IntegrityAg

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Commercial in Confidence

Livestock Emissions Baseline and Emissions Reduction and Removals Pathways

Landscapes Hills and Fleurieu

Executive Summary

Background: The Hills and Fleurieu region of South Australia supports a diverse range of agricultural industries central to the region's economy and land use. With a strong ethos of environmental stewardship and climate resilience, the Landscapes Hills and Fleurieu Board (LHF) has committed to achieving net zero agricultural emissions by 2050. This ambition is underpinned by a series of strategic initiatives, including farm-level emissions profiling, soil and vegetation carbon stock assessments, and the development of tailored emissions reduction guidelines for producers.

To support this vision, LHF has partnered with Integrity Ag to consolidate existing research and model practical, cost-effective Emission Reduction and Removal (ERR) pathways. These efforts are designed to reflect the realities of local production systems. The ERR pathways incorporate both established and emerging mitigation options, offering producers and policymakers a clear roadmap to reduce emissions without compromising on productivity.

Emission baseline: This report estimates greenhouse gas (GHG) emissions for the Hills and Fleurieu region using Scope 1 emissions only, which include direct on-farm sources such as methane from livestock and nitrous oxide from fertiliser use. In line with regional carbon accounting practices in Australia, Scope 2 and 3 emissions were excluded due to their potential for double counting. Emissions were calculated using the Greenhouse Gas Accounting Framework (GAF) tools, which align with national inventory methods and were updated to include the most recent global warming potential values (Forster et al., 2021). Activity data specific to the region was sourced from the Australian Bureau of Agricultural and Resource Economics (ABARES), South Australian GHG Inventory activity data, and other publicly available data.

The emissions baseline estimates for each sector are shown in Table 1. These reflect the main component of agricultural emissions, enteric methane, being driven by feed intake.

Table 1: Baseline emissions for the major livestock sectors in the Hills and Fleurieu region

Sector	Baseline emission (t CO_2-e) estimate
Dairy	114,630
Beef	85,900
Sheep	57,800

Pathways: A business-as-usual (BAU) and two emissions reductions pathways, conservative and ambitious, were developed. The BAU pathway was based on historical emissions trends over a recent period with consistent animal numbers. Assumptions for the conservative and ambitious pathways differed only in the adoption levels assumed, no increases in mitigation effectiveness of products or significant changes to the system mix were included.

Table 2 includes results showing the impact of available options on emissions reduction, comparison to the business-as-usual pathway, and the extent of tree planting required to achieve net zero under the different pathways.

Across all sectors, the most effective ways to reduce emissions over time was to focus on the biggest contributing source of emissions, enteric methane, and to target these emissions firstly through enzyme inhibitors, followed by rumen modifiers. For all sectors, productivity and genetic gains made up the next largest contributors to emissions reductions.

In all cases, substantial areas of tree planting are required to achieve net zero. Across all three sectors the total planting area required to achieve net zero represents 12.2% and 11.0% of the grazed modified pasture area in Hills and Fleurieu (216,600 ha), in the conservative and ambitious pathways, respectively. Reductions in emissions compared to business-as-usual decrease the total area of tree planting required to achieve net zero across the three sectors by 12.2% in the conservative pathway and 20.6% in the ambitious pathway. Thus, the greater the efforts towards emissions reductions, the more attainable it is to achieve net zero through tree planting.

Table 2: 2050 emissions, percent reductions compared to BAU and tree planting area required to achieve net zero across sectors and pathways

Sector/ pathway	2050 emission (t CO_2-e)	Percent reduction compared to 2050 BAU	Hectares of tree planting required to be net zero in 2050
Dairy			
BAU	123,230	--	13,330
Conservative	109,950	10.8%	11,890
Ambitious	99,910	18.9%	10,800
Beef			
BAU	92,350	--	9,990
Conservative	78,740	14.7%	8,510
Ambitious	69,620	24.6%	7,530
Sheep			
BAU	62,140	--	6,720
Conservative	55,390	10.9%	5,990
Ambitious	51,050	17.8%	5,520

Conclusions/Recommendations: Achieving net zero across all sectors will require extensive tree planting, along with feed-based interventions such as enzyme inhibitors and rumen modifiers and productivity and genetic improvements. The potential emission reductions may be higher than projected if technologies under development have greater effectiveness than assumed here and/or there are at least partially additive interactions between feeding strategies. Investigating the productivity benefits of rumen modifiers in Hills and Fleurieu systems could improve near term adoption of these products. Understanding current farm practices is essential to accurately estimate emissions and track reductions over time. Other near-term actions are developing a robust Measurement, Monitoring, Reporting and Verification (MMRV) framework for regional-level tracking and supporting farm-level reporting that achieves business objectives.

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1 Introduction

The Hills and Fleurieu region of South Australia is a diverse and productive agricultural landscape, home to a wide range of farming systems that play a central role in the region's economy and land use. With a strong commitment to environmental stewardship and climate resilience, the region is actively pursuing strategies to reduce greenhouse gas (GHG) emissions across its agricultural sectors.

This report presents an assessment of baseline GHG emissions and outlines potential pathways for emissions reduction and removal (ERR) across the region's beef, sheep, and dairy industries. It builds on previous work undertaken in the region, including farm-level emissions profiling and efforts to identify practical, cost-effective mitigation options through industry-specific guidelines and marginal abatement cost analyses. By consolidating existing data and modelling future scenarios, this project aims to provide a clear and actionable roadmap for emissions reduction that reflects the realities of local production systems.

The ERR pathways developed and outlined in this report are designed to support LHF's long-term vision for climate resilience, sustainable land management, and the target of net zero emissions by 2050. These pathways incorporate a range of mitigation options—some already in use, others emerging—and consider both conservative and ambitious adoption scenarios. Designed to inform decision-making at both the regional and farm levels, the pathways enable producers and policymakers to prioritise actions that deliver meaningful emissions reductions while maintaining productivity.

2 Emissions Baselines

The three main GHG's produced by agriculture are methane, nitrous oxide, and carbon dioxide, unlike industrial, residential, or other commercial sectors that are dominated by carbon dioxide emissions. The major GHG emission in ruminant livestock sectors (cattle, sheep) is methane.

