IntegrityAg

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Commercial in Confidence

Guideline for Emission Reduction Options

Landscapes South Australia: Hills and Fleurieu

Executive Summary

The Hills and Fleurieu region in South Australia, is a significant agricultural area, with extensive grazing covering 45% of the land, and substantial areas dedicated to cropping and horticulture, including vineyards. A key focus of the Hills and Fleurieu Landscape Board is climate change mitigation. The board aids land managers in understanding emissions and exploring carbon market opportunities. This guideline aims to equip the board and local farmers with the knowledge and tools to reduce greenhouse gas emissions in agriculture, outlining emission reduction options by sector and providing implementation details, costs, and potential abatement.

The Guideline describes mitigation options for beef, dairy, sheep, cropping and perennial horticulture sectors. There are several options that are similar between all sectors, such as optimal fertiliser use. However, some options are specific to sectors and all options will vary in their potential and costs across the sectors. Options specific to livestock sectors include feed additives such as Agolin and Bovaer. Forage Brassicas are included as options for dairy and sheep and Asparagopsis is an option for beef in total mixed ration systems. Cropping includes precision agriculture and perennial horticulture includes micro-irrigation/ fertigation. The technical potential for emissions reduction as well as factors that influence the level of adoption are discussed and are used to inform the development of Marginal Abatement Cost Curves (MACCs) for each industry. A short discussion on prospective options is included to provide details on strategies that are still in development and may become viable over the next 5 to 10 years.

The Marginal Abatement Cost Curve (MACC) estimates the cost to reduce emissions per tonne of CO_2-e by combining technical mitigation effectiveness and adoption rates. Technical mitigation refers to the effectiveness of the option in the absence of barriers, such as cost or access. Adoption is influenced by factors like system suitability, logistics, and productivity benefits. There is some inherent uncertainty due to speculative cost assumptions and knowledge gaps regarding the levels of current adoption. The values for abatement and cost are based on assumptions, highlighting the importance of transparency in marginal abatement cost analysis.

The review of options and the results of the MACCs show that the best options for livestock operations include productivity gains through management and optimised fertiliser use. Renewable energy and genetic gains are cost-effective options but can only reduce a small proportion of livestock emissions. In dairy, Agolin is another good option, as it is associated with a productivity benefit. Many of the considered options for cropping and perennial horticulture are associated with productivity gains.

Tree and soil carbon are addressed both in terms of their potential impact on the carbon account as well as their productivity benefits. Tree carbon sequestration rates in the region vary, with the highest rates reaching 19-20 tonnes CO_2-e per hectare per year over 25 years. Planting trees strategically with farm goals in mind can provide shade and shelter, soil and water benefits, biodiversity outcomes, as well as carbon sequestration. Soil carbon sequestration potential varies substantially across H&F. Summaries of potential by industry are provided. Like trees, there are multiple interacting benefits of increased soil carbon, in addition to carbon sequestration.

Table of Contents

Table of Tables

Table of Figures

1. Introduction

Hills and Fleurieu is a unique region in South Australia south of Adelaide, with a population of approximately 130,000. The region is characterised by its diverse landscapes, including 6,700 square kilometres of land, ocean, offshore islands and numerous biodiversity hotspots. The region is a significant agricultural production area, boasting sufficient groundwater and surface water resources.

Extensive grazing is the predominant land use, comprising 45% of the land area. There is also a substantial area of cropping and horticulture, including vineyards (Figure 1). For example, the Mount Lofty Ranges and Macclesfield regions support fruit trees. and McLaren Vale is one of South Australia's most significant wine growing regions. The production from agriculture sectors within the Hills and Fleurieu region contributes more than $400 million annually to the South Australian economy (Landscape South Australia Hills and Fleurieu 2021).

The LHF Landscape Board, one of nine regional landscape boards, plays a crucial role in supporting communities and land managers in improving the management of the region's landscapes. Climate change is one of the six key focus areas for the LHF Landscape Board, alongside land, water, nature, community, and First Nations. The Hills and Fleurieu landscape board have a net zero target by 2026 for organisational emissions. The board also supports land managers to understand their emissions and potential opportunities in carbon markets through the Carbon Farming Outreach Program and free emission profiles for farmers in the region.

This Guideline aims to equip the LHF Landscape Board and local farmers with the knowledge and tools necessary to make informed decisions and take meaningful action towards reducing the greenhouse gas emissions of agriculture in the region. Emission reduction options are outlined grouped by agricultural sector and include information relevant to implementation and details about their relative cost and potential abatement. The agricultural sectors covered are beef, dairy, sheep, cropping and perennial horticulture, including viticulture.

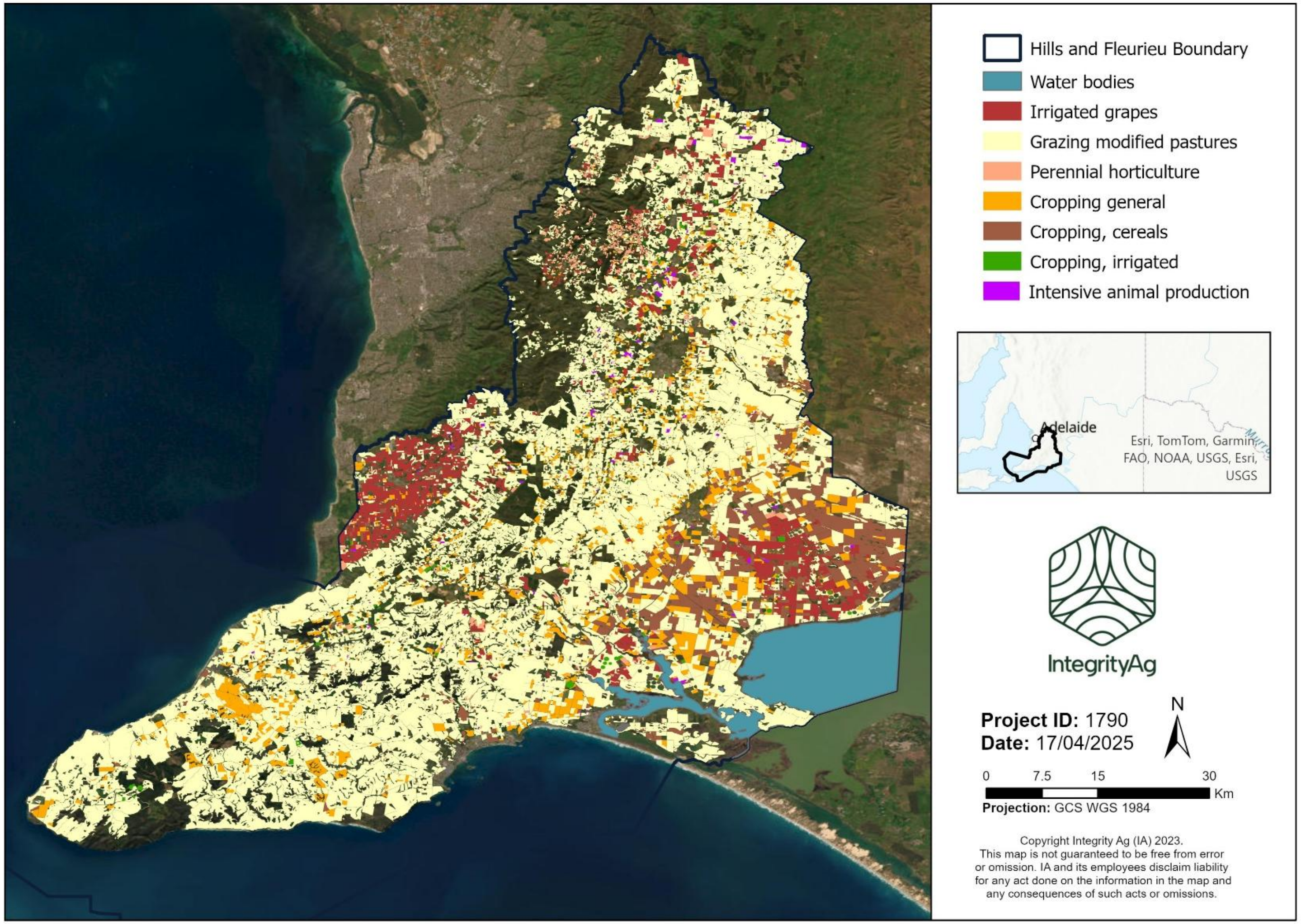

Figure 1. Land use of several agricultural sectors in the Hills and Fleurieu region based on the Australian Land Use and Management Classification (version 8)

1.1 Emissions from agriculture

Agriculture is unlike industrial, residential, or other commercial sectors that are dominated by carbon dioxide emissions. The major emission of livestock sectors is methane, and the major emission of cropping and horticultural sectors is typically nitrous oxide emissions. Only in some irrigated or greenhouse production operations is carbon dioxide the predominant emission. This is due to the use of electricity, diesel, and embedded emissions from purchased products, such as fertilisers and herbicides, comprising a much larger proportion of emissions in these production systems.

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 fraction of the emissions in extensive beef and sheep farms but can comprise a substantial proportion of emissions in some irrigated cropping or greenhouse horticultural operations. The emissions associated with the production of products used on farm are referred to as Scope 3 emissions. Figure 2 illustrates the emissions scopes for agricultural producers.

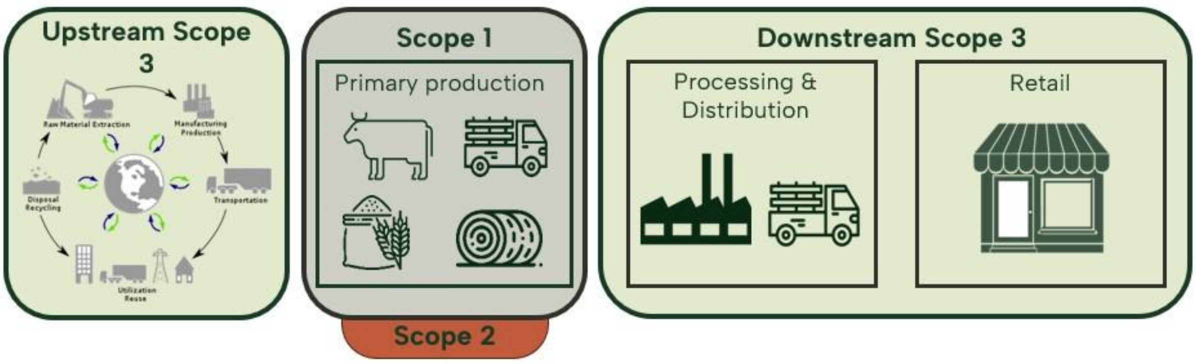

Figure 2: Emissions scopes 1,2 and 3 for agricultural producers

There are two important metrics commonly used to report greenhouse gas emissions. The first is total emissions. The second is the emissions intensity (EI), or the amount of emissions per unit of product, for instance a tonne of wheat. Products that are made efficiently will have a low EI. Prioritising low EI products in the market helps to drive demand for products with the least emissions and to encourage efficiency gains. Total emissions estimates are required to track progress towards emission reduction targets set to avoid the worst impacts of climate change.

The three major greenhouse gases produced by agriculture differ in the extent to which they warm the atmosphere and therefore cannot be compared to each other on a per tonne basis. Global warming potentials (GWP) are measurements of the amount of heat that is trapped by a greenhouse gas in a specified period, relative to carbon dioxide. This allows emissions of each gas to be compared by converting gases to a common metric, carbon dioxide equivalents (CO_2-e). Typically, the 100-year GWP values from the IPCC assessment reports are used. In the most recent IPCC report (6^{th} assessment report) the GWP for methane is 27 and for nitrous oxide is 273 (Forster et al., 2021).

1.1.1 Methane

Enteric methane is a by-product of ruminant digestion and the primary emission from livestock production. In extensive beef and sheep farms enteric methane often comprises over 70% of emissions. This value is slightly less (55-65%) in dairies, since they have more manure and electricity emissions than beef and sheep sectors.

Manure methane can be a substantial source of emissions from intensive production systems where manure is stored in anaerobic conditions, this includes feedlots and dairies. For instance, manure methane comprises an average of about 10% of emissions in dairies (Christie *et al.* 2016).

1.1.2 Nitrous oxide

Nitrous oxide is emitted from nutrient rich soils and emissions are greatest in warm and wet conditions. There are also indirect emissions of nitrous oxide which occur following other nitrogen losses such as leaching. Any management activity that increases the nitrogen content of soil increases the potential for nitrous oxide emissions, including deposition of animal urine and dung in the paddock and fertiliser application.

Since cropping and horticulture are not associated with enteric methane emissions, nitrous oxide comprises a much larger component of these sectors' emissions than the livestock sectors. In many cases nitrous oxide is the primary source of emissions of cropping and horticultural farms.

1.1.3 Carbon dioxide

Direct carbon dioxide emissions from petrol and diesel use on farm (Scope 1) or emissions associated with the electricity used on farm (Scope 2) are a small fraction of emissions from livestock farms. Irrigated and greenhouse production systems have the greatest carbon dioxide emissions (Scope 1 and 2) and in some cases are the predominant emissions.

The power and fuel used to produce the products purchased on farm comprise Scope 3 emissions (Figure 2), such as fertilisers and herbicides. These are often carbon dioxide emissions, but may also be methane or nitrous oxide emission converted to CO_2-e. For instance, when purchasing supplementary feed or cattle.

Lastly, agriculture contributes to carbon dioxide emissions through land use and land use change. This occurs when forest is cleared for agricultural production and can occur with some management practices such as overgrazing. This can occur on farm (Scope 1) or be associated with purchased products (Scope 3). Unlike the other emissions sources, agricultural land can also serve as a carbon sink, sequestering carbon dioxide from the atmosphere into trees and soils. Increasing carbon stocks in vegetation and soils lead to a reduction in net farm emissions.

1.2 Marginal abatement cost curves

Marginal abatement cost curves have been generated for emission reduction options in each industry covered in this report. Along the x axis of these graphs is the percentage of abatement, which is influenced by both technical mitigation effectiveness and expected adoption rates. By applying technical mitigation and likely adoption rates, we estimate the percentage reduction in emissions and the associated cost of that amount of emission reduction. This produces the estimation of cost per tonne of CO_2-e for each emission reduction and removal option.

