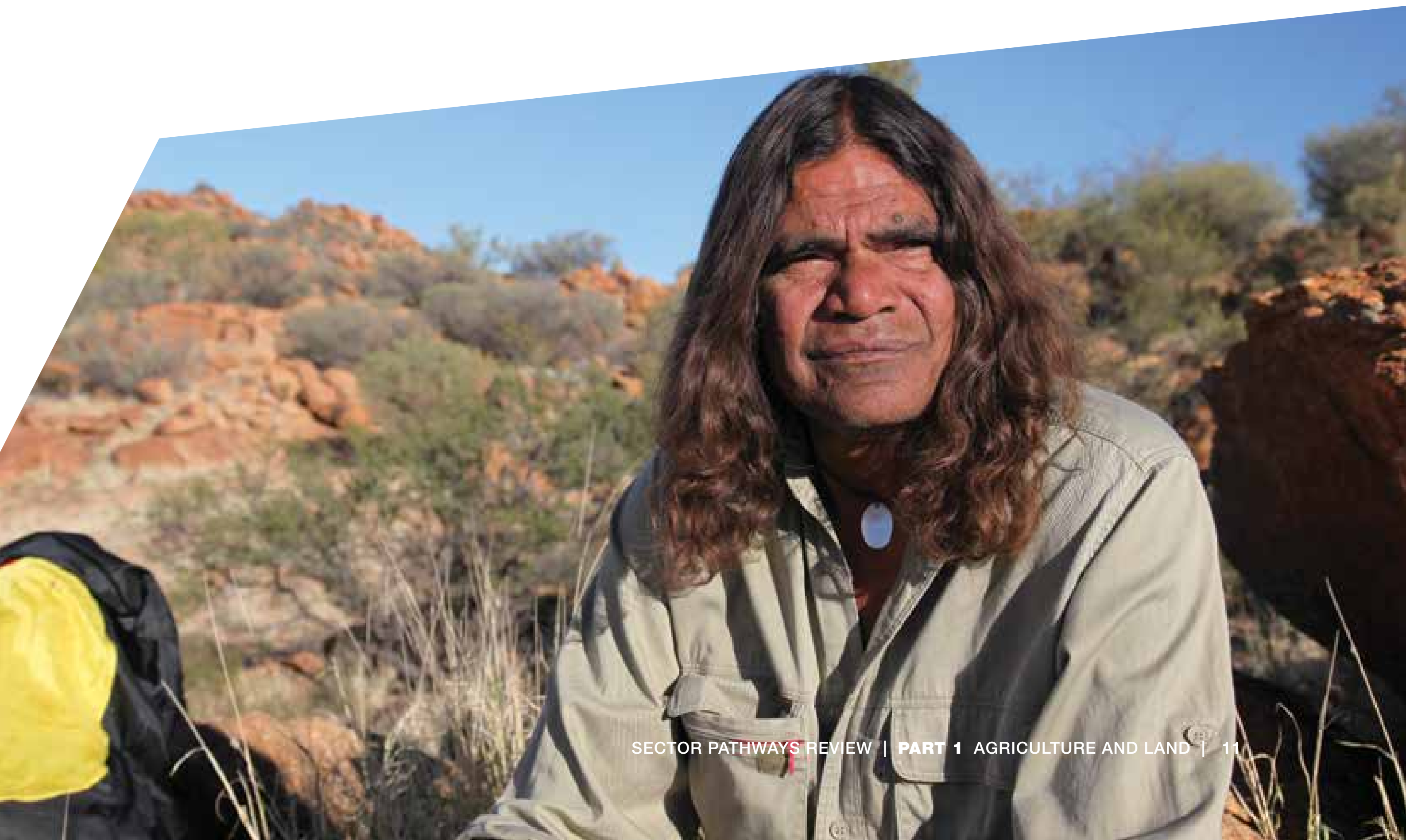
Cell-cultured protein is an emerging opportunity and currently expensive to produce in comparison to meat from livestock (Garrison et al., 2022; Specht, 2020). Costs are likely to reduce as production reaches industrial scale (Specht, 2020). Producing cultured protein may have environmental and biodiversity benefits (Treich, 2021). Cultured protein production is independent of climate and seasonal and climatic variations and can be decoupled from other risks to traditional production methods (Bajic et al., 2022). However, cultured protein requires significant amounts of electricity, and emissions benefits from switching to cultured proteins are maximised when renewable electricity is used for its production (CE Delft, 2021).