Emissions that occur on the farm such as enteric methane emissions from cattle, are called Scope 1 emissions. Scope 2 emissions are the emissions associated with the generation of electricity used on farms. These emissions make up a small proportion of the emissions in extensive beef and sheep farms. The emissions associated with the production of products used on farm are referred to as Scope 3 emissions. Figure 1 illustrates the emission scopes for agricultural producers.

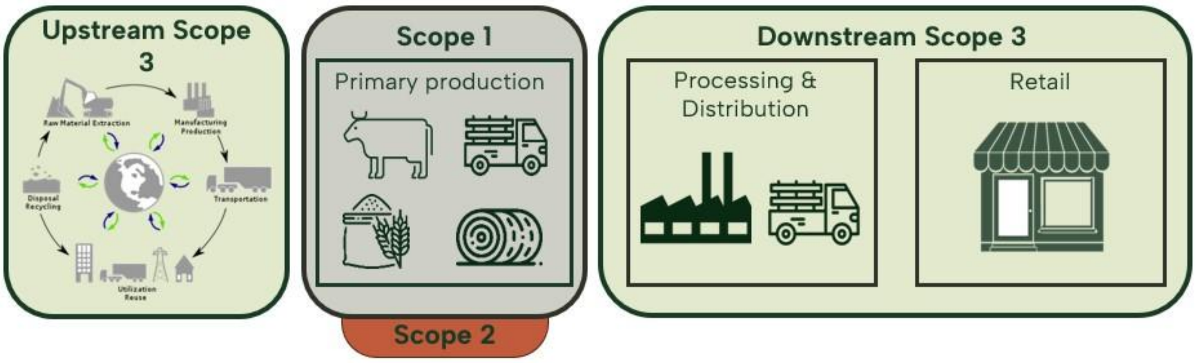

Figure 1: Emission scopes 1, 2, and 3 for agricultural producers

The emission baseline estimates for the Hills and Fleurieu region are for Scope 1 emissions, which is consistent with the Australian National Greenhouse Gas Inventory (NGGI) methods approach when calculating emissions at a regional level for the agricultural sector. Both Scope 2 and 3 emissions were excluded from this regional analysis to avoid double counting. Additionally, Scope 2 emissions will be negligible within a few years, as South Australia is on track to achieve its 100% renewable electricity target in 2027. Scope 3 emissions will either originate from outside the Hills and Fleurieu region or be included as Scope 1 emissions from other entities within the region.

The Greenhouse Gas Accounting Framework (GAF) calculators were used to estimate emissions for three livestock sectors: dairy, beef (farm and feedlot) and sheep. These calculators contain the calculations from the Australian NGGI and are thus consistent with national accounting methods. The GAF tools were updated to include the most recent GWP_{100} values of 27 for methane and 273 for nitrous oxide (Forster et al., 2021). These factors were used to convert methane and nitrous oxide to CO_2-equivalent (CO_2-e) amounts.

The primary inputs, known as 'Activity Data', that were used to calculate industry-specific emissions were sourced from ABARES data for the Hills and Fleurieu region. Herd structures for the region were assumed to be similar to the average beef, sheep and dairy farms in South Australia. Use of lime was based on the total for the region, allocated primarily by land area and the intensity of farming, with dairy regions applying higher rates than other sectors, due to more intensive pasture management.

Fertiliser and fuel use rates were extrapolated from data available from the South Australian Dairy Farm Monitor project for dairy and Southwest Victorian Livestock Farm Monitor project for sheep and beef. Use of mineral supplementation was considered non-material and excluded for all sectors.

2.1 Dairy

The baseline emissions estimate for dairy is shown in Table 3. As an intensive farm production system, dairy had the highest emissions of the three sectors, despite lower total animal numbers and land area than beef. This is driven primarily by the increased feed intake of dairy cattle, greater manure methane outputs and higher inputs to support feed requirements. Lactating animals have higher energy requirements and higher feed intake, which produces greater methane emissions. Additionally, herd structures are different, with over half the dairy herd consisting of adult milking cows, compared to beef systems that have less than 40% adult animals.

Given the publicly available data this is based on, it is unsurprising that the emission profile is generally as expected for a dairy farm. Enteric methane accounts for the largest proportion of emissions–though less than for beef or sheep, while manure methane represents a larger proportion than those sectors.

Table 3: Dairy emissions baseline with predominant emissions sources

Emission type	Emission (t CO_2-e)	Percent
CH_4 – Enteric methane	77,650	68%
CH_4 – Manure management	12,510	11%
N_2O – Leaching and runoff	8,200	7%
N_2O – Direct fertiliser	5,650	5%
N_2O – Urine and dung	4,040	3%
CO_2 – Fuel	2.030	2%
N_2O – Atmospheric deposition	1,930	2%
CO_2 – Lime	1,170	1%
Total (major emission sources)	**113,180**	**99%**
Total (all emission sources)	**114,630**	**100%**

Listed emissions are from sources that contribute >1.0% to the emissions profile.

2.2 Beef

The baseline emissions estimate for beef is shown in Table 4. Beef had the second highest emissions of the livestock sectors investigated. Although there are fewer beef cattle than sheep, emissions are driven by feed intake and thus cattle, which are larger and eat more, have greater emissions than sheep.

Given the publicly available data this is based on, it is unsurprising that the emission profile is generally as expected for beef. Enteric methane accounts for the largest proportion of emissions (84%) with manure management (5%) and urine and dung (4%) comprising the next largest contributors to emissions.

Table 4: Beef emissions baseline with predominant emissions sources

Emission type	Emission (t CO_2-e)	Percent
CH_4 – Enteric methane	72,550	84%
CH_4 – Manure management	3,820	5%
N_2O – Urine and dung	3,610	4%
CO_2 – Lime	2,710	3%
N_2O – Leaching and runoff	2,010	2%
Total (major emission sources)	**84,680**	**98%**
Total (all emission sources)	**85,900**	**100%**

Listed emissions are from sources that contribute >1.0% of the emissions profile.

2.3 Sheep

The baseline emissions estimate for sheep is shown in Table 5. Given the lower intakes of sheep compared to cattle it is expected that the sheep sector would have the least emissions of the major livestock industries in the Hills and Fleurieu region.