Technical mitigation refers to the effectiveness of the option in the absence of barriers, such as cost or access. The option acts on a particular GHG, so will only reduce a portion of the overall farm emissions. For instance, in livestock operations, options that reduce enteric methane have greater potential to reduce total emissions since enteric methane comprises the majority of emissions. These values are based on the scientific literature but there may be some uncertainty where the values produced have exhibited variable responses, such as fertilisers with inhibitors. Options, with sufficient research, such as Bovaer, can be predicted with accuracy, but can otherwise be narrowed to a range.

Adoption is affected by several factors, such as whether the option is suitable for a given production system, the logistics of implementation, and seasonality. For instance, some options are only effective in intensive systems such as feedlots, and adoption is limited to these systems rather than being used across all meat production. Options that have a productivity benefit tend to be cost-effective and are therefore more likely to be implemented than one that does not. Other factors influencing adoption are speculative such as cost assumptions of options between now and 2030, the speed of uptake, and in some cases assumptions about the level of current adoption. This highlights that adoption tends to be more uncertain than the technical mitigation potential, with uncertainty increasing as results are projected over a longer timeframe. The impact of economic, logistic, and other limitations to implementation on total emissions reduction potential is illustrated in Figure 3.

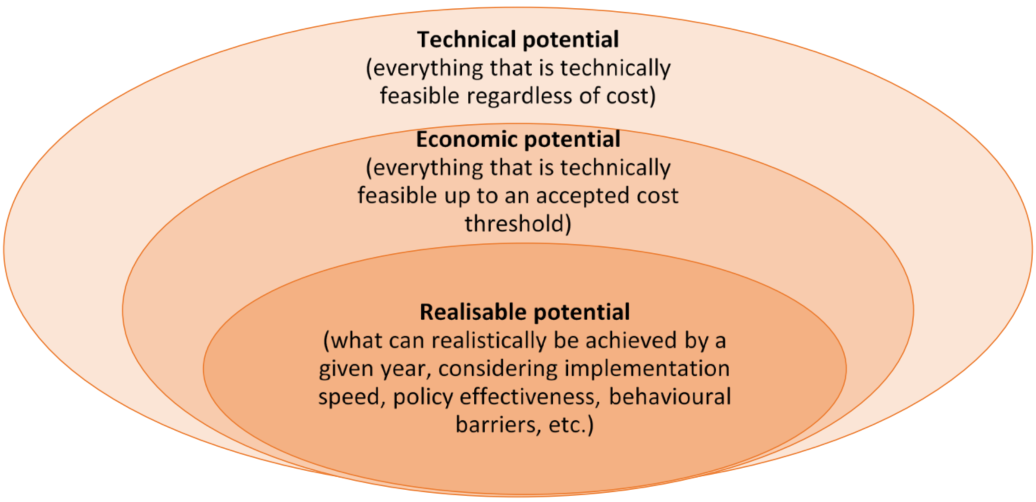

Figure 3: Diagram of the impacts of economic and other constraints on emissions reduction potential (Ministry for the Environment 2020)

It is important to recognise that the values for abatement and cost in the MACC graphs are determined by the assumptions made for mitigation and adoption. For this reason, the assumptions used to create each industry MACC are outlined in the tables and text, to provide full transparency. We have addressed any inherent uncertainty in the assumptions in several ways. Firstly, by using conservative emission reduction values in the MACC. Secondly, by applying threshold analysis to test at what point a small productivity benefit changes from being an expensive option, to one that generates revenue. Thirdly, by carefully considering each emission reduction option in the specific context of each industry and assessing whether production benefits are still relevant for that industry. In this way the analysis incorporates methods to reduce uncertainty in the assumptions as much as possible.

It is also important to acknowledge that not all the options are additive. For instance, Agolin and Bovaer both act as methane inhibitors and the mitigation associated with these products cannot be assumed to be additive on a given property. Similarly, decreases in fertiliser use would reduce the total potential of nitrification inhibitors. Emission reductions that act on the same greenhouse gas are most effective when they are applied in separate systems. While this issue is unlikely to have major implications in this analysis due to the adoption rates, it is nonetheless important to recognise. This demonstrates that when implementing multiple options in a given sector, it is essential to understand not only the farm production systems, but also how reduction and removal options function within these systems, and the impact of any integration effects.

2. Emission reduction options by industry

2.1 Beef

Table 1 summarises the main characteristics of emissions reductions options for beef operations including the types of systems the option can be implemented, the technical mitigation potential, the expected uptake and the ability of the option to be accounted for and verified. This information served as the assumptions for the beef MACC (Figure 4) Section 1.2 includes an explanation of marginal abatement cost curves (MACCs).

2.1.1 Productivity gains from improved management

Improving the productivity of the herd results in efficiencies that reduce emissions intensity. Implementing "best practice" should also achieve a net financial benefit. The cost and revenue impacts will depend on several factors including the system, location, and method used to increase productivity.

The extent to which emissions intensity is reduced is influenced by the potential for improvement and status of other productivity parameters. Management practices can have long term compounding impacts such as improved genetics and others are seasonally dependent management decisions. The values shown are indicative of likely improvements.

These options will be captured with annual reporting and thus will be included in emissions calculators including the Sheep and Beef Greenhouse Accounting Framework (SB-GAF) without any additional data requirements.

Delivering whole-herd efficiency is a priority for all producers and assists in reducing the carbon footprint. Delivering better productivity can occur through a combination of genetics, nutrition, and management. The following are the focus areas:

- Lifetime average daily gain. Increasing weight gain reduces the emissions produced over the life of an animal. Best in class performance is in the order of 300kg HSCW at 14 months. Increasing gain must be managed along with meat quality.
- Weaning rates. Maintaining the minimum cow inventory possible, including careful cull cow management, is important because the carbon footprint is impacted by total beef turnoff. In the range of 85%-90% is high performance when measured as calves weaned divided by cows exposed to the bull. Efficiency includes maximising turnoff of fat cows.
- Cow weight. Most of the feed is eaten by the breeding herd, and this is driven by mature weight. Aiming for moderate weight cows around 500 kg liveweight or about the same as the steer progeny, or lighter. This can get up to 600 kg at turnoff when fat.
- Mortality management. Aside from being a loss in the system, mortalities reduce beef turnoff which results in more emissions relative to beef output. Minimising losses improves the carbon footprint.

Table 1. Beef system emission reduction options and their expected reduction potential and update.

Emission reduction option	Applicable systems	Reduction in target emissions in applicable system	Expected uptake	Can be included in GAF calculation	Can be 3rd party verified
Productivity gains (management)	All	5–15% of animal emissions depending on context%	High	Yes	Yes
Productivity gains (genetic)	All	0.2% per year of animal emissions until peak reached	High	Yes, when reflected in fertility, survival, feed intakes, etc	Yes, when reflected in fertility, survival, feed intakes, etc
Bovaer	Total Mixed Ration	30–50% of enteric methane emissions	Low, costly	No but can be addressed with additional calculations in GAF	Expected 2025
Agolin	All	5%–10% of enteric methane emissions	Moderate	No but can be addressed with additional calculations in GAF	Expected 2025
Asparagopsis	Total Mixed Ration	50–80% of enteric methane emissions	Very low, costly	No but can be addressed with additional calculations in GAF	Expected 2025
Fats and oils in grass fed cattle	Feed pad	4% reduction in enteric methane per day per 1% increase of dietary fat	Low	No but can be addressed with additional calculations in GAF	Expected 2025
High concentrate diets	Feed pad	Each 1% reduction in NDF reducing enteric methane produced per day by around 2.3 grams.	Moderate	Yes	Expected 2025
Optimised fertiliser use	All	3.5% reduction in emissions relating to nitrogen fertilisers	Low	Yes	Yes
Use of inhibitor coated fertiliser	All	~25% reduction in fertiliser nitrous oxide emissions	Low	No, emission reduction too variable	No
Renewable energy	All	30% reduction in emissions relating to electricity (SA grid currently 70% renewable)	High	Yes	Yes

Low ≤5%; Moderate 6–15%, High 16%–25%

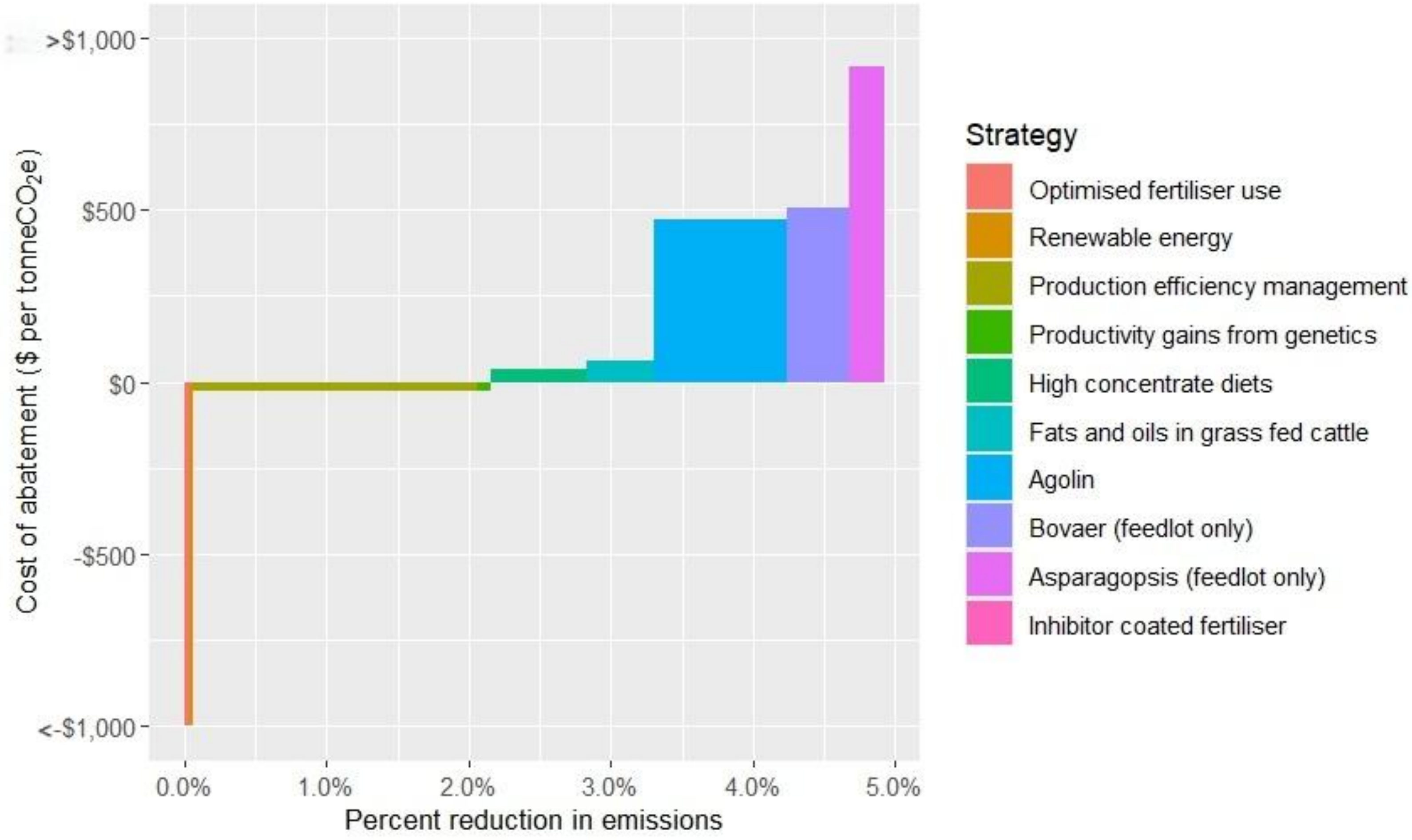

Figure 4: Marginal abatement cost curve for beef sector emission reduction strategies. See Table 1 and text for details on assumptions. This assumes no productivity benefit for any feed additive or inhibitor coated fertiliser. Several options can have variable costs/benefits and this would give a different result. Productivity gains from genetics and management are shown as a small benefit for visualisation purposes but are assumed to be $0 / tonne CO_2-e.

2.1.2 Productivity gains from genetics

Feed conversion ratio (FCR) is an important determinant of the carbon footprint in livestock systems. Any practice delivering better FCR will reduce the carbon footprint, all other factors being equal. Measuring and demonstrating an improvement will reduce carbon footprint and feed costs and is an ideal intervention that should be cost-effective.

It is possible to breed for better Residual Feed Intake (RFI) which over time may deliver better outcomes for integrated suppliers. This is analogous to the Sustainable Breeding Index for dairy. A similar metric is in development for beef.

2.1.3 Feed strategies

2.1.3.1 Bovaer

Bovaer is an enzyme inhibitor that reduces the production of enteric methane. It is also called 3-NOP. It is most effective when it is fed consistently throughout the day. Thus, it results in greater reductions in feedlots and other systems with total mixed ration feeding programs. Dose and NDF (neutral detergent fibre) also influence the reduction in emissions observed with Bovaer. In a feedlot providing a diet with NDF of 30% the estimated emission reduction at a dose of 100 mg/kg is 38%. With an NDF of 50% the estimated emission reduction is 24% (Eckard *et al.* 2024).

The limitation to highly intensive operations means that in its current form, adoption would be low and essentially be limited to feedlots and other systems with either total mixed ration or more intensive partial mixed ration. A Bovaer product that can be used in extensive systems is in development.

There are no concerns for animal, product quality, or environmental health of using Bovaer at recommended doses. It has been approved for use in over 50 countries including the EU, Canada and Australia. There are typical Work Health and Safety requirements for handling Bovaer. Current information also suggests no significant positive or negative impact on productivity.

2.1.3.2 Agolin

Agolin is a rumen modifier made of essential oils that reduces enteric methane production. It has lower effectiveness than Bovaer but can be applied to more systems and is available as an organic product. This product has a stronger evidence base in dairies than in beef. A 14% reduction in enteric methane emissions in four beef heifers was not statistically significant in one study (Castro-Montoya et al., 2015). In a study of Agolin in water at 6 µl/L daily, methane production was significantly reduced compared to control animals (5.1%) and compared to week one (16.4%) (Batley *et al.* 2024). For the beef MACC, it was assumed to give an 8% reduction in enteric methane emissions based on the limited work in beef and the results in dairy systems. Based on a lack of support for productivity benefits based on currently available data in beef systems, it was also assumed that there is no productivity co-benefit.