These emerging technologies require more R&D. Precision fermentation requires further development of microorganism engineering and strain development and optimisation and improvements in feedstock selection and processes (CSIRO, 2023). Cell-based agriculture requires further R&D to optimise cell culture media and identifying appropriate and sustainable cell source (CSIRO, 2023).

An emissions reduction contribution could be achieved through switching preferences away from higher-emissions products, such as beef and lamb, towards animal meats with a lower emissions intensity, such as chicken, pork and kangaroo. Australia has already seen a dietary shift towards pork and chicken and away from beef and lamb in recent decades, potentially driven by shifting consumer preferences and price (ABARES, 2019; Wong et al., 2015). Plant-based proteins, such as those in legumes, are also available now and options for plant-based 'meat' are increasing (CSIRO, 2022b).

The average Australian diet has a climate footprint of approximately 3.4 kg CO_2-e per person per day (CSIRO, 2023). Although younger Australians are likely to give more consideration to sustainability when making choices on their food, confusing options and information can present barriers (CSIRO, 2022b).

Consumption of red meat in Australia has been relatively stable, with a slight decline since 2014 (MLA, 2023). Cost is the predominant reason people reduce red meat consumption, with health and environmental concerns less significant drivers (MLA, 2023). The majority (65 per cent) of red meat grown in Australia is exported (ABARES, 2022a). Therefore, behavioural drivers and other influences on the food choices of individuals, both in Australia and overseas, are important considerations when determining potential emissions impacts of shifts in food consumption patterns. Certification of products and improved consumer information on sustainability of food can aid consumer decision-making (CSIRO, 2023).



AL.3 Barriers, opportunities and enablers

There are a range of barriers and opportunities facing the agriculture and land sector's transition to a net zero economy. These include financial, workforce, data and information, and supply chain barriers.

In considering these barriers and opportunities, it is important to acknowledge the multi-faceted task facing farmers and other land managers in the transition. This includes adapting to the impacts of climate change, evolving farming practices to improve sustainability and maintain productivity, and balance demands on their land for other uses, such as accommodating infrastructure, carbon and biodiversity sequestration. Therefore, it is important to consider the sector's unique context and develop approaches that enable farmers to adopt solutions that suit their individual circumstances.

AL.3.1 Technical constraints

There are technical and logistical barriers associated with some agricultural abatement activities, such as delivering feed supplements to cattle outside of dairy and feedlot farming systems. New solutions to ensure cattle are administered with correct dosages at required frequencies are needed to scale the use of feed additives in pasture and extensive systems.

Manure management practices are applicable to confined or semi-confined farming where manure can be stored and processed. These technologies are not viable for reducing methane emissions from pastured livestock manure where the manure is deposited directly onto pasture (Herrero et al., 2016; Rivera & Chará, 2021). Although there are options to reduce methane emissions from pasture cattle, these are likely to be impractical in the large area of pasture-based systems in Australia.

AL.3.2 Green premiums

Economically affordable emissions reductions are limited in the agriculture industry and cost is a common barrier to uptake of nearly all technologies.

Uptake of emissions reduction technologies in the agriculture industry will generally lead to increased costs to agri-businesses as most of the proposed solutions do not yet deliver consistent and significant productivity benefits. Agri-businesses are usually small to medium sized and typically have modest profit margins. Agri-business is the commercial side of agriculture, its pursuit of sustainability and the value chain that links producers and consumers (UQ, 2023). They are therefore unlikely to take on additional cost in their operations without an associated increase to productivity.

Uptake of emissions reduction technologies in the agriculture industry will generally lead to increased costs to agri-businesses as most of the proposed solutions do not yet deliver consistent and significant productivity benefits.

High costs are limiting farmers' use of feed supplements in dairies and feedlots. The authority has heard from stakeholders that the current cost of delivering feed supplements to cattle is up to $2 per animal per day. The authority also heard the cost would need to decline to 20 cents per animal per day, or alternatively ACCU prices increase to around $130/t CO_2-e, for the technology to become commercially viable at the current cost of feed additives. The National Farmers' Federation suggests this cost barrier can be overcome through an increase in the price of animal products produced with a lower carbon footprint, enhanced productivity through supplement use and/or a carbon mitigation payment (NFF, 2023b). It is likely that the limited availability of feed supplements currently in supply chains are also contributing to relatively high prices (NSW Government, 2023b).