Given the publicly available data this is based on, it is unsurprising that the emission profile is generally as expected for sheep. Enteric methane accounts for the largest proportion of emissions (81%) with urine and dung (5%) comprising the next largest contributor to emissions.

Table 5: Sheep emissions baseline with predominant emissions sources

Emission type	Emission (t CO_2-e)	Percent
CH_4 – Enteric methane	46,540	81%
N_2O – Urine and dung	3,060	5%
N_2O – Leaching and runoff	2,490	4%
CH_4 – Manure management	2,340	4%
CO_2 – Lime	1,530	3%
CO_2 – Urea	660	1%
Total (major emission sources)	**56,610**	**98%**
Total	**57,800**	**100%**

Listed emissions are from sources that contribute >1.0% of the emissions profile.

3 Emissions Reduction and Removal Pathways

There were two pathways assessed: a conservative and an ambitious pathway. The conservative pathway had lower maximum adoption rates and/or slower uptake, therefore maximum adoption was reached later. The ambitious pathway assumed stronger market drivers, more extensive and effective engagement, and/or regulatory requirements resulted in greater adoption rates. Descriptions of the mitigation options and the pathway assumptions and results for dairy, beef and sheep are provided in this section.

The conservative and ambitious scenarios were compared to a business-as-usual (BAU) emissions trajectory, which was based on recent historical emissions trends during a period of stable livestock numbers. It should be noted that impacts outside of historical variability, for instance substantially increasing lime applications in the future, would not be captured in the BAU scenario. The BAU also assumes no emissions of CO_2 or removals of CO_2 from the atmosphere in the land sector. This means natural regeneration or restoration activities, excluding tree planting scenarios described below for the pathways, will offset any losses of forest carbon elsewhere. This is most realistic if clearing is minimised.

3.1 Emissions reduction and removal options

3.1.1 Productivity improvements

Increased production efficiency leads to emissions reduction per unit of product produced (kg of meat, litre of milk, etc) and can be achieved through better feed conversion, higher reproductive efficiency, and reduced mortality. For example, increasing average daily gain shortens the time to market, reducing lifetime emissions. Similarly, improving weaning or calving rates and minimising unproductive animals ensures that more output is achieved from fewer inputs. Additionally, productivity gains per animal can help reduce emissions when the percentage of 'maintenance emissions' from animals are reduced as a portion of total production. Maintenance emissions refer to non-productive periods in an animal's life, such as dairy heifers prior to milking age. These efficiency gains, driven by genetics, nutrition, and management, offer both environmental and financial benefits.

There are trends suggesting increasing efficiency gains are possible in livestock systems (Beukes et al., 2010; Karanja et al., 2012). Efficiency gains are critical to ensuring future emissions do not increase more than BAU projections as demand increases (Moate et al., 2015; National Farmers' Federation, 2019). It is assumed here that emissions reductions possible through efficiency gains are limited for all sectors for two reasons. Firstly, the BAU emissions trajectories used in this report are based on historical data that incorporates efficiency gains over time, meaning that the future BAU scenario also has efficiency gains embedded into it and will need ongoing productivity improvements to be realised. Secondly, climate change impacts are creating a more challenging environment for farmers to maintain production, meaning greater efficiencies are needed to maintain production levels (Bell et al., 2012; Hochman et al., 2017; Karanja et al., 2012). A conservative assumption has therefore been used regarding the impact of production efficiency on total sector emissions.

3.1.2 Genetics

The genetics option in the pathways are focused on traits that are known to reduce emissions, including the selection of animals that produce less methane per unit of product produced. These options will reduce emissions over the current methods of selection, and therefore are in addition to gains achieved through genetic selection for productivity. Genetic options have the advantage of the emissions reductions being cumulative.

Since there are currently dairy bulls ranked on the Sustainability Index (SI) it is assumed that small gains could be achieved starting in 2028 with increased selection incorporating the SI starting in 2026. Since further research is needed to develop and validate indices based on methane production in the beef and sheep sectors, the start of adoption has been delayed in these sectors—until 2030 for beef and 2035 for sheep. The emissions reductions per year are scaled based on research by Nguyen et al (2023).

3.1.3 Enteric methane: enzyme inhibitors

These options reduce methane by inhibiting enzymes necessary for enteric methane production. They have demonstrated high effectiveness (>40%) in cases where the inhibitor is mixed into every bite of food, as seen in feedlots (Almeida et al., 2023; George et al., 2024). Currently, options that can be applied in extensive systems are in development. Enzyme inhibitors are typically more expensive than other feed options and generally have less support for a productivity benefit (Almeida et al., 2023; Glasson et al., 2022). However, it is assumed that market drivers and other requirements will encourage adoption of these options in a proportion of the herd or flock due to their greater methane reductions.

The assumptions for this option are based on products such as Bovaer and Asparagopsis. Adoption in extensive systems will begin to occur in 2030 and it is assumed this product is less effective than what is achieved in feedlots though still higher than other feed additives. It is also assumed that most animals would be fed either an enzyme inhibitor or a rumen modifier by 2050. The combined adoption rate of enzyme inhibitors and rumen modifiers never exceeds 85%, as no individual animal is administered both supplements. This is due to the limited understanding of the effects of using these feed additives in combination.

3.1.4 Enteric methane: rumen modifiers

Rumen modifiers alter the rumen environment and microbial activity in ways that either reduce methanogenesis directly or limit the availability of substrates needed for methane production. Reductions in methane with these products is typically less than 30% (Batley et al., 2024; Belanche et al., 2020; Roque et al., 2019). However, they do not need to be included in every bite of food and can currently be used in extensive systems. Rumen modifiers are generally cheaper than enzyme inhibitors and there is better support for productivity benefits in some rumen modifiers (Belanche et al., 2020; Prathap et al., 2024).

The assumptions for this option are based on products such as Agolin, Mootral, and Polygain. Adoption can occur in all systems from the first year. It is assumed the maximum adoption of rumen modifiers will be reached faster, by 2040, in the ambitious scenario, since systems with a productivity benefit will likely adopt this option sooner.

As time goes on there will be increasing demand for options providing greater reductions in emissions. As mentioned in the previous section, it is assumed that most animals would be fed either an enzyme inhibitor or a rumen modifier by 2050.

The combined adoption rate of enzyme inhibitors and rumen modifiers does not exceed 85% as animals are not given both supplements.