2.1.3.3 Asparagopsis

There is high confidence in the ability of the seaweed Asparagopsis to drastically reduce enteric methane emissions in total mixed ration systems. It has shown good results in feedlots with no impact on animal health or meat quality over 200 days (George *et al.* 2024). However, since this is a more expensive option than Agolin and Bovaer; adoption is not expected. It is included in the MACC at an adoption rate that is proportional to the cost differential between Bovaer and Asparagopsis to illustrate the impacts of both increased effectiveness but also increased cost. It is only included in the beef MACC due to this and other limitations which are described in the prospective options section.

2.1.3.4 Fats and oils in grass-fed cattle

High lipid content commodities such as vegetable oil, cottonseed, canola seed, and soybean have shown substantial reductions in methane emissions. Proposed mechanisms for the effect include replacing fermentable organic matter in the diet and unsaturated fatty acids acting as a hydrogen sink (Beauchemin *et al.* 2020). To ensure animal health and productivity, it is suggested the total dietary fat does not exceed 6 to 8%.

The technical mitigation potential was determined to be approximately 4% reduction in methane per 1% increase of dietary fat (Moate *et al.* 2011; Beauchemin *et al.* 2020). A meta-analysis found that all metrics of methane, including g/day, g/ kg dry matter intake (DMI), and g/ kg milk yield decreased significantly when diets contained >5% fat. This study also determined that mitigation was most strongly associated with mono and poly-unsaturated fatty acid (Patra 2013). Sunflower oil at approximately 5% DM reduced methane emissions (g/day) by 22% (McGinn *et al.* 2004). A study of canola oil at 4.6% of DM resulted in a statistically insignificant (P=0.09) decrease in methane yield (g/kg DM) of 21%.

This option is available for total mixed ration systems and more intensive partial mixed ration systems that currently have a ration with less than about 6% dietary fat. In systems that are not total mixed ration the mitigation potential will depend on the extent to which fats and oils are supplemented throughout the year. A cost-benefit analysis of the specific oil being considered is needed to determine if the productivity gains will outweigh the added costs. In the marginal abatement cost analysis, we have conservatively assumed no productivity benefit and the fat is slightly more expensive (10%) than the cost of grain for the high-concentrate feed option. Thus, the cost of abatement is likely at the high end. It is worth noting that the use of some supplements may prevent qualifying for some certifications and can be associated with high Scope 3 emissions. Due care should be applied when selecting a product with a good understanding of its source.

Detailed data on feed input and diet characteristics are required to incorporate the use of fats and oils in the carbon account. Records are also required to demonstrate these changes for third party verification.

2.1.3.5 High concentrate feed

Increasing grain in the diet increases production efficiency and can reduce methane emissions. Grain finished cattle have higher average daily gain (Beauchemin et al., 2011; Wiedemann et al., 2015).and enables cattle to achieve target weights in less time. Feeding grain also reduces methane emissions (McGeough *et al.* 2010; Moate *et al.* 2020; Almeida *et al.* 2025). For instance, a meta-analysis of four feedlot studies found that an increase in dietary neutral detergent fibre (NDF) of 1% was associated with a 2.3 gram increase in methane production (methane/d) (Almeida *et al.* 2025), thus high grain diets with low NDF result in less methane emissions. These factors lead to lower lifetime emissions than grass-finished cattle (Wiedemann *et al.* 2017) and lower emissions intensity of grain-finished supply chains (Thomas *et al.* 2021). The reduction in emissions and emissions intensity occurs only for the finishing period, typically 100 days or less.

This can be achieved through grain finishing on-farm or moving to higher grain levels in the ration during finishing. It is recommended this is done by consulting a professional nutritionist. This is important to manage the risk of acidosis. To incorporate the impacts of this change on the carbon account estimate, characteristics of the diet before and after the increase in concentrates is required as well as reliable records of feed delivered to bunk sufficient to determine feeding rate (kg DMI/head) and feed conversion ratio.

The cost reflected in the MACC is an increase in the grain proportion of the diet, not changes to the system required to add grain to an entirely extensive system nor the whole system implications of moving cattle to a feedlot for grain finishing. It assumes that grain is slightly more expensive than the replaced diet (~$40 more per tonne) and 10% cheaper than adding fat.

2.1.4 Nitrous oxide emissions reductions

2.1.4.1 Optimised fertiliser use

Applying only the fertiliser that is required during periods at appropriate times and in forms most likely to be available to plants reduces the potential for nitrogen losses, including emissions of nitrous oxide. This also allows for reduced waste and in some cases a reduction in the amount of fertiliser required to achieve the same production, reducing the Scope 3 emissions of purchased fertiliser.

Assuming fertiliser application can be reduced without reducing productivity, this option saves money for each tonne of CO_2-e avoided. However, the small contribution of these emissions to livestock systems and the scope for reducing fertiliser without affecting production means that the total abatement potential is comparatively low.

2.1.4.2 Inhibitor coated fertiliser

Fertilisers coated with nitrification inhibitors have been shown to reduce nitrous oxide emissions associated with fertiliser application. The impact is variable with several factors including moisture, pH and temperature influencing effectiveness (Puttanna *et al.* 1999; Cui *et al.* 2021). High temperatures, starting at about 20ºC, reduce efficacy (Puttanna *et al.* 1999). Application can be timed to avoid high temperatures; generally, fertilisation does not occur in summer when temperatures are usually higher than this. There is also a trade-off between reduced nitrous oxide emissions and increased volatilisation of ammonia gas which leads to indirect nitrous oxide emissions (Lam *et al.* 2017). Activities such as deep placement (10 cm) of nitrification inhibitors have been shown to result in lower total direct and indirect nitrous oxide emissions (Zhang *et al.* 2022). Even at its most effective, the relatively small contribution of these emissions to livestock systems lead to a comparatively low total abatement potential.

There are studies showing increased nitrogen use efficiency with nitrification and urease inhibitors (Lam *et al.* 2018). This leads to the positive impacts of the inhibitor paying for the added costs in some circumstances (Xia *et al.* 2017; Lam *et al.* 2018). The details around the conditions required to achieve these benefits require more research so we have not included co-benefits in the MACC analysis, but it should be noted the MACC value reported is a high-end estimate of the abatement cost for this option.

2.1.5 Carbon dioxide emissions reductions

2.1.5.1 Renewable energy

In South Australia, currently grid energy is over 70% renewable, and the target is 100% renewables by 2027. This means South Australia's grid electricity is associated with less emissions than all other states except Tasmania and emissions from electricity will continue to decline in the coming years.

Due to the low emissions associated with electricity use and the low contribution of these emissions to livestock operations, the total potential abatement from renewable energy options is low. However, this option provides a return on investment, typically within 3 to 5 years, and is worthwhile solely for economic reasons.

2.1.5.2 Purchasing low-carbon emission inputs

In many cases it is difficult to determine which products have lower embedded emissions and to incorporate those changes in the carbon account. Often the differences in these emissions are not accounted for in a specific way due to the small contribution they make to total emissions. This is especially the case with chemical inputs. The products are discussed in more detail in the prospective options section. However, the purchasing of supplementary feed with lower emissions or lower emissions intensity can be made and incorporated into the carbon account.

Supplementary feed: If the suppliers of supplemental feed have their own carbon footprint you can include this information in your purchasing decisions. The reporting of their emissions intensity can be incorporated into your carbon footprint calculations. Given the increasing risk around deforestation, careful sourcing of supplemental feed will become increasingly important for more than emissions accounting.

The amount of emissions this could reduce will depend on the extent and frequency of use of supplemental feed and the carbon footprints of the available supplementary feed options. This varies substantially and the associated cost assumptions would be speculative. Due to these factors this option is not included in the MACC. For farmers that have a noticeable proportion of emissions coming from the purchase of supplementary feed, it can be worthwhile including information on the carbon footprint of potential feed option into purchasing decisions.

2.2 Dairy

Table 2 summarises the main characteristics of emissions reductions options for dairy operations including the types of systems the option can be implemented, the technical mitigation potential, the expected uptake and the ability of the option to be accounted for and verified. This information served as the assumptions for the dairy MACC (Figure 5). Section 1.2 includes an explanation of marginal abatement cost curves (MACCs).

Table 2. Dairy system emissions reduction options and their expected reduction potential and uptake

Emission reduction option	Applicable systems	Reduction in target emissions in applicable system	Expected uptake	Can be included in GAF	Can be 3rd party verified
Productivity gains (management)	All	5–15% of animal emissions depending on context%	High	Yes	Yes
Productivity gains (genetic)	All	0.2% per year of animal emissions until peak reached	High	Yes, when reflected in fertility, survival, feed intakes, etc	Yes, when reflected in fertility, survival, feed intakes, etc
Sustainability Index	All	0.3% by 2030	Low, will take time as most bulls not ranked	No, method not developed	No, method not developed
Bovaer	Cows fed >2x per day	15–30% of enteric methane emissions	Low, costly	No but can be addressed with additional calculations in GAF	Expected 2025
Agolin	All	5–10% of enteric methane emissions	High	No but can be addressed with additional calculations in GAF	Expected 2025
Feeding wheat	Feed pad	~10% of enteric methane emissions	Low and for only 8 weeks	No but can be addressed with additional calculations in GAF	No
Forage Brassicas	Those with existing cropping	~10% of enteric methane emissions	Low and for 3 months	No but can be addressed with additional calculations in GAF	No, method for verifying of intakes not developed
Optimised fertiliser use	All	7.5% reduction in emissions relating to nitrogen fertilisers	Low, already broadly used	Yes	Yes
Balancing energy: protein ratios in spring	Feed pad	50% of urine N_2O emissions	Low, already broadly used	No but can be addressed with additional calculations in GAF	No
Use of inhibitor coated fertiliser	All	~25% reduction in fertiliser nitrous oxide emissions	Low, costly	No, emission reduction too variable	No
Renewable energy	All	30% reduction in emissions relating to electricity (SA grid currently 70% renewable)	High	Yes	Yes

Low ≤5%; Moderate 6–15%, High 16%–25%

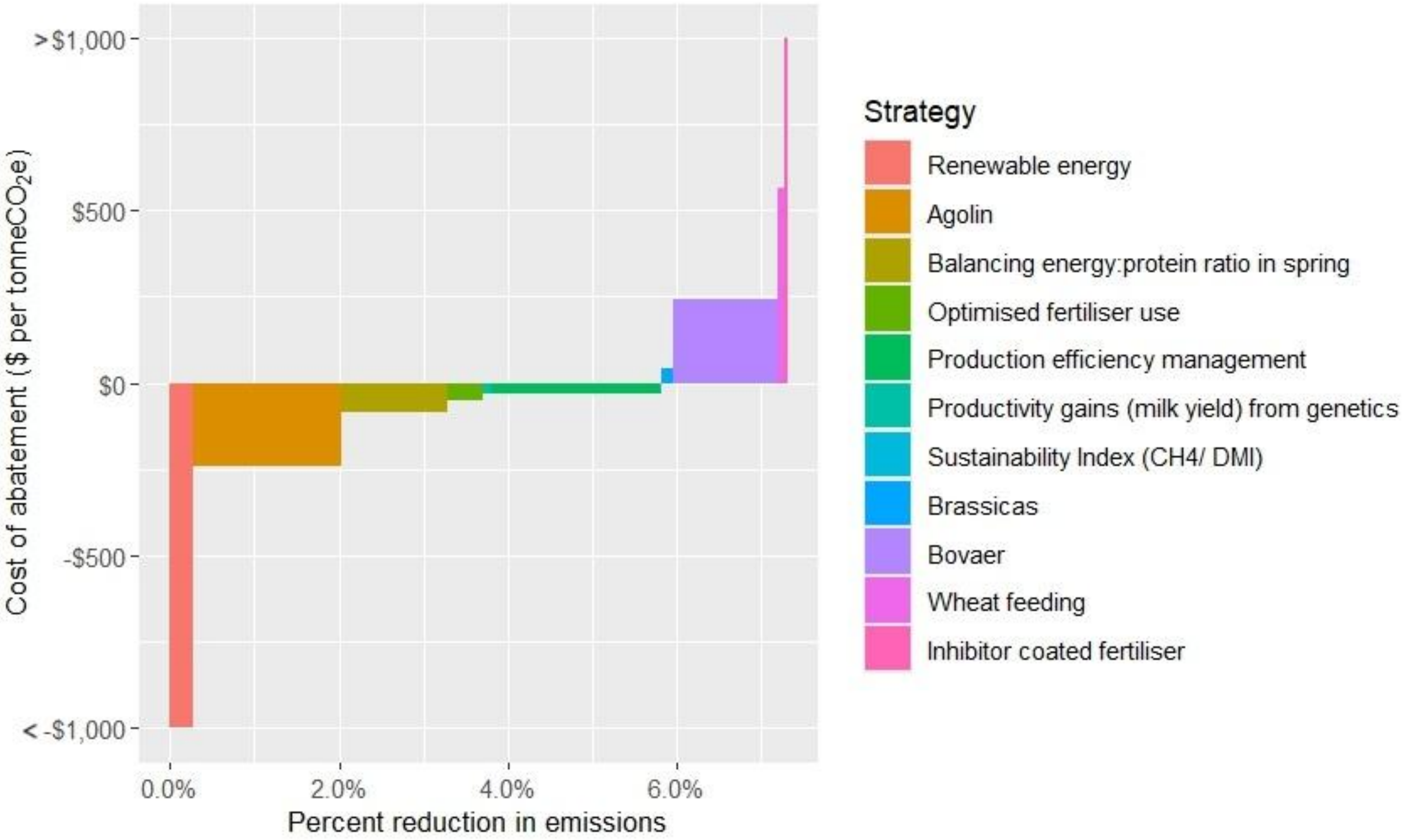

Figure 5: Marginal abatement cost curve for dairy sector emission reduction strategies. See Table 2 and text for details on assumptions used. It is important to note this includes a small productivity benefit for Agolin and no productivity benefit for inhibitor coated fertiliser. Several options can have variable costs/benefits and this would give a different result Productivity gains from genetics and management are shown as a small benefit for visualisation purposes but are assumed to be $0 / tonne CO_2-e.

2.2.1 Productivity gains from improved management

Improving the whole-herd productivity results in efficiencies that reduce emissions intensity. These options represent “best practice” implemented with an aim to achieve a net financial benefit. The potential and extent of this benefit will depend on several factors including the system, location, and method used to increase productivity.