Fertilisers coated in nitrification inhibitors are more expensive than conventional fertilisers (Fertilizer Australia, 2023) and this is preventing their widespread uptake (Folina et al., 2021).

Targeted funding for research and early-stage commercialisation of technologies could help address these challenges. In the 2023 Annual Progress Report, the authority recommended that the Australian Government fund an extensive challenge-based program of research and early-stage commercialisation of agriculture emissions reduction technologies (CCA, 2023a). This program could help to reduce cost barriers, quantify potential productivity benefits and increase uptake of emerging technologies in the sector. New ACCU scheme methodologies can also play a role in addressing cost barriers to adoption of emerging emissions reduction technologies (DCCEEW, 2024a). However, the development of new methodologies must be underpinned by robust and comprehensive research and data. Government initiatives that continue to build this evidence base, such as the MERiL Program (Minister for Agriculture, 2022), have proven to be highly effective and welcomed by stakeholders.

Other financing instruments, such as the existing research and development tax incentive, can encourage further research and development efforts (ATO, 2024). Looking beyond domestic investment, there could be opportunities to attract international research and development investment, such as from institutions like the Global Methane Hub (see more detail below). Australia could also leverage domestic public spending on agriculture mitigation solutions by connecting with similar international research initiatives.

The Global Methane Hub aims to provide $200 million in investment into research on reducing livestock methane emissions (Global Methane Hub, 2023). The research focus is on a range of topics including: exploring alternative livestock feed additives, breeding low-methane livestock, and developing a methane vaccine. This is an important suite of research which could directly benefit Australian beef producers and highlights the importance of participation in international research partnerships.

Establishment of new tree plantings can have high upfront costs and opportunity costs associated with shifting from agricultural production to timber, carbon or environmental plantings (CSIRO, 2022a). High land prices in productive agricultural areas and relatively low carbon prices are a barrier to landholders from establishing forest projects (CSIRO, 2022a), due to the potential opportunity cost of switching from one type of production to another.

Potential barriers to limiting deforestation and protection of existing forests are the limited financial and regulatory requirements to assign an economic value and factor carbon and biodiversity impacts into decision making.

Carbon and environmental markets are an opportunity to harness investment to achieve land-based carbon removal and other environmental and social outcomes. The authority has heard from stakeholders that the restoration of degraded agricultural areas could provide near-term emissions reductions, restore endangered habitats and simultaneously enhance biodiversity.

Trends in nature-related risk disclosure are following those in climate-related disclosure, with a number of food, agriculture and forestry companies committing to the Taskforce for Nature-related Financial Disclosures (TNFD, 2024). Increasing measurement and disclosure of the risks and dependencies on nature by businesses and institutions is also likely to support appropriate valuing of natural capital and biological sequestration. Other supply chain trends are also likely to influence the sector, such as new EU legislation preventing deforestation in the supply chain of key commodities, including cattle and beef products, and paper and wood products (European Commission, 2023).

Beyond preparing for these trends and the potential income gained through participation in markets, there are broader benefits of building and maintaining natural capital on farms. These include improved agricultural productivity and resilience to climate impacts and market shocks (MLA, 2024b). Continuing to grow the evidence base for these benefits can support the sector to prioritise activities that store carbon and protect nature alongside food and fibre production.

AL.3.3 Supply chain constraints

There may be logistical and supply chain barriers to establishing new forest projects at large scales. These include the cost and access to suitable land areas, and the availability of labour, skills and knowledge (CSIRO, 2022a; Whittle et al., 2019). Another key barrier is water availability, with some jurisdictions either regulating or considering water use in decision-making for new plantations, and the majority of commercial plantations being restricted to high or medium rainfall regions (ABARES, 2018a; Greenwood Strategy, 2021). These barriers may negatively impact the potential pace and scale of land-based removal achievable through reforestation.

There are potential limitations on the supply of equipment and appropriate seeds and tube-stock in large volumes for new plantings (CSIRO, 2022a). Access to timber milling is also a consideration for scaling up plantation forestry activities, as distance to mills and processing is a significant contributor to costs and consequently financial viability (CSIRO, 2022a). There is also the risk of social impacts if there are large-scale shifts in land use from agriculture to carbon farming, as highlighted in the authority's 2023 review of the ACCU scheme (CCA, 2023b).