3.1.5 High concentrate feed in cattle

Increased grain in the diet reduces methane production relative to dry matter intake (Almeida et al., 2025), and increases average daily gain (Wiedemann et al., 2015). These factors contribute to lower lifetime emissions from grain finished cattle (Wiedemann et al., 2017). The specifics of the situation will determine if this option is cost effective. As with all options that increase grain in the diet, consulting a nutritionist is recommended to avoid the risk of acidosis.

In the conservative pathway, increases in grain feeding occur at the historic rate of growth in the proportion of animals going to feedlots. In the ambitious pathway there is an additional modest increase in grain feeding on farms that is limited to those that can provide supplementary feed in a way that can be measured. This on-farm grain feeding has lower mitigation effectiveness compared with high concentrate feed in feedlots due to the lower grain content over time.

3.1.6 High wheat concentrations in dairy diets

Dairy diets are already high in concentrates, leaving limited room to increase grain content without negative effects. However, wheat feeding can further reduce methane emissions without lowering milk yield. Feeding 6 kg of wheat per day for 8 weeks reduced methane emission per dry matter intake by 10.6% (Moate et al., 2020). Because the rumen adapts to this strategy, it is conservatively assumed that it is applied for 8 weeks per individual animal. For example, this means that in a herd with a 5-year average lifespan, around 20% of cows would be eligible for wheat feeding each year. The specifics of implementation—including herd structure and timing—must be considered to assess cost, which will also depend heavily on the price difference between wheat and the grain it replaces. Given the high grain inclusion rate, consultation with a nutritionist is essential to avoid acidosis. Due to these constraints, minimal adoption was assumed in the conservative scenario and modest adoption in the ambitious scenario.

3.1.7 Increased fat in grass-fed animals

Increasing the fat content of grass-fed animals has been shown to reduce methane emissions (Beauchemin et al., 2020; Patra, 2014). The specifics of a given situation such as the cost of the supplement and the likely associated productivity gains need to be assessed to determine the cost effectiveness of this option at the farm level. It is also important to understand the source, as some fats can affect market access and be associated with high Scope 3 emissions. Although they were not addressed in these pathways, fats with high Scope 3 emissions will detrimentally impact the amount of emissions per unit of product.

This option was not included for the dairy pathways as they tend to provide the maximum recommended fat content of about 7%. Given the requirement to be able to measure supplementary feeding, it is assumed adoption will be minimal in the conservative pathway and modest in the ambitious pathway. Given the low maximum adoption it is assumed it will be reached before 2050.

3.1.8 Brassicas

Forage crops including canola and forage rapeseed have demonstrated emissions reductions in cows and sheep (Della Rosa et al., 2022; Storlien et al., 2015; Sun et al., 2016). This option requires existing cropping areas and provides an emissions reduction for part of the year, typically a season. Development of verification methodology is required for this option. Because there is difficulty determining Brassica intake, adoption for this option starts in 2030 for dairy and sheep.

3.1.9 Balancing energy : protein ratios in dairy diets

Ensuring a good energy : protein balance, particularly in spring when crude protein content of pastures is high, reduces the nitrous oxide emission losses from urine in dairy systems (Christie et al., 2014). A farm-specific analysis is required to determine if the cost and implementation of increased grain in the diet in spring will be offset by the associated increase in milk production. A nutritionist is recommended when increasing the grain content of the diet to avoid the risk of acidosis.

It is assumed this option is well known and given the potential for increased milk production, adopted in many systems. Thus, further opportunities are limited. The pathways assume remaining gains will be achieved by 2035 in the conservative scenario and 2031 in the ambitious scenario.

3.1.10 Optimal fertiliser use

Reductions in the use of fertiliser and targeted application both spatially and temporally reduce nitrogen losses and nitrous oxide emissions associated with fertiliser application (Abalos et al., 2022; Rosas et al., 2015). The assumption was that the reduction in fertiliser use would not impact productivity, and therefore a conservative estimate of nitrous oxide emissions reductions was applied. Given this is an option that saves money, it is assumed that there is limited potential for further gains. Therefore, the remaining emissions reductions that are possible without impacting production will occur by 2035 in the conservative and 2030 in the ambitious pathway. It is assumed these gains continue to 2050, meaning the practice changes that are implemented by 2035 continue, but no further reductions are possible.

3.1.11 Inhibitor-coated fertilisers

A moderate effectiveness of nitrification coated fertilisers was assumed (Puttanna et al., 1999). The conservative pathway assumes an intermediate amount of implementation due to determination of the situations in which these products provide a return on investment leading to adoption in those circumstances. The ambitious pathway can be thought of as an optimistic case in which these products are profitable on double the area of the conservative pathway, or incentives become available that double the maximum adoption.

3.1.12 Anaerobic digestors in dairy systems

Anaerobic digestors capture methane from effluent and convert it to energy. They are highly effective at reducing manure methane emissions. They are feasible and can provide a return on investment in large operations. Minimal adoption was assumed for the conservative pathway and modest adoption was assumed for the ambitious pathway.

For the ambitious pathway this is equivalent to implementation by less than 10 farms large enough to support the technology.

3.1.13 Renewable energy

Given the exclusion of Scope 2 emissions, no reductions were associated with on-farm renewables replacing grid energy. The historic trend and goal for 100% renewable grid by 2027 suggest there will be no Scope 2 emissions from the grid as of 2028.

The ability of renewables to reduce Scope 1 emissions was assumed to begin in 2035 with availability of electric tractors that meet farmers' requirements. There are several benefits of these tractors aside from reduced emissions including self-driving, which saves labour costs, and eradicates fumes and noise. It is likely some farmers will switch to electric tractors based on these benefits. Thus, a modest uptake is assumed in the conservative pathway and an intermediate uptake assumed in the ambitious pathway.

3.1.14 Carbon sequestration in vegetation

The regional average carbon sequestration rate (FLINTpro, 2024) was used to determine the number of hectares of vegetation required to achieve net zero emissions by 2050. These rates started off low in year one and increased to a maximum of 14.3 tonnes of CO_2-e in year 6 before slowly declining as trees reached maturity. At 25 years the average sequestration rate was 4.2 tonnes of CO_2-e.