Mitigation rates are variable and influenced by the current productivity level, potential for improvement and status of other productivity parameters. Management practices can have long term compounding impacts such as improved genetics and others are seasonally dependent management decisions.

These options will be captured with annual reporting and thus will be included in D-GAF or ADCC calculations without any additional data requirements.

Management options that improve production efficiency are win-win in that they are cost effective and reduce the emissions produced per unit of product (litre of milk, kg fat and protein corrected milk, etc). Delivering better productivity can occur through a combination of genetics, nutrition, and management.

Options that reduce waste and ensure each cow is performing at its best will assist in reducing emissions intensity. These options include those that increase calving rate, decrease mortality, and improve the conversion of feed to milk:

- Pregnancy rates. The use of feeding strategies can help to improve reproductive performance of breeding cows by optimising the body condition score at the time of insemination.
- Replacement rates. Maintaining the minimum cow inventory possible can be pursued by reducing the number of replacement cows required and removing non-productive animals. This will help to improve the carbon footprint because it is impacted by animal numbers and milk production.
- Health and mortality management. Health issues in the milking herd results in reduced milk production. Dairy cows have a maintenance period prior to first milking where they are generating emissions, but not yet producing milk. Improving animal health can increase the productive period in a cow’s life, compared to the maintenance period.

2.2.2 Productivity gains from genetics

Feed conversion ratio (FCR) is an important determinant of the carbon footprint in livestock systems. Any practice delivering better FCR will reduce the carbon footprint, all other factors being equal. Measuring and demonstrating an improvement will reduce carbon footprint and feed costs and is an ideal intervention that should be cost-effective.

The Sustainability Index is available for selecting animals that produce less methane per kilogram of protein equivalent produced. This index performs similar to the BPI. The main limitation is a lack of bulls ranked on this index. Once implemented the annual gains are small but cumulative and will have a much larger impact past 2030.

2.2.3 Feeding strategies

2.2.3.1 Bovaer

Bovaer is an enzyme inhibitor that reduces the production of enteric methane. It is also called 3-NOP. It is most effective when it is fed consistently throughout the day. Thus, it results in greater reductions in feedlots and other systems with total mixed ration feeding programs. Unless the dairy is a total mixed ration system, the mitigation expected is lower than in feedlots. Dose and NDF (neutral detergent fibre) influence the reduction in emissions observed with Bovaer, but in a system where it is only fed twice a day this is less influential. For the dairy MACC, Figure 5, it is assumed that there are enough total mixed ration or intensive partial mixed ration systems that 5% of dairy cows could achieve a 20% reduction in methane emissions with Bovaer. The technical requirement for needing to be fed more than twice a day and the cost associated with Bovaer leads to the low potential adoption by 2030. A Bovaer product that can be used in extensive systems is in development and this will require a separate analysis to determine abatement potential and cost.

There are no concerns for animal, product quality, or environmental health of using Bovaer at recommended doses. It has been approved for use in over 50 countries including the EU, Canada and Australia. There are typical Work Health and Safety requirements for handling Bovaer. Current information also suggests no significant positive or negative impact on productivity in Australian dairies.

2.2.3.2 Agolin

Agolin is a rumen modifier made of essential oils that reduces enteric methane production. It has lower effectiveness than Bovaer but can be applied to more systems and is available as an organic product. A meta-analysis using data primarily from dairy cattle found daily methane production was reduced by 8.8% and methane production per unit feed was reduced by 12.9% (Belanche *et al.* 2020). There is variability across studies and more research is required to understand the sources of the variation and to determine the impact of Agolin on methane emissions over long timeframes.

In dairy systems, available evidence through the previously described meta-analysis suggests a potential productivity gain with Agolin of 4% increase in milk yield. The dairy MACC used a conservative estimate of 3% increase in milk yield to allow for differences in conditions.

Given the high potential of Agolin and the low risks involved, determining the potential of Agolin to reduce emissions and increase milk yields in dairies within Hills and Fleurieu is warranted. Determining the productivity benefit will require a reasonable sample size since the goal is to detect a small change (3-5%) but will be technically easier than measuring the reduction in methane emissions.

2.2.3.3 Fats and oils in grass-fed cattle

Increasing the energy concentration of the diet of grass-fed animals reduces emissions. This option is not included in the dairy MACC since dairy diets are already typically high in fats and diets should not exceed about 6-8% dietary fat. However, if the current diet is below this level of fat composition, it is worth considering increasing fat content of the diet.

The technical mitigation potential was determined to be approximately 4% reduction in methane per 1% increase of dietary fat (Moate *et al.* 2011; Beauchemin *et al.* 2020). A meta-analysis found that all metrics of methane, including g/day, g/ kg DMI, and g/ kg milk yield decreased significantly when diets contained >5% fat. This study also determined that mitigation was most strongly associated with mono and poly-unsaturated fatty acid (Patra 2013). Sunflower oil at approximately 5% DM reduced methane emissions (g/day) by 22% (McGinn *et al.* 2004). A study of canola oil at 4.6% of DM resulted in a statistically insignificant (P=0.09) decrease in methane yield (g/kg DM) of 21%.

This option is available for total mixed ration systems and more intensive partial mixed ration systems that currently have a ration with less than about 6% dietary fat. In systems that are not total mixed ration the mitigation potential will depend on the extent to which fats and oils are supplemented throughout the year. A cost-benefit analysis of the specific oil being considered is needed to determine if the productivity gains will outweigh the added costs. It is worth noting that the use of some supplements may prevent qualifying for some certifications and can be associated with high Scope 3 emissions, including potentially higher emissions associated with some crops or transportation of feed to the farm. Due care should be applied when selecting a product with a good understanding of its source.

Detailed data on feed input and diet characteristics are required to incorporate the use of fats and oils in the carbon account. Records are also required to demonstrate these changes for third party verification.

2.2.3.4 Wheat feeding

Feeding grain reduces methane emissions (McGeough *et al.* 2010; Moate *et al.* 2020; Almeida *et al.* 2025). For instance, a meta-analysis of four feedlot studies found that an increase in dietary NDF of 1% was associated with a 2.3 gram increase in methane production (methane/d) (Almeida *et al.* 2025), thus high grain diets with low NDF result in less methane emissions. However, similar to fats, dairy diets are typically high in concentrates without much scope for increases in the proportion of grains without negative impacts.

The primary potential for further reducing emissions in dairies with concentrates is to increase the proportion of wheat in the diet for a limited period (approximately 8 weeks). Feeding wheat specifically, as opposed to other grains, has been shown to reduce emissions. A diet with 6 kg of wheat reduced methane emissions by 6% per day and 10.6% per unit DMI compared to the diet with no wheat. This did not reduce milk yield but resulted in a 6.1% decrease in milk fat and a 7.1% increase in milk protein compared to no wheat (Moate *et al.* 2020). Greater amounts of wheat had negative impacts on production and milk fat.

Wheat is typically more expensive than other grains used in dairy diets. The expense of replacing barley with wheat in the diet is high compared to the small reduction in emissions that can be achieved making this a high-cost option. This can be managed to some extent by timing the inclusion of wheat when prices are comparatively low. If considering this option, consult a nutritionist to ensure the change does not cause acidosis or other issues.

2.2.3.5 Brassicas

Common forage crops are canola/rape, swede and leafy turnips. These Brassicas are typically grown in cool temperate zones of southern Australia, but some varieties can be grown in broadacre areas with earlier sowing. It is thought that compounds in brassicas reduce retention time in the rumen, lowering emissions (Sun 2020). This is a seasonal option, so the maximum methane reduction is limited by the duration of the year Brassicas are in the diet.

In dairy cows fed pasture and either concentrates or crushed rapeseed, methane production was reduced by 12.0% (g/day) and yield was reduced by 10% on the rapeseed diet (Storlien *et al.* 2015). In another study, cows on the diet with forage brassicas had the lowest methane intensity (g/kg energy corrected milk) and lower methane yield (g/kg DM) than those on a diet comprised of Lucerne and chicory and similar emissions compared to dairy cows fed lucerne and brassicas (Williams *et al.* 2016). Canola was demonstrated to decrease enteric methane emissions by 40% (12.6 versus 22.5 g/kg DM intake) in heifers compared with ryegrass in winter (Sun *et al.* 2016).

Although this option has demonstrated enteric emissions reduction and is applicable to extensive systems, the ability to verify the intake of Brassicas is a limiting factor. Since there is more interaction with the animals in dairy systems, this is considered a potential option for dairies.

2.2.4 Nitrous oxide emissions reductions

2.2.4.1 Optimised fertiliser use

Applying only the fertiliser that is required during periods it is most likely to be available to plants reduces the potential for nitrogen losses, including emissions of nitrous oxide. This also allows for reduced waste and in some cases a reduction in the amount of fertiliser required to achieve the same production, reducing the Scope 3 emissions of purchased fertiliser.

Assuming fertiliser application can be reduced without reducing productivity, this option saves money for each tonne of CO_2-e avoided. However, the small contribution of these emissions to livestock systems and the scope for reducing fertiliser without affecting production means that the total abatement potential is comparatively low.

2.2.4.2 Inhibitor coated fertiliser

Fertilisers coated with nitrification inhibitors have been shown to reduce nitrous oxide emissions associated with fertiliser application. The impact is variable with several factors including moisture, pH and temperature influencing effectiveness (Puttanna *et al.* 1999; Cui *et al.* 2021). High temperatures, starting at about 20ºC, reduce efficacy (Puttanna *et al.* 1999). Application can be timed to avoid high temperatures; generally, fertilisation does not occur in summer when temperatures are usually higher than this. There is also a trade-off between reduced nitrous oxide emissions and increased volatilisation of ammonia gas which leads to indirect nitrous oxide emissions (Lam *et al.* 2017). Activities such as deep placement (10 cm) of nitrification inhibitors have been shown to result in lower total direct and indirect nitrous oxide emissions (Zhang *et al.* 2022). Even at its most effective, the relatively small contribution of these emissions to livestock systems lead to a comparatively low total abatement potential.

There are studies showing increased nitrogen use efficiency with nitrification and urease inhibitors (Lam *et al.* 2018). This leads to the positive impacts of the inhibitor paying for the added costs in some circumstances (Xia *et al.* 2017; Lam *et al.* 2018). The details around the conditions required to achieve these benefits require more research so we have not included co-benefits in the MACC analysis, but it should be noted the MACC value reported is a high-end estimate of the abatement cost for this option.

2.2.4.3 Balancing protein: energy of diet in spring

Adding grain to the diet in spring when crude protein of pastures is high, reduces N in the urine reducing nitrous oxide emissions from urine patches. Estimated reductions in nitrous oxide emissions from urine with this option are about 50% (Christie *et al.* 2014)

This option also increases milk production, depending on the stage of lactation. Cows in early or mid-lactation tend to have a larger milk yield increase while on grain than those late in lactation. Changes in the diet that are used to calculate emissions will capture this emissions reduction. The assumptions made for the MACC resulted in the productivity gain from added grain in the diet outweighing the cost of the grain. Although these were conservative assumptions, this is not always the case as milk and grain prices vary but this option typically ranges from a small cost to a small gain.

2.2.5 Carbon dioxide emissions reductions

2.2.5.1 Renewable energy/ energy efficiency

In South Australia, currently grid energy is over 70% renewable, and the target is 100% renewables by 2027. This means South Australia's grid electricity is associated with less emissions than all other states except Tasmania and emissions from electricity will continue to decline in the coming years.

Due to the cooling and storing of milk by dairies, they have a larger proportion of emissions from electricity production and/or diesel use on farm compared to beef or sheep systems. Still the total abatement potential from renewable energy is low compared to dairy emissions overall. However, this option provides a return on investment and its worthwhile solely for economic reasons.

2.2.5.2 Purchasing low-carbon emission inputs

In many cases it is difficult to determine which products have lower embedded emissions and incorporate those changes in the carbon account. Often the differences in these emissions are not accounted for in a specific way due to the small contribution they make to total emissions. This is especially the case with chemical inputs. The products are discussed in more detail in the prospective options section. However, some purchases that make up a majority of Scope 3 emissions have more potential; in dairy this is often supplemental feed.

Supplementary feed: If the suppliers of supplemental feed have their own carbon footprint you can include this information into your purchasing decisions. The reporting of their emissions intensity can be incorporated into your carbon footprint calculations. Given the increasing risk around deforestation, careful sourcing of supplemental feed will become increasingly important for more than emissions accounting.

The amount of emissions this could reduce will depend on the extent and frequency of use of supplemental feed and the carbon footprints of the available supplementary feed options. This varies substantially and the associated cost assumptions would be speculative. Due to these factors this option is not included in the MACC. For farmers that have a noticeable proportion of emissions coming from the purchase of supplementary feed, it can be worthwhile including information on the carbon footprint of potential feed options into purchasing decisions.

2.3 Sheep

Table 3 summarises the main characteristics of emissions reductions options for sheep operations including the types of systems the option can be implemented, the technical mitigation potential, the expected uptake and the ability of the option to be accounted for and verified. and verified. This information served as the assumptions for the sheep MACC (Figure 6). Section 1.2 includes an explanation of marginal abatement cost curves (MACCs).

2.3.1 Productivity gains from improved management

Improving the whole-flock productivity results in efficiencies that reduce emissions intensity. These options represent “best practice” implemented with an aim to achieve a net financial benefit. ,The potential and extent of this benefit will depend on several factors including the system, location, and method used to increase productivity.

Mitigation rates are variable and influenced by the current productivity level, potential for improvement and status of other productivity parameters. Management practices can have long term compounding impacts such as improved genetics and others are seasonally dependent management decisions.

These options will be captured with annual reporting and thus will be included in SB-GAF calculations without any additional data requirements.

Management options that improve production efficiency are win-win in that they are cost effective and reduce the emissions produced per unit of product (kg of meat or wool) (Alcock and Hegarty 2011). Delivering better productivity can occur through a combination of genetics, nutrition, and management.

Options that reduce waste and ensure each animal is performing at its best will assist in reducing emissions intensity. These options include those that increase lambing rate, decrease mortality, and improve feed nutrition to reduce time to slaughter for sheep meat (Alcock and Hegarty 2011):

- Lambing rates. Maintaining the minimum ewe inventory possible, including careful cull management to improve breeding stock and reduce the carbon footprint. Meat production is impacted by total turnoff.
- In self-replacing prime lamb systems, consider mating maiden ewes at 7 months (v 19 months), assuming target weights are reached by the joining period.
- Average daily gain. Increasing weight gain through improved feed nutrition reduces the time to slaughter for sheep meat production. It also reduces the emissions produced over the life of the animal.
- Health and mortality management. Aside from being a loss in the system, mortalities reduce live weight sales which results in more emissions relative to output. Improving animal health issues and minimising losses improves carbon footprint for wool and lamb production.