> Balancing competing land uses is key to not only avoiding unintended consequences but also to earn social license. Stakeholders highlighted that it will be important that actions to increase land-based removal also achieve multiple benefits, like biodiversity, social and cultural outcomes.

Stakeholders have suggested that a barrier for many landholders in participating in reforestation activities and carbon markets is the complexity of the ACCU scheme and the challenge to navigate the regulatory processes (The Next Economy, 2023).

Land-based removals are likely to play a major role in Australia's pathway to net zero emissions by 2050. This, along with production of renewable fuel feedstocks, has the potential to add to the growing pressures on the land and water resources that provide food, fibre, biodiversity and cultural value. The establishment of new infrastructure to decarbonise the energy sector is also an increasingly important consideration for landholders and broader rural and regional communities, whose land or productivity may be impacted (AEIC, 2023).

Balancing competing land uses is key to not only avoiding unintended consequences but also to earn social license. Stakeholders highlighted that it will be important that actions to increase land-based removal also achieve multiple benefits, like biodiversity, social and cultural outcomes. Multiple stakeholders also raised concerns that the agriculture and land sector may not have the available carbon dioxide removal capacity to provide a low-cost source of abatement for other sectors (GrainGrowers and National Farmers' Federation submissions, 2024).

AL.3.4 Benefit sharing

Registered First Nations employment is concentrated within a small number of industries. Ninety per cent of agricultural workers who self-identify as First Nations are currently employed in regional or remote areas, primarily in sheep, cattle and grain farming (ABARES, 2023). The native food and botanicals industry as well as the carbon farming industry are already significant employers of First Nations people (Federation of Victorian Traditional Owner Corporations & Victorian State Government, 2021; Gebbie et al., 2021). Anticipated growth of these industries to support the transition to net zero has the potential to provide additional workforce and economic opportunities First Nations communities, provided benefits are shared equitably.

Acknowledgement of the non-carbon benefits of First Nations-led carbon farming projects has historically been limited to price premiums in the voluntary market (ILSC, 2022b). Sale of carbon credits generated by First Nations owned and operated projects receive a premium from buyers seeking to increase investment in businesses operating with strong 'Environmental, social, and governance (ESG)' values (ILSC, 2022a; NSW Government, 2023a). In previous submissions to the authority's 2023 ACCU scheme review, stakeholders highlighted concerns that these financial benefits do not always flow directly back to the First Nations communities (Kimberley Land Council and Wilinggin Aboriginal Corporation submissions, 2023).

The emergence of government initiatives which explicitly recognise non-carbon benefits, such as the Queensland Land Restoration Fund and the federal government's Nature Repair Market have the potential to improve the financial viability of First Nations carbon industry projects by formally rewarding caring for Country practices (DCCEEW, 2024c; Queensland Government, 2024). Associated compensation could assist projects to attract equity and diversify revenue streams, buffering against variability in carbon credit spot prices. Historically, difficulty in accessing equity has resulted in under-capitalisation of First Nations businesses, which can have flow-on effects including limiting potential for growth (Australian Government, 2018). Limited equity can also place small businesses at higher risk in the event of significant market shocks, such as the COVID-19 pandemic (Katare et al., 2021).

The benefits of growth in the First Nations carbon farming industry extend far beyond the production and sale of carbon credits. These additional benefits often referred to as 'core benefits' because of their equivalent, if not greater value to First Nations compared to carbon sequestration (Aboriginal Carbon Foundation, 2024). The financial resources generated through First Nations ownership in the growing carbon market have assisted in bringing First Nations peoples back to Country and supported the handing down of Traditional Knowledge from Elders to future generations (ILSC, 2022b). Projects can facilitate First Nations peoples to fulfil cultural obligations to look after Country. The carbon farming industry also provides meaningful and ongoing employment opportunities in very remote areas (ILSC, 2022a) where First Nations employment is as low as 51 per cent, well below the national average (Jobs and Skills Australia, n.d.).