It was assumed that planting rates would intensify over time, with annual increases in the area of trees planted. Due to this and with the aim of the analysis being to plant a sufficient area of trees to achieve net zero by 2050, substantial sequestration would continue beyond 2050 under these scenarios. Although older plantings would reach maturity and enter a phase of declining sequestration over time, later plantings, that cover a larger area, would continue to drive the accumulation of carbon stocks in vegetation. Thus, the year with the largest area of planting, 2050, will contribute substantial sequestration when the maximum sequestration rate is reached in 2056. Sequestration occurring after 2050 is not included in this analysis.

3.2 Dairy

The assumptions for the conservative and ambitious pathways for dairy are displayed in Table 6 and the resulting emissions trajectories, including carbon sequestration in tree plantings, are shown in Figure 2. The conservative pathway reduces emissions compared to BAU by 10.8% while the ambitious pathway reduces emissions compared to BAU by 18.9%. This equates to a 0.43% per year and a 0.76% per year emissions reduction over 25 years. Like all pathways, enzyme inhibitors contributed the most to this emissions reduction, 6.1% in the ambitious pathway in 2050. This was followed by rumen modifiers at 3.4%. The lower percentage contribution of enzyme inhibitors compared to other sectors is due to an assumed preference for rumen modifiers that have evidence for improving productivity in dairies. Productivity improvements and genetics have the next greatest contribution to emissions reduction. The assumption of methane emissions being included in breeding decisions earlier than other sectors results in genetics contributing slightly more than it does for beef and noticeably more than in sheep. Under the ambitious pathway, anaerobic digesters contribute a 1.2% reduction in emissions by 2050 and replacing diesel with renewable options, such as electric tractors, solar pumps, etc leads to a 0.9% reduction in emissions by 2050 in dairies.

Assuming regional average sequestration rates in tree plantings, the amount of land that would need to be planted over 25 years for the conservative and ambitious pathways are 11,890 ha and 10,800 ha, respectively. In the ambitious pathway this starts at 33 ha in 2026 and increases to 831 hectares in 2050. High levels of tree planting are more realistic for extensive sheep and beef systems with larger land parcels, than for dairy systems. For example, this area of tree planting represents 45.9% and 41.7% of dairying land area for the two pathways, respectively, and is unrealistic. However, it is potentially achievable over the area of grazed modified pastures (5.5% and 5.0%, respectively). This would suggest that tree-planting would need to be extended beyond dairy sector lands to achieve net zero and may be possible if these plantings occur on the grazed modified pastures used for sheep and beef production. The benefits of trading carbon credits between agricultural businesses have been previously proposed and has several benefits, including ensuring credits generated from biological sources offset emissions from biological sources, as opposed to fossil fuels (Parliamentary Commissioner for the Environment, 2019).

Table 6: Dairy – assumptions for the conservative and ambitious emissions removal pathways

Option	Conservative		Ambitious	
	Timeframe	Maximum additional adoption	Timeframe	Maximum additional adoption
Productivity (cumulative)	2026–2050, maximum adoption in 2040	Minimal, remaining improvements that reduce emissions	2026–2050, maximum adoption in 2035	Minimal, remaining improvements that reduce emissions
Genetic gains (cumulative)	2028–2050	Intermediate	2028–2050	High
Enteric methane, Enzyme inhibitor	2030–2050	Modest	2030–2050	Intermediate
Enteric methane, Rumen modifier	2026–2050	Intermediate	2026–2050, max reached in 2040	Considerable
Brassicas	2030–2050	Minimal, and 3 months a year	2030–2050	Modest, and 3 months a year
Wheat feeding	2026–2050	Minimal and for 8 weeks per cow	2026–2050	Modest and for 8 weeks per cow
Balancing energy: protein ratio	2026—2050, maximum in 2035	Modest, and 4 months of the year	2026–2050, maximum in 2031	Modest, and 4 months of the year
Anaerobic digestors	2030–2050	Minimal	2030–2050	Modest
Optimised fertiliser use	2026–2050, maximum adoption in 2035	Modest since largely adopted	2026–2050, maximum adoption in 2030	Modest since largely adopted
Inhibitor coated fertiliser	2026–2050	Intermediate	2026–2050	Considerable
Electric vehicles/ tractors	2035–2050	Intermediate	2035–2050	Considerable

Minimal: ≤5%; Modest: >5.0–<20%; Intermediate: 20–<40%; Considerable: 40–<60%; High: 60–<80%