2.3.2 Productivity gains from genetics

Feed conversion ratio (FCR) is an important determinant of the carbon footprint in livestock systems. Any practice delivering better FCR will reduce the carbon footprint, all other factors being equal. Measuring and demonstrating an improvement will reduce carbon footprint and feed costs and is an ideal intervention that should be cost-effective.

It is possible to breed for better Residual Feed Intake (RFI) which over time may deliver better outcomes for integrated suppliers. This is analogous to the Sustainable Breeding Index for dairy. Significant development is required to make this an option that can be incorporated into breeding decisions. However, research in New Zealand shows moderate heritability of RFI (Johnson *et al.* 2022).

2.3.3 Feeding strategies

2.3.3.1 Bovaer

Bovaer would likely be effective at reducing methane emissions in sheep in feedlots. There is limited information on the impacts of Bovaer on sheep with only one published study of 6 sheep fed a diet of 60% lucerne and 40% oats. In this experiment methane was reduced by 21% per kg DMI after 30 days There was no impact of Bovaer on DMI (Martinez-Fernandez *et al.* 2014). Given the mode of action, Bovaer is likely to reduce enteric methane in sheep (van Gastelen *et al.* 2019). However, the extent of this reduction and its variation with diet and other factors requires more research. The lack of knowledge and methods currently limits the ability of incorporating this option into a carbon account for sheep. Additionally, the impacts will only occur for the length of time sheep are in the feedlot, which is a major limitation to the potential adoption.

2.3.3.2 Agolin

Agolin is a rumen modifier made of essential oils that reduces enteric methane production. It has lower effectiveness than Bovaer but can be applied to more systems and is available as an organic product. Unpublished results of 2 Australian studies suggest a larger impact on enteric methane emissions in sheep than beef, over 20% reductions in methane production per day. This research also suggests no negative and potentially a small productivity gain with Agolin in sheep. In the MACC, a conservative methane reduction of 10% and no productivity benefit is assumed. When a 1% increase in liveweight gain was assumed, Agolin became an economically beneficial option for sheep systems. On-farm trials to determine the productivity benefit with Agolin in sheep is an important research gap to address.

Table 3. Sheep system emissions reduction options and their emissions reduction potential and uptake

Emission reduction option	Applicable systems	Reduction in target emissions in applicable system	Expected uptake	Can be included in GAF	Can be 3rd party verified
Productivity gains (management)	All	5–15% of animal emissions depending on context%	High	Yes	Yes
Productivity gains (genetic)	All	0.2% per year of animal emissions until peak reached	Moderate	Yes, when reflected in fertility, survival, feed intakes, etc	Yes, when reflected in fertility, survival, feed intakes, etc
Bovaer	Total Mixed Ration	15–20% of enteric methane emissions	Low, costly	No but can be addressed with additional calculations in GAF	No
Agolin	All	5%–10% of enteric methane emissions	Moderate	No but can be addressed with additional calculations in GAF	No
Fats and oils in grass fed cattle	Feed pad	4% reduction in enteric methane per day per 1% increase of dietary fat	Low	No but can be addressed with additional calculations in GAF	No
Forage Brassicas	Those with existing cropping	~15–25% of enteric methane emissions	Low and for 3 months	No but can be addressed with additional calculations in GAF	No, method for verifying of intakes not developed
Optimised fertiliser use	All	3.5% reduction in emissions relating to nitrogen fertilisers	Moderate	Yes	Yes
Use of inhibitor coated fertiliser	All	~25% reduction in fertiliser nitrous oxide emissions	Low	No, emission still too variable	No
Renewable energy	All	30% reduction in emissions relating to electricity (SA grid currently 70% renewable)	High	Yes	Yes

Low <5%; Moderate 5–15%, High 15%–25%

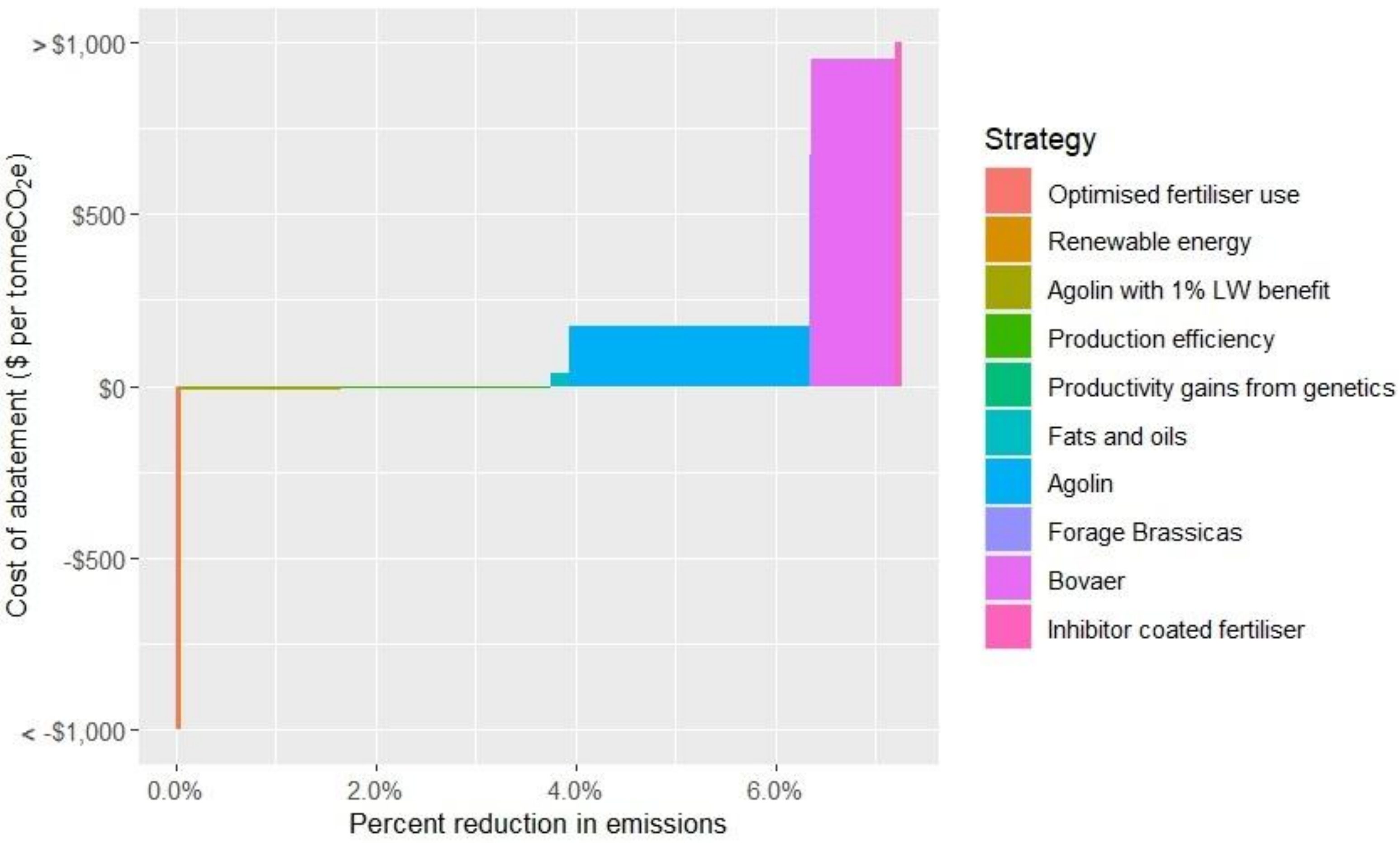

Figure 6: Marginal abatement cost curve for sheep sector emission reduction strategies. See Table 3 and text for details on assumptions used. This includes two Agolin scenarios, one with no productivity benefit and one with 1% increase in LW gain with sheep. There are no productivity gains included for inhibitor coated fertiliser. Several options can have variable costs/benefits, and this would give a different result. Productivity gains from genetics and management are shown as a small benefit for visualisation purposes but are assumed to be $0 / tonne CO_2–e.

2.3.3.3 Fats and oils in grass-fed sheep

Increasing fat in the diets of sheep reduces methane emissions, with each percentage increase in supplemental dietary fat reducing methane by 4.3% (Patra 2014). However, similar to cattle, fat can only make up so much of the diet (about 5%) (Agriculture Victoria 2018) before there are negative consequences including reduced dry matter and NDF digestibility (Patra 2014).

In systems that are not total mixed ration, the mitigation potential will depend on the extent to which fats and oils are supplemented throughout the year. A cost-benefit analysis of the specific oil being considered is needed to determine if the productivity gains will outweigh the added costs. It is worth noting that the use of some supplements may prevent qualifying for some certifications and can be associated with high Scope 3 emissions. Due care should be applied when selecting a product with a good understanding of its source.

The information required for inclusion in a GAF calculation includes details of the nutritional characteristics of the diet before and after the addition of oil to the diet, the number of days the ration is fed, and the classes of cattle fed the new ration.

2.3.3.4 Brassicas

Many studies show methane reduction in sheep on diets containing Brassicas, particularly forage rapeseed (Brassica napus L.). Increasing proportion of forage rapeseed in the diet results in greater reduction in enteric methane. Inclusion of 25% to 50% reduced enteric methane by less than 6%. A diet of 75% forage rapeseed reduced enteric methane emissions by 11% and a diet of 100% forage rapeseed reduced emissions by 37% compared to a diet of perennial ryegrass. (Della Rosa *et al.* 2022). Another study with 100% inclusion found reductions of 22% after 15 weeks (Sun *et al.* 2015) and a meta-analysis reported significant reduction in enteric methane emissions with both summer and winter forage rape, but a greater reduction with winter forage rape which had lower lignin concentrations. This study also found reductions in enteric methane emissions with swede in winter and leafy turnip and forage radish in summer (Sun *et al.* 2016). Although the reductions can be substantial at high inclusion rates, the seasonality of this option means the annual reduction would be less, for instance a 20% reduction occurring for 1 season would be a 5% reduction over the year. If inclusion rates are lower, then the mitigation is further reduced.

The ability to verify the intake of Brassicas is another limiting factor. To understand the emission reduction that occurs on farm, data needs to be collected on the amount of the Brassica comprising the diet for which animals and for what length of time. This currently limits the ability of this option to be included in carbon accounting. Given this option is already being used and could be included fairly simply into many systems, there is a need to develop a method for estimation and verification of emission reductions but on-farm research is required.

2.3.4 Nitrous oxide emissions reductions

2.3.4.1 Optimised fertiliser use

Applying only the fertiliser that is required during periods at appropriate times and in forms most likely to be available to plants reduces the potential for nitrogen losses, including emissions of nitrous oxide. This also allows for reduced waste and in some cases a reduction in the amount of fertiliser required to achieve the same production, reducing the Scope 3 emissions of purchased fertiliser.

Assuming fertiliser application can be reduced without reducing productivity, this option saves money for each tonne of CO_2-e avoided. However, the small contribution of these emissions to livestock systems and the scope for reducing fertiliser without affecting production means that the total abatement potential is comparatively low.

2.3.4.2 Inhibitor coated fertiliser

Fertilisers coated with nitrification inhibitors have been shown to reduce nitrous oxide emissions associated with fertiliser application. The impact is variable with several factors including moisture, pH and temperature influencing effectiveness (Puttanna *et al.* 1999; Cui *et al.* 2021). High temperatures, starting at about 20ºC, reduce efficacy (Puttanna *et al.* 1999). Application can be timed to avoid high temperatures; generally, fertilisation does not occur in summer when temperatures are usually higher than this. There is also a trade-off between reduced nitrous oxide emissions and increased volatilisation of ammonia gas which leads to indirect nitrous oxide emissions (Lam *et al.* 2017). Activities such as deep placement (10 cm) of nitrification inhibitors have been shown to result in lower total direct and indirect nitrous oxide emissions (Zhang *et al.* 2022). Even at its most effective, the relatively small contribution of these emissions to livestock systems lead to a comparatively low total abatement potential.

There are studies showing increased nitrogen use efficiency with nitrification and urease inhibitors (Lam *et al.* 2018). This leads to the positive impacts of the inhibitor paying for the added costs in some circumstances (Xia *et al.* 2017; Lam *et al.* 2018). The details around the conditions required to achieve these benefits require more research so we have not included co-benefits in the MACC analysis, but it should be noted the MACC value reported is a high-end estimate of the abatement cost for this option.

2.3.5 Carbon dioxide emissions reductions

2.3.5.1 Renewable energy/ energy efficiency

In South Australia, currently grid energy is over 70% renewable, and the target is 100% renewables by 2027. This means South Australia's grid electricity is associated with less emissions than all other states except Tasmania and emissions from electricity will continue to decline in the coming years.

Due to the low emissions associated with electricity use and the low contribution of these emissions to livestock operations, the total potential abatement from renewable energy options is low. However, this option provides a return on investment and its worthwhile solely for economic reasons.

2.3.5.2 Purchasing low-carbon emission inputs

In many cases it is difficult to determine which products have lower embedded emissions and to incorporate those changes in the carbon account. Often the differences in these emissions are not accounted for in a specific way due to the small contribution they make to total emissions. This is especially the case with chemical inputs. The products are discussed in more detail in the prospective options section. However, the purchasing of supplementary feed with lower emissions or lower emissions intensity can be made and incorporated into the carbon account.

Supplementary feed: If the suppliers of supplemental feed have their own carbon footprint you can include this information into your purchasing decisions. Their reporting of their emissions intensity can be incorporated into your carbon footprint calculations. Given the increasing risk around deforestation, careful sourcing of supplemental feed will become increasingly important for more than emissions accounting.

The amount of emissions this could reduce will depend on the extent and frequency of use of supplemental feed and the carbon footprints of the available supplementary feed options. This varies substantially and the associated cost assumptions would be speculative. Due to these factors this option is not included in the MACC. For farmers that have a noticeable proportion of emissions coming from the purchase of supplementary feed, it can be worthwhile including information on the carbon footprint of potential feed option into purchasing decisions.