There are also important benefits for Australia's environmental conservation and land management practices. Savanna fire management projects through the ACCU scheme have had a significant impact on the prevention of higher emissions late dry-season wildfires (Edwards et al., 2021). Environmental benefits of the broader First Nations carbon farming industry can include increased carbon storage, greater structural diversity and water yield, and increased habitat diversity and biodiversity (Gebbie et al., 2021). Incorporating First Nations cultural practices and Traditional Knowledge alongside western science can improve future land management initiatives undertaken by government and landholders (Kimberley Land Council, 2024).

AL.3.5 Information and data gaps

First Nations workers have played an important historical role in Australian agriculture, but this role has often been underacknowledged due to persistent data gaps (KPMG & NFF, 2023). According to ABARES analysis of 2021 census data, 1.8 per cent of the agricultural workforce identifies as First Nations. This represents an 80 per cent increase on the number of workers identifying as First Nations in 2016 (ABARES, 2018b). While these figures are encouraging, a proportion of this growth may be due to more accurate capture of existing workforce participants rather than onboarding of new workers. Given that the census only provides five-yearly data on First Nations participation, there is value in the agriculture and land sector considering opportunities for more frequent reporting on workforce demographics. This would assist in ensuring that First Nations contributions to the agriculture and land sector are adequately recognised and that the success of strategies to increase workforce participation can be evaluated.

Farmers are increasingly required to understand their on-farm emissions whilst managing risks to their businesses (DAFF 2023). Global and domestic agricultural markets are shifting, with increased interest in and expectations for environmental sustainability. Woolworths and McDonalds each have Science-Based Targets Initiative commitments (SBTi, 2024) and Australia's big four banks have signed the Net-Zero Banking Alliance (UNEP, n.d., 2021).

Land managers are also faced with decisions about whether to sell the carbon stored on their land into carbon offsets market or retain it for their own use. The authority has recommended landholders are provided with impartial, practical guidance and support to enable them to make informed decisions on retaining carbon for their own business, supplying the ACCU scheme offsets market, or undertaking farm forestry or other activities (CCA, 2023a). Stakeholders have welcomed funding into the Carbon Farming Outreach Program and have suggested that upskilling trusted professionals (e.g. agronomists, business and legal advisors) could enhance emissions reduction efforts as these are the experts that farmers look to for credible information and advice.

AL.4 Emissions pathways

Modelling by the CSIRO undertaken on behalf of the authority provides an indicative, least-cost pathway for the agriculture and land sector's decarbonisation based on assumed technology costs and uptake over the period to 2050 (Figure AL.2).

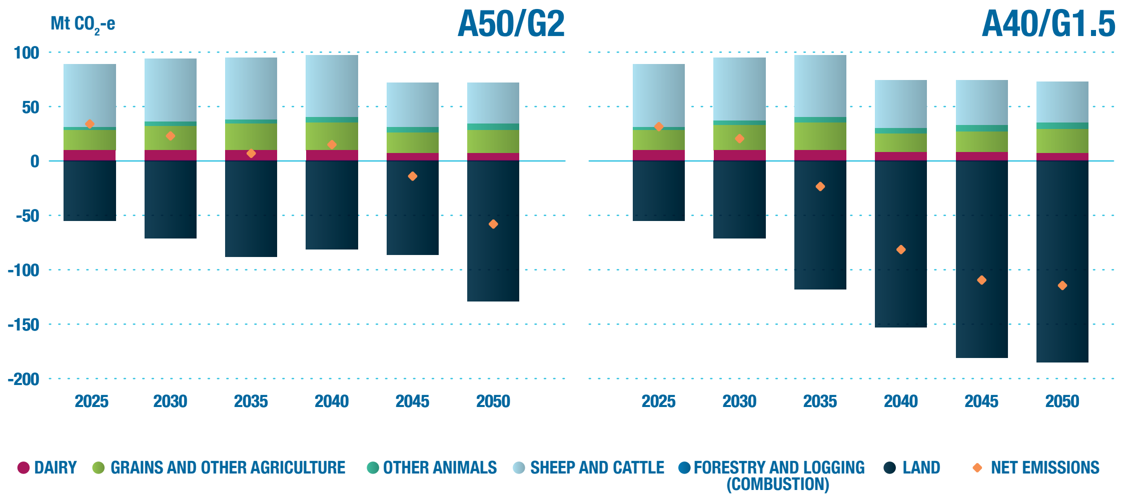
This modelling and additional analysis undertaken by the authority for this report defines agriculture and land as a single sector. This is based on the delineation of sectors by the Australian Parliament, in its referral of the sectoral pathways review to the authority (CCA, 2024). As such, net emissions for the sector are reported as combined agriculture and land emissions.