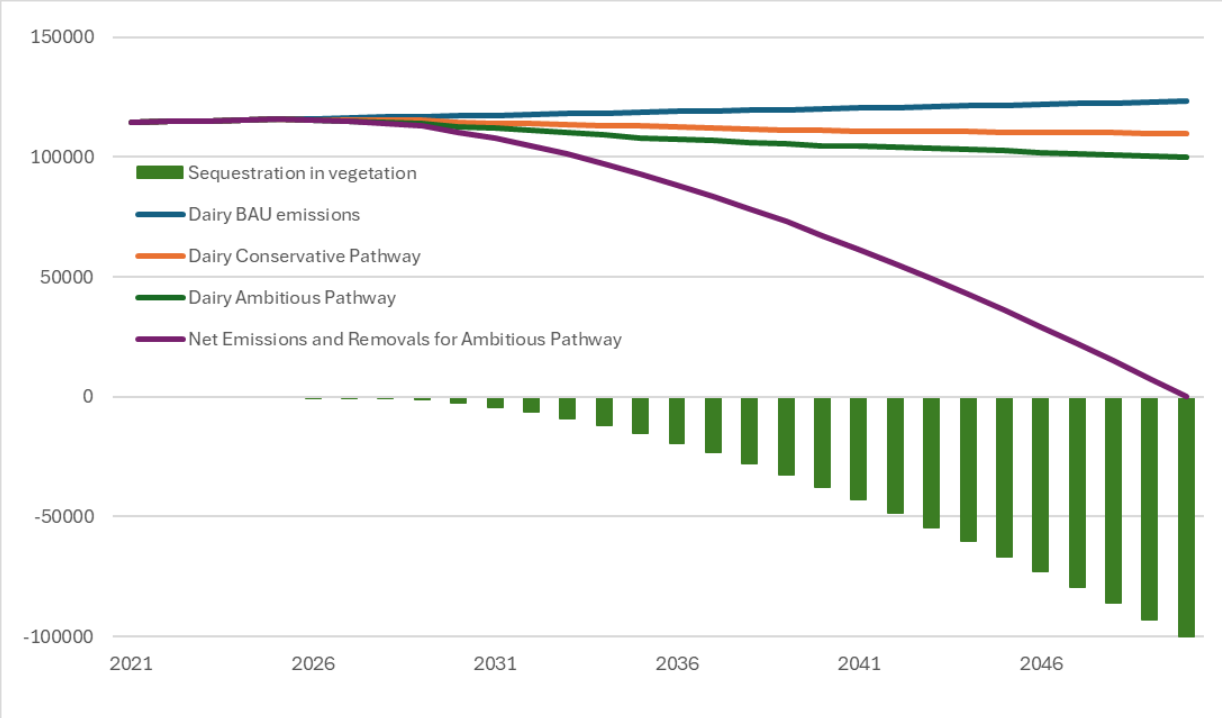

Figure 2: Dairy emissions reduction and removal pathway

3.3 Beef

The assumptions for the conservative and ambitious pathways for beef are displayed in Table 7 and the resulting emissions trajectories, including carbon sequestration in tree plantings, are shown in Figure 3. The conservative pathway reduces emissions compared to BAU by 14.7%, while the ambitious pathway reduced emissions compared to BAU by 24.6%. A substantial portion of the emissions reduction in beef are attributable to enzyme inhibitors, 13.0% in the ambitious scenario. Rumen modifiers give the next largest reduction, 3.4%. The difference between these two is larger than in other sectors, because less adoption of rumen modifiers is assumed. This is because there is less evidence of productivity gains with rumen modifiers in cattle systems. The large emission reductions achievable in feedlot cattle also improve emissions reductions with enzyme inhibitors compared to other sectors. Productivity improvements and genetics provide the next largest reductions. Increases in the proportion of animals on high concentrate diets lead to a 1% reduction in emissions. The remaining options for beef contribute 0.9% in 2050.

Assuming regional average sequestration rates in tree plantings, 8,510 ha would need to be planted over 25 years under the conservative emissions pathway and 7,530 ha would need to be planted over 25 years in the ambitious pathway. In the ambitious pathway this starts at 23 ha per year in 2026 and increases to 579 hectares in 2050. Compared to the estimated area of beef land, this area of tree planting is 7.1% and 6.3% for the conservative and ambitious scenarios, respectively. In the case of BAU, 9,990 ha, or 8.4% of the estimated area of beef land would need to be planted.

Table 7: Beef – assumptions for the conservative and ambitious emissions removal pathways

Option	Conservative		Ambitious	
	Timeframe	Maximum additional adoption	Timeframe	Maximum additional adoption
Productivity (cumulative)	2026–2050, maximum adoption in 2040	Minimal, remaining improvements that reduce emissions	2026–2050, maximum adoption in 2035	Minimal, remaining improvements that reduce emissions
Genetic gains (cumulative)	2030–2050	Intermediate	2030–2050	Considerable
Enteric methane, Enzyme inhibitor	feedlots 2026–2050; extensive 2030 to 2050	High in feedlots, Intermediate in extensive	feedlots 2026–2050; extensive in 2030 to 2050	High in feedlots, Considerable in extensive
Enteric methane, Rumen modifier	2026–2050	Intermediate	2026–2050, max adoption reached in 2040	Considerable
Fats in grass fed animals	2026–2050, max adoption in 2035	Modest and four months of the year	2026–2050, max adoption in 2040	Intermediate, and 4 months of the year
High concentrate feed	2026–2050	In line with feedlot trend, increase modest	2026–2050, on farm starts in 2035	Same in feedlots plus modest feeding on farm
Optimised fertiliser use	2026–2050, maximum adoption in 2035	Modest since largely adopted	2026–2050, maximum adoption in 2030	Modest since largely adopted
Inhibitor coated fertiliser	2026–2050	Intermediate	2026–2050	Considerable
Electric vehicles/ tractors	2035–2050	Intermediate	2035–2050	Considerable

Minimal: ≤5%; Modest: >5.0–<20%; Intermediate: 20–<40%; Considerable: 40–<60%; High: 60–<80%