2.4 Cropping

Table 4 summarises the main characteristics of emissions reductions options for cropping operations including the types of systems the option can be implemented, the technical mitigation potential, the expected uptake and the ability of the option to be accounted for and verified. This information served as the assumptions for the cropping MACC (Figure 7). Section 1.2 includes an explanation of marginal abatement cost curves (MACCs).

2.4.1 Addressing yield gaps

Due to the comparatively low emissions generated from the production of Australian crops, addressing any yield gaps is a first step in cropping systems. Even in cases where yield gaps need to be addressed with increased nutrient application, the savings in emissions associated with avoided indirect land use change offset the emissions associated with the purchase and application of fertilisers (Simmons *et al.* 2020)

Given overapplication of nutrients results in increased emissions, emissions intensity, and other environmental issues, minimising the yield gap without over applying nutrients both to reduce the cost of inputs and emissions associated with fertiliser is a challenging aim that changes based on seasonal conditions. Complicating this are climate impacts that increase the difficulty of addressing the yield gap (Hochman *et al.* 2017).

There are several methods for achieving this complex task with some more relevant than others on specific farms. These methods, which represent best practice, include controlling fallow weeds, taking advantage of improved genetics, matching variety to planting date, ensuring best conditions during critical periods, soil amelioration, and minimising nutrient limitations (Hunt *et al.* 2020; Porker *et al.* 2025). Practices associated with precision agriculture and use of enhanced efficiency fertilisers, particularly coated with nitrification inhibitors, are discussed in more detail below.

This is a complex issue that could lead to lower emissions intensity of the product but higher farm-level emissions for the benefit of reduced land use change elsewhere. As such the emission reduction occurs on an emission intensity basis. Like productivity options in other sections of this Guideline, it is assumed that there is a small reduction in emissions on a subset of farms and the costs of implementation are offset by increases in production.

2.4.2 Precision agriculture

Precision agriculture is characterised by the use of technology to collect data to inform and implement decisions that increase crop yields Although not the sole purpose, precision agriculture techniques optimise fertiliser use in cropping systems. The techniques involved include soil testing and monitoring, including soil mapping and timing optimisation, split fertiliser application and variable rate application.

Emission reductions are variable and depends on several factors including the system being replaced, the technology being used, and environmental conditions. Although the rates vary widely across the literature, the one of the primary determinants is the change in the amount of fertiliser applied and that portion of the impact would be accounted for in emissions accounting. Other more specific techniques such as spatially and temporally specific applications or deep placement are not incorporated into the account. Similar to other sectors, we assumed a 5% reduction in fertiliser purchase could be achieved with precision agricultural techniques without a long-term cost to the farming system (Balafoutis et al. 2017). In case studies farms in Western Australia and New South Wales the payback period of many precision agricultural techniques were two to five years and the increase in gross margin required to break even was typically $6/ha or less particularly when the area benefiting was 1000 ha or more (Robertson *et al.* 2007).

2.4.3 Inhibitor coated fertilisers

Fertilisers coated with nitrification inhibitors have been shown to reduce nitrous oxide emissions associated with fertiliser application. The impact is variable with several factors including moisture, pH and temperature influencing effectiveness (Puttanna *et al.* 1999; Cui *et al.* 2021). High temperatures, starting at about 20ºC, reduce efficacy (Puttanna *et al.* 1999). Application can be timed to avoid high temperatures; generally, fertilisation does not occur in summer when temperatures are usually higher than this. There is also a trade-off between reduced nitrous oxide emissions and increased volatilisation of ammonia gas which leads to indirect nitrous oxide emissions (Lam *et al.* 2017). Activities such as deep placement (10 cm) of nitrification inhibitors have been shown to result in lower total direct and indirect nitrous oxide emissions (Zhang *et al.* 2022).

This option has a higher potential in cropping systems where nitrous oxide emissions from fertiliser make up a substantial proportion of total emissions. A 25% emission reduction applied to fertiliser N_2O emissions was assumed in the MACC. This is a moderate emissions amount which slightly lower than average since fertiliser applications are likely to occur in autumn when average high temperatures are in the low to mid-20s.

There are studies showing increased nitrogen use efficiency with nitrification and urease inhibitors (Lam *et al.* 2018). This leads to the positive impacts of the inhibitor paying for the added costs in some circumstances (Xia *et al.* 2017; Lam *et al.* 2018). The details around the conditions required to achieve these benefits require more research, so we have not included co-benefits in the MACC. Thus, the MACC value reported is a high-end estimate of the abatement cost for this option. For illustrative purposes, if a crop value of $380/ tonne is assumed, an increase in pasture production of 3% would offset the cost of purchasing the inhibitor coated fertiliser.

Table 4. Cropping system emission reduction options and their emissions reduction potential and uptake

Emission reduction option	Applicable systems	Reduction in target emissions in applicable system	Expected uptake	Can be included in GAF	Can be 3rd party verified
Yield gap	All	Emissions intensity reduction	High	Yes	Yes
Precision agriculture	All	Assumed a 10% reduction in fertiliser related emissions	High	Yes	Yes
Use of inhibitor coated fertiliser	All	~25% reduction in fertiliser nitrous oxide emissions	Low	No, emission still too variable	No
Renewable energy	All	30% reduction in emissions relating to electricity (SA grid currently 70% renewable)	High	Yes	Yes

Low <5%; Moderate 5-15%, High 15%-25%

Table 5. Perennial horticulture emission reduction options and their emissions reduction potential and uptake

Emission reduction option	Applicable systems	Reduction in target emissions in applicable system	Expected uptake	Can be included in GAF	Can be 3rd party verified
Optimal fertiliser use	All	Assumed a 10% reduction in fertiliser related emissions	Moderate; focus on systems with substantial nitrous oxide emissions	Yes	Yes
Micro/ drip irrigation systems	All	30% reduction in fertiliser related emissions	Low, already broadly adopted	Yes	Yes
Use of inhibitor coated fertiliser	All	~25% reduction in fertiliser nitrous oxide emissions	Low	No, emission still too variable	No
Renewable energy	All	30% reduction in emissions relating to electricity (SA grid currently 70% renewable); Greater potential in systems with high percentage of diesel emissions.	Moderate; focus on systems with substantial Scope 1 or 2 CO_2 emissions	Yes	Yes

Low <5%; Moderate 5-15%, High 15%-25%

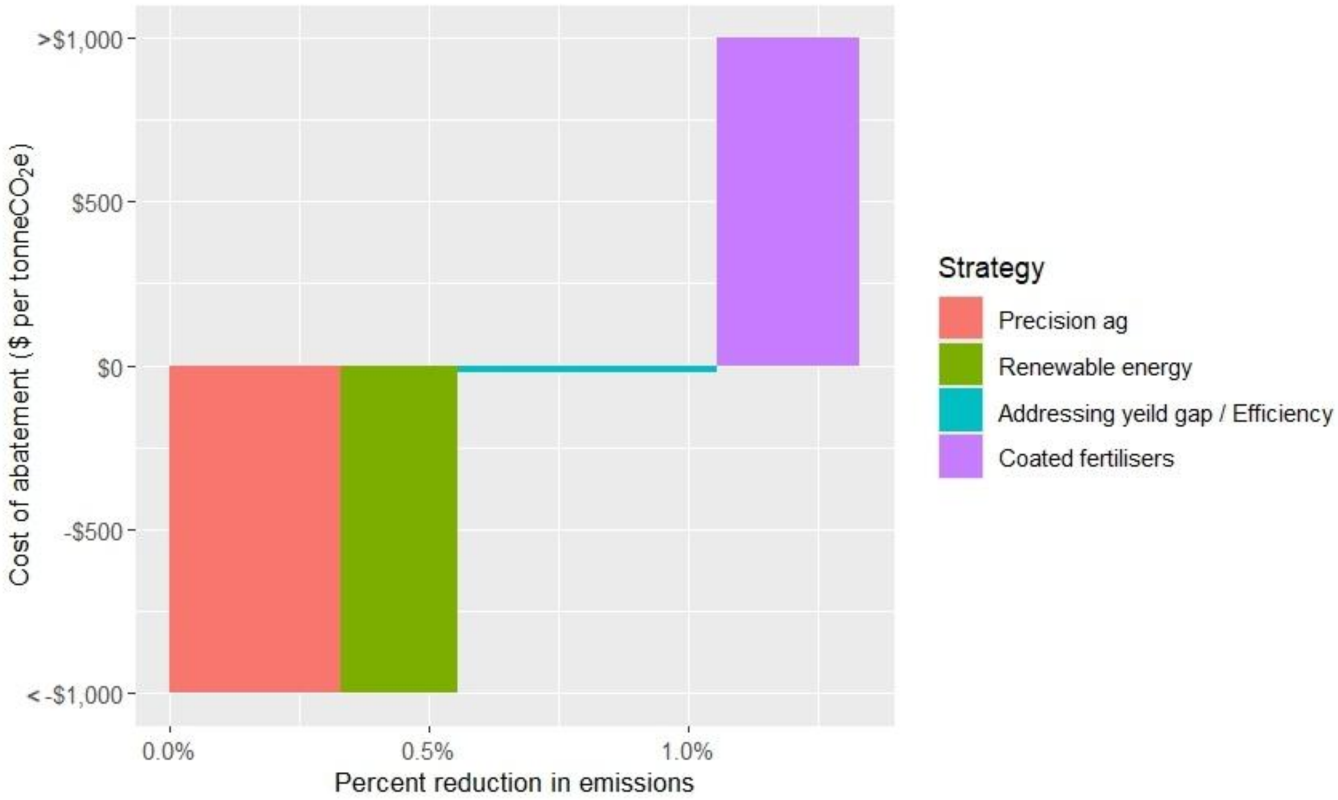

Figure 7: Marginal abatement cost curve for crop sector emission reduction strategies. See emission reduction options text for details on assumptions used. There are no productivity gains included for inhibitor coated fertiliser (see text). Several options can have variable costs/benefits, and this would give a different result. Productivity gains from addressing the yield gap is shown as a small benefit for visualisation purposes but assumed $0 / tonne CO_2–e.

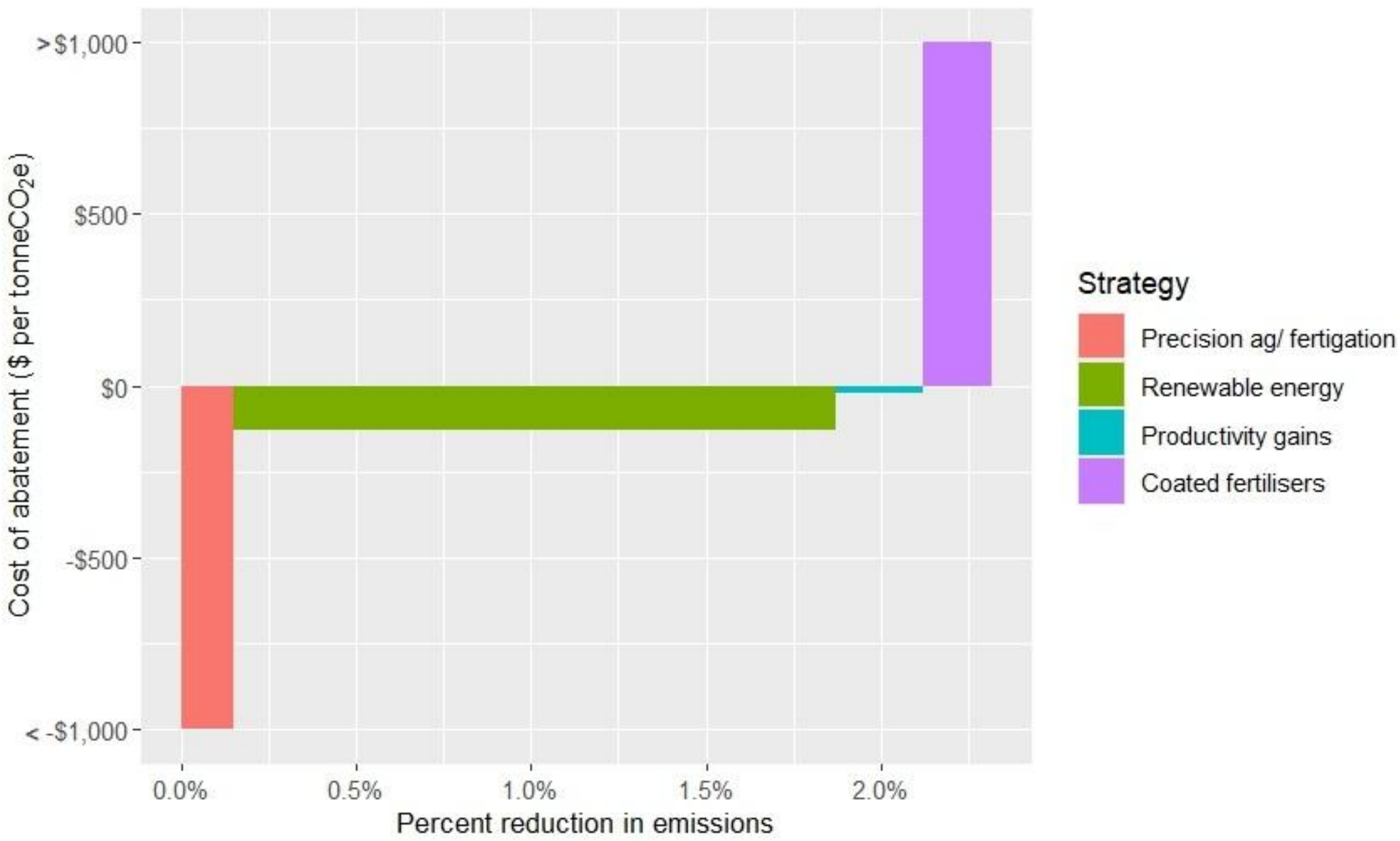

Figure 8: Marginal abatement cost curve for perennial horticulture sector emission reduction strategies. See emission reduction options text for details on assumptions used. There are no productivity gains included for inhibitor coated fertiliser (see text). Several options can have variable costs/benefits, and this would give a different result. Productivity gains from addressing the yield gap is shown as a small benefit for visualisation purposes but assumed $0 / tonne CO_2-e.

2.4.4 Renewable energy

In South Australia, currently grid energy is over 70% renewable, and the target is 100% renewables by 2027. This means South Australia's grid electricity is associated with less emissions than all other states except Tasmania and emissions from electricity will continue to decline in the coming years.