Under CSIRO's modelling, the agriculture subsector's emissions are projected to remain stable through the 2030s followed by a modest decrease to 2050 (A50/G2). Total agriculture emissions are projected to decrease by 20 per cent on current levels to 71 Mt CO_2-e by 2050.

Agricultural abatement options with significant potential are generally expensive in comparison to many other industries. The CSIRO's modelling results indicate that agriculture is slower to decarbonise and could contribute 47 per cent of Australia's gross emissions in 2050 in a net zero by 2050 scenario (A50/G2).

The land sink is projected to increase modestly (becomes more negative) to 2040 and then more than doubles by 2050, reaching approximately 129 Mt CO_2-e sink in 2050 (A50/G2). This increase is driven by the implied abatement incentive of our chosen carbon emissions trajectories. Under this scenario approximately 3 M ha of land is converted to forest to provide these projected levels of sequestration (see Table AL.4).

Figure AL.2: CSIRO's modelling projections of sources and sinks for agriculture and land sector for A50/G2 and A40/G1.5 scenarios



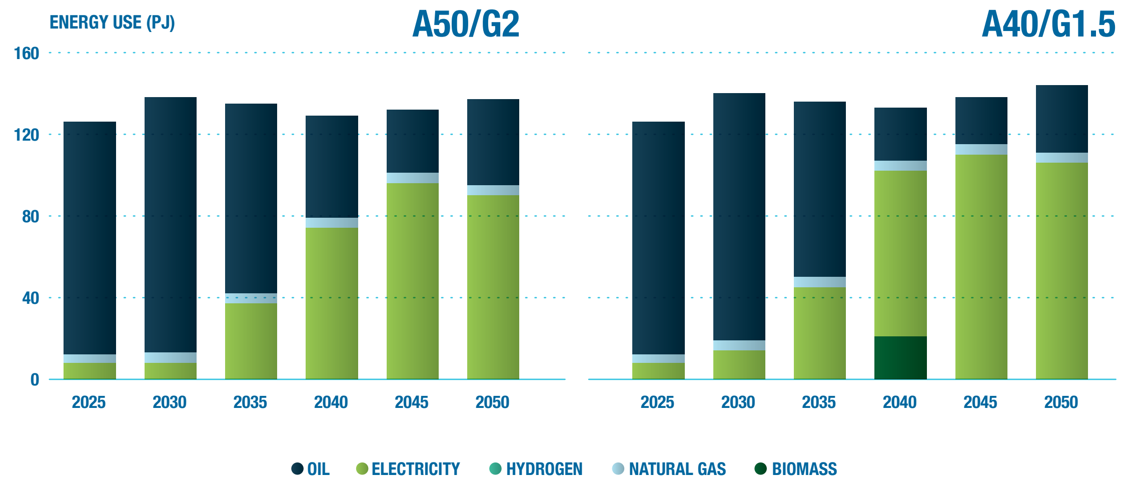
Source: CSIRO modelling in AusTIMES commissioned by the Climate Change Authority

The CSIRO modelling commissioned by the authority indicates that agriculture emissions reduce modestly to 2050, reaching 73 Mt CO_2-e. A downward trend in livestock emissions is the primary driver of these projected emission reductions, driven by the assumed deployment of technologies, such as feed supplements. Emissions from other sources remain relatively stable.

The land sink is projected to increase significantly (become more negative) through to 2050 in the A40/G1.5 scenario, providing a carbon sink of approximately 185 Mt CO_2-e. Under this scenario approximately 5.9 M ha of land is converted to forest to provide these project levels of sequestration (see Table AL.4).

Achieving the projected emission reductions in both CSIRO modelling scenarios relies heavily on the availability and uptake of feed supplements. Improvements in the emissions intensity of crop production are also assumed in this scenario through uptake of low-emissions fertilisers. However, these emissions reductions are largely offset by increased crop production from increasing crop productivity.