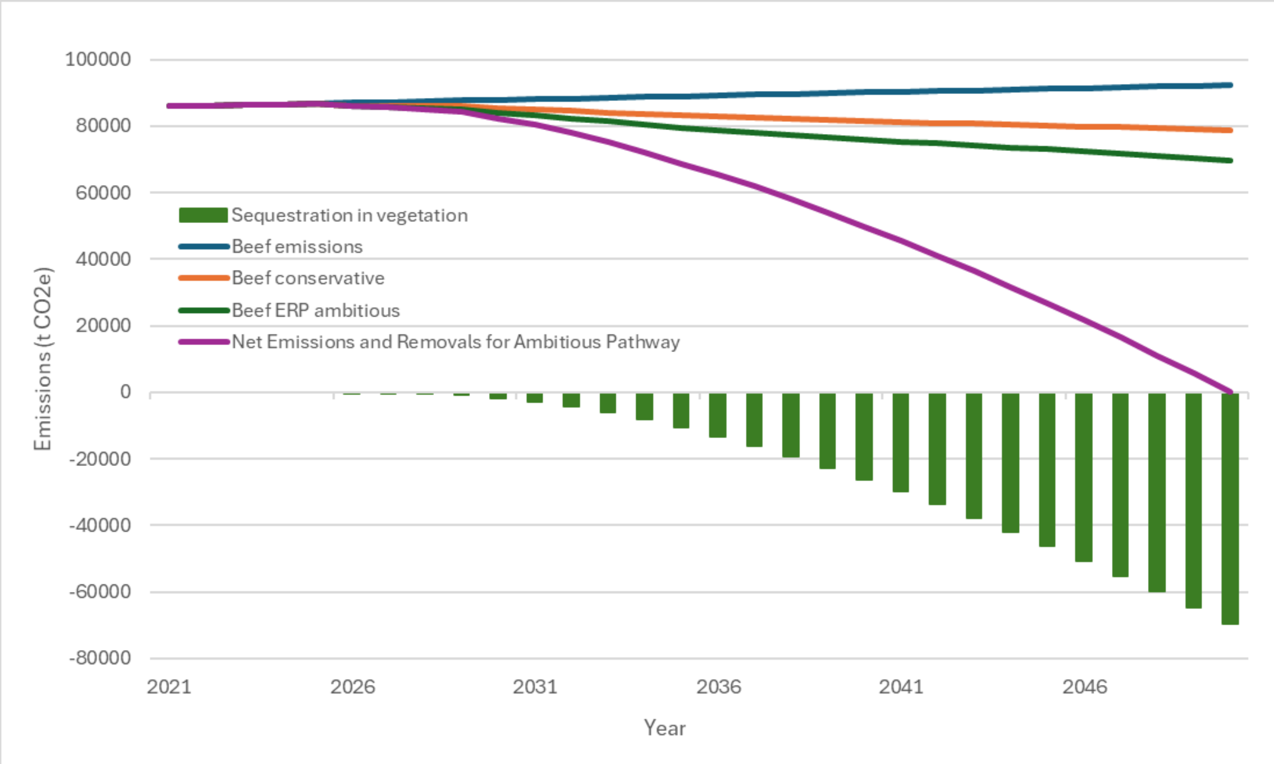

Figure 3: Beef: emissions reduction and removal pathways

3.4 Sheep

The assumptions for the conservative and ambitious pathways for sheep are displayed in Table 8 and the resulting emissions trajectories, including carbon sequestration in tree plantings, are shown in Figure 4. The conservative pathway reduces emissions compared to BAU by 10.9% while the ambitious pathway reduced emissions compared to BAU by 17.8%. Again, enzyme inhibitors contributed the most to emissions reduction, 8.1% in the ambitious pathway in 2050, followed by 3.2% for rumen modifiers. This reflects an intermediate case where the comparative adoption of enzyme inhibitors and rumen modifiers are the same as beef, but unlike beef there are no animals getting the higher effectiveness in feedlots. Productivity and genetics have the next greatest contribution to emissions reduction. Because methane emissions were incorporated into breeding decisions later than in other sectors, genetics contributed less to emissions reductions in this sector. The remaining options combined reduce emissions by 1.6% in 2050.

Assuming regional average sequestration rates in tree plantings, 5,990 ha would need to be planted over 25 years under the conservative emissions pathway and 5,520 ha would need to be planted over 25 years in the ambitious pathway. In the ambitious pathway this starts at 17 ha per year in 2026 and increases to 425 hectares in 2050. Compared to the estimated area of sheep land use, this area of tree planting is 8.4% and 7.7% for the conservative and ambitious scenarios, respectively. In the case of BAU 6,720 ha, or 9.4% of the estimated area of sheep land use would need to be planted.

Table 8: Sheep – assumptions for the conservative and ambitious emissions removal pathways

Option	Conservative		Ambitious	
	Timeframe	Maximum additional adoption	Timeframe	Maximum additional adoption
Productivity (cumulative)	2026–2050, maximum adoption in 2040	Minimal, remaining improvements that reduce emissions	2026–2050, maximum adoption in 2035	Minimal, remaining improvements that reduce emissions
Genetic gains (cumulative)	2035–2050	Intermediate	2035–2050	Considerable
Enteric methane, Enzyme inhibitor	2030 to 2050	Intermediate	2030 to 2050	Considerable
Enteric methane, Rumen modifier	2026–2050,	Intermediate	2026–2050, max adoption reached in 2040	Considerable
Fats in grass fed animals	2026–2050, max adoption in 2035	Modest and four months of the year	2026–2050, max adoption in 2040	Intermediate, and 4 months of the year
Brassicas	2030–2050	Minimal and three months a year	2030–2050	Modest and three months a year
Optimised fertiliser use	2026–2050, maximum adoption in 2035	Modest since largely adopted	2026–2050, maximum adoption in 2030	Modest since largely adopted
Inhibitor coated fertiliser	2026–2050	Intermediate	2026–2050	Considerable
Electric vehicles/ tractors	2035–2050	Intermediate	2035–2050	Considerable

Minimal: ≤5%; Modest: >5.0–<20%; Intermediate: 20–<40%; Considerable: 40–<60%; High: 60–<80%

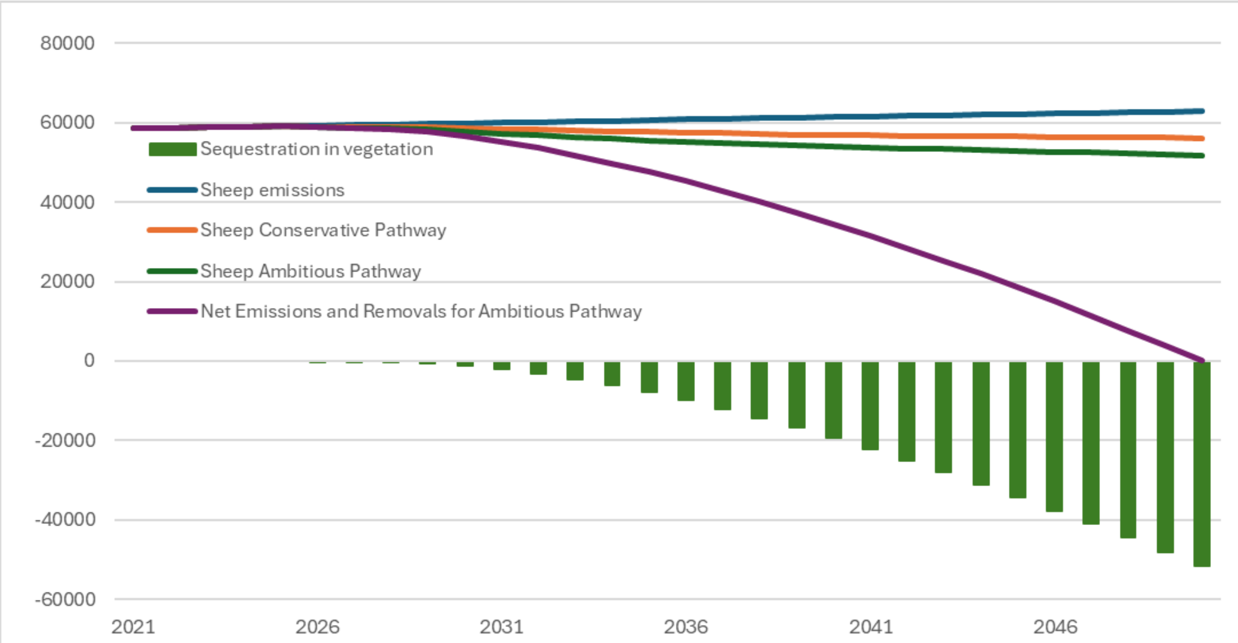

Figure 4: Sheep emissions reduction and removal pathways

4 Conclusions/Recommendations

This work calculated the baseline emissions for dairy, beef, and sheep industries in the Hills and Fleurieu region and provided conservative and ambitious ERR Pathways in working towards net zero in 2050. The shortfall in meeting net zero was then addressed through sequestration, by building carbon stocks in tree plantings.