In irrigated cropping systems renewable energy has the potential to substantially reduce total farm emissions, due to the power required for pumping. The numbers in the MACC are not applicable to irrigated cropping. Irrigated cropping makes up less than 1% of the land area, so this was excluded from the MACC. Due to the low emissions associated with electricity use and the low contribution of these emissions to dryland cropping operations, the total potential abatement from renewable energy options is low. However, this option provides a return on investment and its worthwhile solely for economic reasons in both irrigated and non-irrigated cropping systems.

2.4.5 Purchasing low-carbon emission inputs

This option is not well developed currently and as such is described in more detail in the prospective options section. It will have a much larger impact on cropping than on livestock sectors, since the purchase of inputs including lime, fertiliser, herbicides, and pesticides comprise a significant proportion of cropping emissions. However, the information required to include Scope 3 in purchasing decisions is currently difficult to access and, depending on the product, incorporating the impacts of changed purchasing into the carbon account can be difficult.

2.5 Perennial horticulture

Table 5 summarises the main characteristics of emissions reductions options for perennial horticulture operations including the types of systems the option can be implemented, the technical mitigation potential, the expected uptake and the ability of the option to be accounted for and verified. This information served as the assumptions for the perennial horticulture MACC (Figure 8). Section 1.2 includes an explanation of marginal abatement cost curves (MACCs).

2.5.1 Inhibitor-coated fertilisers

Fertilisers coated with nitrification inhibitors have been shown to reduce nitrous oxide emissions associated with fertiliser application. The impact is variable with several factors including moisture, pH and temperature influencing effectiveness (Puttanna *et al.* 1999; Cui *et al.* 2021). High temperatures, starting at about 20ºC, reduce efficacy (Puttanna *et al.* 1999). Application can be timed to avoid high temperatures; generally, fertilisation does not occur in summer when temperatures are usually higher than this. There is also a trade-off between reduced nitrous oxide emissions and increased volatilisation of ammonia gas which leads to indirect nitrous oxide emissions (Lam *et al.* 2017). A meta-analysis of nitrous oxide emissions from perennial fruit trees found that nitrification inhibitors reduced nitrous oxide emissions by an average of 73% (range: 51% to 87%) (Gu *et al.* 2019) and research for Australia has led to a recommended reduction in emissions factor with the inhibitor, DMPP of 55% for horticulture (Grace *et al.* 2023). Inhibitors used in fertigation systems have shown reductions in nitrous oxide emissions of 60% compared to systems without inhibitors or fertigation (Sunling *et al.* 2024). A 50% emission reduction applied to fertiliser N_2O emissions was assumed in the MACC. This option has a higher potential in those horticultural systems where nitrous oxide emissions from fertiliser make up a substantial proportion of total emissions.

There are studies showing increased nitrogen use efficiency with nitrification and urease inhibitors in cropping systems (Lam *et al.* 2018). This leads to the positive impacts of the inhibitor paying for the added costs in some circumstances (Xia *et al.* 2017; Lam *et al.* 2018). The details around the conditions required to achieve these benefits, particularly in perennial horticulture, requires more research so we have not included co-benefits in the MACC analysis, but it should be noted the MACC value reported is a high-end estimate of the abatement cost for this option. This is particularly noteworthy in fruit where some fruits, such as citrus, has been shown to have yield increase with the nitrification inhibitor DMPP (Quiñones *et al.* 2009). The high value associated with fruit crops results in a yield increase of less than 1% offsetting the cost of the inhibited coated fertiliser..

2.5.2 Micro irrigation/ fertigation systems

The impact of being able to control soil water and, in the case of fertigation systems, nutrient levels, leads to low emissions in orchards and vineyards with micro irrigation and fertigation systems. In a New South Wales cherry and apple orchard with micro irrigation, nitrous oxide emissions were between 0.3 to 0.7 kg N_2O per hectare per year which is some of the lowest reported in the world. (Gordon Rogers Applied Horticultural Research 2019). A global meta-analysis found drip irrigation to reduce nitrous oxide emissions by 32% and 46% compared to furrow and sprinkler systems, respectively (Kuang *et al.* 2021). This was used to conservatively estimate a 30% reduction in fertiliser related emissions with micro-irrigation/ fertigation for the MACC.

Although research specific to the costs and benefits of micro irrigation and fertigation in fruit trees grown in this area are unavailable, these options have been shown to reduce water and chemical use, increase yields and fruit quality and reduce labour costs over other types of systems (Shirgure *et al.*; Maraseni *et al.* 2012; Jeyabaskaran *et al.* 2021). Cost assumptions used in the MACC resulted in a 3-year payback period.

Given the yield and efficiency benefits of these systems they have already been widely adopted. Thus, despite their effectiveness, the potential adoption going forward is low due to the prevalence of these systems. Much of the emissions reduction impact would be captured in typical record keeping for carbon accounting, for instance that collected on fertiliser and irrigation use.

2.5.3 Renewable energy

In South Australia, currently grid energy is over 70% renewable, and the target is 100% renewables by 2027. This means South Australia's grid electricity is associated with less emissions than all other states except Tasmania and emissions from electricity will continue to decline in the coming years. There is variability across perennial horticulture sectors so the extent to which renewable energy can reduce emissions will depend on energy use and the extent to which renewables have already been adopted in the sector.

In some perennial horticultural systems renewable energy has the potential to substantially reduce total farm emissions. Replacing grid electricity can reduce Scope 2 emissions which can comprise a substantial proportion of perennial horticulture emissions. Diesel use is the main contributor to emissions from Australian grape growing (Hirlam *et al.*

2023). Thus, switching to electric vehicles and/or renewable energy sources for pumping, boilers, and reducing the use of diesel generators will have a much larger impact in vineyards than reported in other sectors, particularly the livestock sectors.

When renewable energy is replacing grid energy, it is worthwhile solely for economic reasons. Switching to electric vehicles is dependent on several factors and are unlikely to provide return on investment in agriculture systems currently. See prospective options for more details on electric tractors.

2.5.4 Purchasing low-carbon emission inputs

Purchasing low carbon emission inputs will be more effective for some perennial horticultural operations than others. This can have a significant impact in high input systems where fertilisers, herbicides and pesticides make up a substantial portion of emissions. As with other sectors the information required to make an informed choice can be difficult to find, and it is not always straight-forward to include this into farm accounting. In next few years, implementation of this option will become easier. Information related to a few products are outlined in the prospective options section.

2.6 Prospective emission reduction options

2.6.1 Feed options for extensive agricultural systems

Asparagopsis: Although effective at reducing enteric methane emissions, there are research gaps and logistical hurdles to adoption in Australia, particularly in extensive systems. The primary hurdle in feedlots is cost, however in other systems there are other hurdles. Like Bovaer, Asparagopsis is most effective in total mixed rations. Effectiveness drops in extensive systems increasing the cost per unit of abatement further. Impacts of long-term feeding of Asparagopsis has not been determined which is relevant for dairies and other industries where animals would be fed the product most of their lives. There are several studies showing formulations of Asparagopsis that reduced dry matter intake (Muizelaar *et al.* 2021). This may have been addressed with more recently available products (George *et al.* 2024) but testing in more livestock sectors is required before recommending Asparagopsis. There are potential concerns over the environmental impacts of producing Asparagopsis at the scale required (Mehlmann *et al.* 2020; Zanolla *et al.* 2022) and animal welfare concerns (Muizelaar *et al.* 2021).

Mootral: Several studies have demonstrated a reduction in methane emissions with Mootral's product Enterix in beef and dairy systems (Roque *et al.* 2019; Vranken *et al.* 2019; Brand *et al.* 2021). The product is appropriate for intensive systems and is eligible for credits in the Verra Verified Standard carbon program. However, it is expensive and currently difficult to access in Australia.

Other feed additives: Several feed additives with varying active ingredients including essential oils, tannins, probiotics, (pull from long list) have been trialled and in some cases are on the market. However, only those with compelling evidence of emissions reductions have been included in the emission reduction options. It is possible that new and effective products will come on the market in the coming years, but at the time of publication these products do not have the scientific support required for inclusion in terms of the mitigation potential or the information required to estimate adoption, such as the potential impacts on production or product quality, impacts on animal heath and welfare or environmental impacts.

Low methane pastures: In addition to Brassicas, the technical mitigation potential of many pasture species is being investigated, including chicory, fodder beat and plantain. In addition to determining their effectiveness at reducing emissions, research is also needed to determine if these species can meet the dietary requirements of livestock at the inclusion rates required to reduce emissions. Low methane pastures have the same challenge as forage Brassica in verification of the emissions reduction due to difficulty measuring intake.

2.6.2 Options to reduce carbon dioxide emissions

Electric tractors: Several factors will likely drive the adoption of electric tractors including silent running, no fumes, and likely self-driving options. On an emissions reduction basis, electric tractors will be more beneficial for system that have a substantial amount of emissions from diesel used in tractors. The timeframe for tractors that meet farm requirements to be available in Australia at competitive prices is unknown.

Biochar: Trees removed for redevelopment of orchards or vineyards can be converted to biochar through pyrolysis. This converts a proportion of the wood to a long-term carbon store and thus reduces the emissions of CO_2-e from redevelopment. This was estimated to reduce the emissions intensity of cherries from an orchard in New South Wales by 44% (Simmons *et al.* 2023). Research on the mitigation potential in various scenarios, the economics and logistics of implementation, and accounting requirements to incorporate this option into the account are required. Other sources and uses of biochar in agriculture require research to determine their technical effectiveness.

2.6.3 Purchasing low-carbon emission inputs

Beef on dairy: Calves bred in the dairy system have a natural efficiency advantage, which results in lower GHG emissions for the calf, because the cow base produces a large volume of milk together with the calf. Most of the impacts from the dairy cow herd are allocated to the milk, meaning impacts to the calf are much lower than in a traditional beef production system.

Previous analyses have shown that beef dairy cattle can reduce the emissions intensity of beef from traditional supply chains by about 30% to 50%.

While beef on dairy is currently an available emission reduction option that is used in some areas, some further development between dairy and beef producers is required before this can be adopted at scale.

Compost/ chicken manure/ organic fertilisers: Although this option is likely to reduce Scope 3 emissions from purchased materials, particularly when sourced locally, there can be trade-offs. The potential to increase soil carbon cannot currently be estimated and included in the carbon account and the high nutrient levels can increase nitrous oxide emissions.

Carbon neutral fertiliser: Net zero fertiliser will allow farmers to purchase fertilisers without the Scope 3 emissions currently associated with its manufacture. The plants that manufacture these fertilisers are currently being built so this could be available for purchase before 2030. Although the accessibility and costs of the product in 2030 are unknown, it is likely that any adoption in agriculture will be limited within this timeframe.

3. Emission removal options

3.1 Soil carbon sequestration

Soil carbon sequestration has a dual benefit in that it can offset emissions, while improving soil-based productivity. Increases in soil carbon provides carbon removals due to movement of CO_2 from the atmosphere into plant biomass through photosynthesis and subsequently from plant litter, roots, and other organic inputs, such as animal waste, into the soil.

This potential for soil carbon sequestration is limited by site characteristics such as rainfall, temperature, soil type, topography, and management. Based on these conditions, there will be an input of organic matter and a decomposition rate which over time will lead the soil to reach a stable carbon level. Rainfall and clay content are two of the most influential factors, with the potential amount of soil carbon stored increasing with both. To increase the soil carbon above this level, management that increases inputs and/or reduces the decomposition rate of carbon needs to be maintained over the long-term. Discontinuing such management will result in the amount of carbon returning to the original amount.

The amount of annual sequestration with typical management practices is small (< 1 tonne CO_2-e per hectare per year). However, when applied to large areas this quickly adds up. This is also true of small declines in soil carbon, so ensuring best practice for soil carbon is important for both long term resilience and carbon emissions.

Given the highly variable nature of the sequestration potential of soil carbon in the Hills and Fleurieu landscape due to historic and current land use, land management and soil type, this option is not included in the MACC. There are likely some areas that could sequester soil carbon through management that would increase production enough to cover the cost of inputs, but this level of detail is outside the scope of this analysis.

3.1.1 Beef/sheep/dairy

Long-term perennial pastures provide high inputs that lead to higher soil carbon stocks than many other land uses. Improved pastures that have been well managed over a long period have little room for further increases in soil carbon. The carbon in these soils is worth maintaining for its Productivity Benefits as well as maintaining the carbon stock.

In unimproved or degraded areas there is scope to increase soil carbon through management to improve soil condition and pasture production. Currently, the key methods to include soil carbon in a carbon account to meet reporting requirements is to register a soil carbon project through the ACCU scheme or utilise an insetting method through the relevant carbon accounting framework. This is an extensive and costly process but can provide a return on investment in some cases.

3.1.2 Cropping

A priority in cropping systems is to ensure management is not resulting in soil carbon losses. Modelling done for the Grains Research and Development Corporation (GRDC) show the annual and regional variability of soil carbon losses and gains in southern Australia average an emission of about 5 tonnes/ha/year between 1990 and 2019 (Sevenster *et al.*

2022). Due to difficulties in measurement and high variability that is driven primarily by climate, it is often assumed that areas that have been well managed for a long period are in equilibrium and not gaining or losing carbon. However, when soil carbon is included, it can have significant impacts on the carbon account (Sevenster *et al.* 2020).

There are some economic options that reduce losses and have the potential to increase soil carbon in cropping systems. Increases in soil carbon in the top 10 cm occur with minimum tillage, residue retention, fertiliser application, and adding a pasture to the rotation (Lam *et al.* 2013; Robertson and Nash 2013). Reducing summer fallow frequency has also been shown to increase soil carbon (Gan *et al.* 2014; Liu *et al.* 2016).

3.1.3 Perennial horticulture

There are more research gaps regarding the current gains or losses of soil carbon and the potential of perennial horticulture to sequester carbon compared to other sectors. However, there is evidence for both soil carbon sequestration in perennial horticultural systems in Australian (Goward and Whitty 2014) and carbon losses from tilled interrow of vineyards (Eldon and Gershenson, 2015). Soil carbon increased over time in orchards in Australia and New Zealand to levels higher than neighbouring pasture, the previous land use (Gentile *et al.* 2016). Apple and pear orchards in the Adeleide Hills had just over 100 tonnes C/ha (Gentile *et al.* 2013).