Figure AL.3: Energy use for the agriculture and land sector for A50/G2 and A40/G1.5 scenarios



Source: CSIRO modelling in AusTIMES commissioned by the Climate Change Authority

Oil, in the form of diesel, is projected to remain the primary source of energy in the agriculture industry across the period to 2035, with an increasing role for electric agricultural vehicles and machinery from 2040 onwards. In CSIRO's modelling of the A40/G1.5 scenario biomass pays a role as fuel in the period 2035-2040 as the model simulates the whole economy reaching net zero emissions in 2040, and draws on the necessary least-cost low emissions fuels that are assumed to be available during that period (see Figure AL.3).

The authority also undertook a ground-up analysis to estimate the abatement potential of individual technologies. The authority employed desktop research and discussion with stakeholders, including relevant experts, to identify key information and inform the analysis.

The ground-up analysis of the agriculture sector consisted of assessment of potential technology uptake rates and emissions abatement potential for priority technologies. The ground-up analysis of land-based carbon removals was based on assumptions regarding realisable planting rates, type and growth rate of plantings to calculate the potential carbon abatement. The ground-up estimates are conservative and drawn from a range of available evidence.

The ground-up analysis was limited in the number of technologies and emissions sources and did not account for complex economic or environmental interactions and processes, such as the cost implications of mitigation on competitiveness and production. Table AL.3 shows the abatement to 2050 of agriculture and land subsectors as calculated through both the ground-up and modelling approaches.

The results of CSIRO's modelling and the authority's ground-up analysis are broadly aligned on the estimated abatement potential within the sector. However, there are areas where the estimates generated by the two approaches do deviate significantly from each other.

The Grains and Other Agriculture subsector emissions increased by 3 Mt CO_2-e to 2050 in CSIRO's modelling scenarios and decreased by 2 to 4 Mt CO_2-e in the authority's ground-up estimates. This difference is due to the modelling scenarios incorporating an increase in agricultural production, which was not included in the ground-up analysis. Both the CSIRO's modelling and the authority's ground-up analysis include the assumption that cattle and sheep numbers remain around current levels out to 2050.

Projections of the existing land sink were based on the government's emissions projections in both the CSIRO's modelling and the authority's ground-up analyses. Additional environmental and carbon plantings are projected by CSIRO's model to deliver between 74 and 130 Mt CO_2-e of land-based removal in the year 2050. The authority's ground-up analysis estimates additional environmental and carbon plantings could deliver between 32 and 39 Mt CO_2-e based on lower planted area assumptions (Table AL.4).

Table AL.3: Projections of emissions reductions to 2050 using estimates from AusTIMES modelling and ground-up analysis

	Projected emissions reductions to 2050 ($Mt\ CO_2$-e)[a]		
Reference: Emissions were -3 Mt CO_2-e in 2022	**AusTIMES and LUTO modelling (A50/G2 scenario)**	**AusTIMES and LUTO modelling (A40/G1.5 scenario)**	**Ground-up estimate**
Sheep and cattle	19	19	7 to 23
Dairy	3	2	2 to 6
Fuel use	5	5	5
Other animals	-3	-3	2
Grains and other agriculture	-6	-7	2 to 4
Agriculture total	18	16	18 to 40
Management of existing land and forests	1	1	-8
Additional Environmental and carbon plantings	74	130	32 to 39
Land total	75	130	24 to 31
Agriculture and land total	92	146	42 to 71

[a] Abatement was calculated as the difference between base year emissions and the projected 2050 emissions from each model. In AusTIMES the base year for the abatement calculation is 2025 and in the ground-up estimates the base year is 2022.

Table AL.4: Area of additional planted forests in CSIRO modelling and ground-up analysis

	Projected area of additional environmental and carbon plantings (million hectares, M ha) in 2050
CSIRO for CCA – A50/G2	3.0
CSIRO for CCA – A40/G1.5	5.9
Ground-up	2.6
Reference point – area of planted forests in Australia in 2023*	2.1

**Source: State of the Forests Report 2023*

AL4.1 Residual emissions

CSIRO modelling commissioned by the authority indicates that by 2050 there are residual agriculture emissions remaining in even the most ambitious scenarios. There could between around 71-73 Mt CO_2-e of residual emissions from agriculture in 2050 under the A50/G2 and A40/G1.5 scenarios respectively. The CSIRO's modelling scenarios indicate that the largest sources of residual emissions in 2050 would be from enteric fermentation, grains and other agriculture. The authority's ground-up analysis indicated residual emissions from enteric fermentation in the range 26 Mt CO_2-e to 46 Mt CO_2-e in 2050.

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