The results highlight the important role of tree planting to provide a potential pathway for livestock industries to achieve net zero emissions. In all sectors, net zero was not possible without extensive areas of tree plantings. Although farmland was not assessed for its suitability for tree plantings or for any impacts on production, the extent of the planting area would be logistically challenging and suggests some areas would likely be planted with no return on investment, or an overall cost. Thus, it is important to focus on optimising emissions reductions as early as possible, to ensure the tree planting is attainable and that it maximises emission removals.

Determining the extent to which options are currently being used or could be used within the Hills and Fleurieu region, would assist in maximising reductions from options. It can assist in targeting extension for promising options and aligning options to those situations they are most suited. For instance, it has been assumed that the proportion of cattle that go to feedlots in South Australia can be applied to the Hills and Fleurieu region. If there are fewer or more feedlots in this region than the statewide average, that will impact the relative opportunity for options that perform best in feedlot conditions.

Similarly to understanding current practice, to effectively capture emissions reductions and removals, a system must be in place to measure changes from a BAU scenario. This means implementing a Measurement, Monitoring, Reporting and Verification (MMRV) framework that can track emissions trends across the Hills and Fleurieu region while also supporting individual producers in doing the same on their farms. The level of detail required to demonstrate emissions change depends on the certainty needed—ranging from broad estimates to fully audited results. These different reporting outcomes require varying levels of effort in data collection, analysis, and the assumptions applied. For the LHF, this would require regional-scale tracking, like the annual reporting of lime use by region, ideally with added information on use by agricultural sector, while enabling tailored support for farmers based on their business needs and the confidence they require when communicating emissions outcomes.

The most promising emission reduction options were enzyme inhibitors and rumen modifiers, since they act on the largest emission source, enteric methane, and have potential to provide reductions in enteric methane year-round. Productivity and genetics provided notable contributions to the reductions in all sectors. Although these options were assumed to have marginal annual benefits, since they reduce methane year-round and once adopted the reductions continue over the course of the pathway, they result in comparatively substantial emissions reductions in 2050. Options that contributed about 1% to the emissions reduction in 2050 included anaerobic digestors in the dairy sector and increased concentrate feeding in the beef sector. All other options individually made up less than 1% of the emissions reductions, with these options combined contributing to a reduction of 1.9% in dairy, 0.9% in beef, and 1.6% in sheep.

Determining the extent that livestock producers in the Hills and Fleurieu region can achieve productivity benefits from promising rumen modifiers is an important step. This could speed up adoption, which would be particularly important in the near term, before enzyme inhibitors become available for use in extensive systems and while the potential for productivity benefits with enzyme inhibitors is explored. For example, this could validate or challenge adoption assumptions of rumen modifiers in dairy that were informed by evidence of milk production gains being stronger for some rumen modifiers. Likewise, there are some early results for sheep production that suggest rumen modifiers may also improve liveweight gain in sheep. Understanding this benefit would improve adoption assumptions and potentially encourage earlier adoption.

Knowing the impacts of combining feeding strategies could have a large impact on the results of these pathways. Increased neutral detergent fibre reduces methane emissions and increases the effectiveness of other additives such as the enzyme inhibitor Bovaer. Understanding the interactions between other combinations of feeding strategies, particularly those with different modes of action, would improve assumptions regarding maximum total adoption. In this case no animal was assumed to be on both an enteric methane enzyme inhibitor and a rumen modifier since research has not established the impacts of combining options. If even a partial additive effect is possible, then both scenarios are likely to underestimate potential emissions reductions achievable with feed strategies.

Another factor that could eventuate in greater emissions reductions than represented here are the impacts of a new technology. The differences between the conservative and ambitious pathways reflect differing adoption only. If a new technology becomes available or assumptions around technologies in development (primarily enzyme inhibitors for use in extensive systems) are overly conservative, this will also increase the potential emissions reduction with these pathways.

Across all grazed modified pasture (the three sector's land area combined), the planting area required under the conservative pathway was 26,400 ha and 23,850 ha under the ambitious pathway. This represents 12.2% and 11.0% of the grazed modified pasture area in the Hills and Fleurieu region for the conservative and ambitious pathways, respectively. Under the ambitious pathway the planting area in the year 2050 would have increased to 1,830 ha. The total area of planting is slightly more than the value that is generally suggested most farms could achieve and remain productive (10% forested area). The current tree cover and specific farm circumstances in the region would need to be examined to determine where, and to what extent of the area trees could be planted to maintain or improve productivity, while also considering the overall cost of these plantings. The general logistics, such as meeting demand of seedling availability and labour, would be a challenge that needed to be managed, particularly as planting areas increased over time.

If farmers undertaking these plantings want to include the plantings into their farm level accounting (e.g. inset) the MMRV requirements would depend on the standard being applied. For instance, if customers, such as retailers, are trying to achieve Science-Based Targets, the accounting of removals are expected to align with the Greenhouse Gas protocol's draft land sector and removals guidance, which includes a commitment to ongoing monitoring and providing quantitative uncertainty estimates. If plantings are associated with ACCU or other carbon credit markets, there would be discounting associated that would result in generated credits being less than the carbon removals reported here. This would be particularly relevant if the dairy industry was purchasing credits from plantings established in beef or sheep production systems. The logistics of implementing and accounting for planting to address dairy emissions on non-dairy land will need further investigation.

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