Cover crops in the interrow have been shown to increase soil carbon sequestration in South Australian vineyards (Marks *et al.* 2022). Several other methods have been shown to increase soil carbon in vineyards compared to conventional management including reduced or no interrow tillage, organic amendments such as manure or compost, biochar amendments, and leaving or incorporating pruning residues into the soil (Payen *et al.* 2021). Mulch and cover crop cuttings increased soil carbon in an UK apple orchard (Weber et al 2022) and reducing compaction in the inter-row was recommended for fruit trees in New South Wales (Gordon Rogers Applied Horticultural Research 2019).

3.2 Tree carbon sequestration

Based on estimates from LOOC-C the greatest average sequestration rate over 25 years within the region was 19-20 tonnes CO_2-e per hectare per year. The lowest 25-year average sequestration was 2-3 tonnes CO_2-e per hectare per. The map in Figure 9 illustrates the potential sequestration rate across Hills and Fleurieu. This is comparable to the results of previous analysis (FLINTpro 2024a), largely due to similar methodology. Carbon yields over 25 years based on FullCAM modelling of trees are provided in Appendix A.

The area that can be planted is influenced by farm size, area of remnant vegetation or previous plantings, and farm characteristics. Planting areas of the farm that are not often used by livestock and/or have low productivity such as rocky outcrops, boggy areas, and steep slopes will provide the benefit of carbon sequestration without loss of pasture areas. Planting shelterbelts to block damaging winds (e.g. wind direction during lambing) or providing shade in summer will also increase the likelihood of a strong return on investment.

It is important to note that any human-induced clearing of woody vegetation that is not required by law, for instance clearing of invasive species, will be included as carbon dioxide emissions in your farm account. There are also market access risks associated with clearing established forest. If you are considering the plantation forestry method to earn ACCUs, permitting and registration requirements should be followed for your area to ensure plantations can be harvested without penalties.

Across the Hills and Fleurieu region carbons stocks remained fairly steady between 2000 and 2015, with notable reductions from 2015 that continued through to 2022 (FLINTpro 2024b). Several drivers contributed to forest loss, including fires in 2015 and 2019, changes in the forest cover in nature reserves, and plantation forestry operations. Forest cover loss on farmland was also identified as changing carbon stocks (FLINTpro 2024b). Preserving existing vegetation in both public and private land is central to ensuring that tree plantings contribute to an overall increase in carbon stocks.

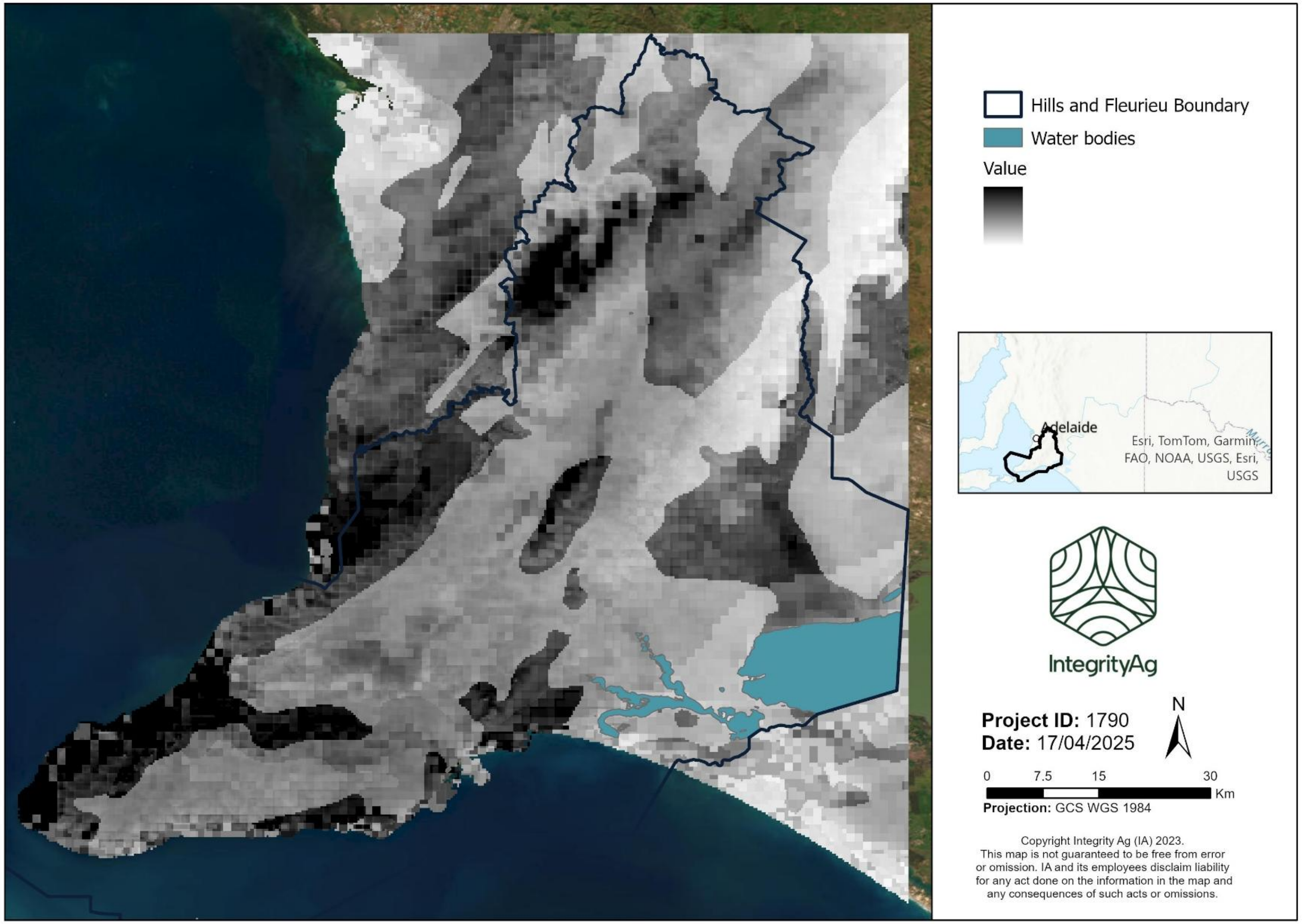

Figure 9 Tree carbon sequestration potential within Hills and Fleurieu

4. Productivity benefits

4.1 Soil carbon

Increased soil carbon can provide benefits to production by increasing soil organic matter, and improving soil structure, increasing water-holding capacity, supporting beneficial microbial activity, and enhancing nutrient cycling and availability. Benefits include:

- Chemical functions show improvement with increased soil carbon.
  - Positively charged ion exchange capacity and pH buffering improve, providing a buffer against soil acidification, and preventing the loss of nutrients such as calcium, potassium, and magnesium (Rice *et al.* 2007; Baldock 2009).
  - The effects of high levels of sodium are also reduced, which prevents negative effects on soil structure and plant growth (Baldock 2009).
  - Nitrogen is generally better retained and obtains higher levels with increased soil carbon, leading to less nitrogen fertiliser required (Jansson and Persson 1982; Stevenson 1982; Stevenson and Cole 1999).
  - Improvements to chemical functions and their interactions in higher carbon soils will generally lead to improved crop yield potential and less variable yields (Stevenson and Cole 1999; Lal 2006; Kato *et al.* 2010; Meyer *et al.* 2015).
  - There are limitations on how much soil carbon can increase chemical functions in that the ratio of carbon to nutrients influences nutrient availability to plants. A high ratio of carbon relative to nitrogen can cause lower availability of nitrogen to plants (Eyles *et al.* 2015).
- Soil porosity, water infiltration, water-holding capacity and retention increases as soil carbon increases (Kay *et al.* 1997; Baldock 2009; Deurer *et al.* 2009; Stockmann *et al.* 2013). These changes contribute to better drought tolerance, especially in low-rainfall sites, and build resilience to climate change (Rice *et al.* 2007; Baldock *et al.* 2012; Palm *et al.* 2014; Powlson *et al.* 2014).
- Rooting structure is increased in high carbon soils, contributing to reduced soil erosion risk (Wander and Nissen 2004; Rice *et al.* 2007).
- Beneficial microbial activity, and microbial biomass carbon increases in high carbon soils. Robust microbial communities are helpful in the suppression of diseases by, e.g. slowing the establishment of pathogens, and/or the severity of diseases (Janvier *et al.* 2007; Larkin 2015).
- Carbon can be sequestered for potential financial benefit, if the soil is adaptively managed to the local context and climatic conditions (Tiefenbacher *et al.* 2021; Moinet *et al.* 2023).

Cumulative benefits to soil structure and quality gained from increased soil carbon can be beneficial in terms of production, finances, and resilience to changing climatic conditions (Victoria *et al.* 2012). It is though important to recognise that production benefits that can be gained from soil carbon are limited by certain factors. These include that soil carbon can only be increased to a maximum stable level as determined by a site's characteristics and climate (Gottschalk *et al.* 2012; Ma *et al.* 2023). Soil carbon can also be lost back to the atmosphere with climate or management changes, such as maintaining stocking rates during drought conditions, and once lost may take a long time to recover (Stevenson and Cole 1999; Luo *et al.* 2010; Baldock *et al.* 2012; Smith 2014; Moinet *et al.* 2023).

4.2 Tree planting

Tree plantings can provide production and environmental benefits. Riparian buffers and well-planned shelterbelts can help by reducing wind speeds, providing shelter, binding soil, and filtering water and reducing water flow speed (Figure 10). Farm forestry plantations can also be planned to achieve these benefits and to provide additional revenue. There are trade-offs to consider and higher maintenance requirements to ensure timber meets market requirements. However, with careful planning, timber species can be included in shelterbelts or even block plantations, to achieve multiple objectives on farm.

4.2.1 Livestock

Tree planting on livestock farms assist with the following benefits to animal health and welfare:

- Lamb and shorn sheep survival improves when sheltered from the chill experienced through cold winds (Lynch *et al.* 1980; Gregory 1995; Bird 1998; Meat and Livestock Australia and Agriculture Victoria Factsheet 2022).
- Dry matter intake and live-weight gain of livestock increases when they have access to shelter in hotter conditions (Lynch and Donnelly 1980a; Lynch *et al.* 1980; Gaughan *et al.* 2001; Ryan *et al.* 2010; Sullivan *et al.* 2011).

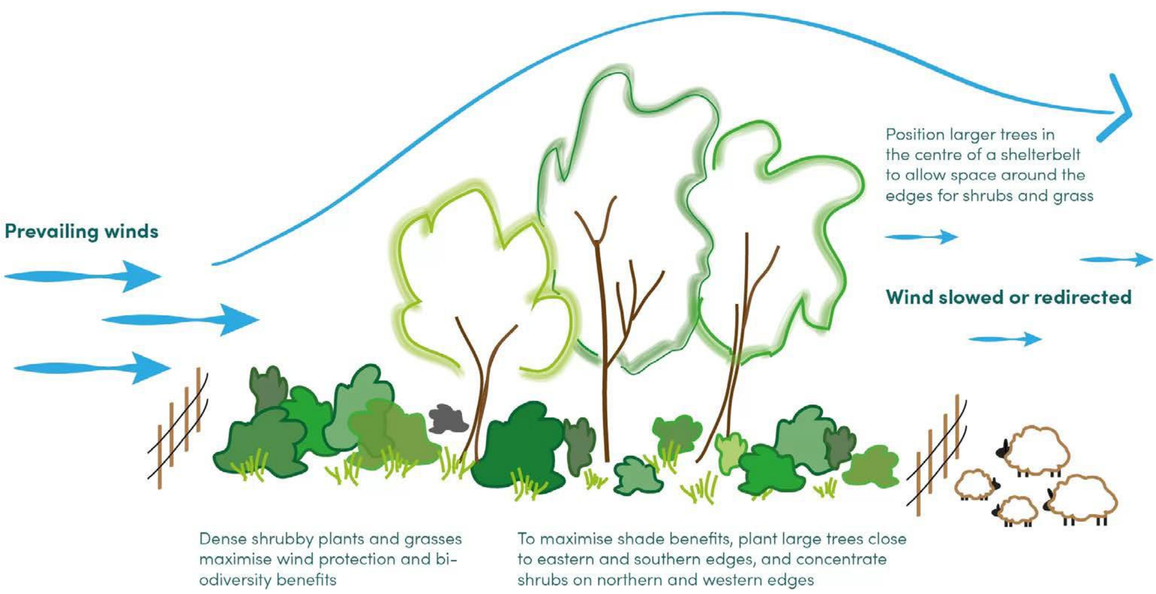

Figure 10 An effective tree shelterbelt design (ANU Sustainable Farms)

Table 6. Research demonstrating the importance of vegetation in production systems

Benefit	Vegetation characteristics	Benefit type and description	References
Lamb and shorn sheep survival	Any with understory; larger area of shelter with greater height	Farm; reduction in wind speeds reduces the chill experience by sheep reducing the likelihood of mortality	Lynch et al. (1980), Gregory (1995), Bird (1998), Meat and Livestock Australia and Agriculture Victoria Factsheet (2022)
Liveweight gain	All (shade and/or shelter)	Farm; reduction of time spent outside the thermoneutral zone improves feed intake and feed conversion efficiency.	Sheep: Lynch and Donnelly (1980a), Lynch et al. (1980) Cattle: Gaughan et al. (2001) Sullivan et al., (2011), Ryan et al. (2010)
Pasture/crop production	Widely spaced shelterbelts	Farm; increases in pasture productivity in the sheltered zone, often at least losses in the competition zone resulting in neutral to positive crop/ pasture responses.	Bennell and Verbyla (2008), Bird (1998), Cleugh et al. (2002), Lynch and Donnelly (1980a)
Water quantity	Riparian zone/ dam, pivot	Farm, reduced evaporative losses and retention of runoff	Lynch et al. (1980), Ryan et al. (2010)
Water quality	Riparian zone/ dam	Farm and beneficiaries downstream	Ryan et al. (2010), Dobes et al. (2021)
Water tables/ salinity	Strategically located block (e.g. upslope from seep)	Farm; reduced water tables/ salinity	George (1991)
Soil	Any with understory	Farm and societal; reductions in wind and water erosion	Ryan et al. (2010)
Carbon sequestration	More per unit area in belt and in forests compared to woodlands, maximum annual rate between 5–10 years slows to small amount over 30 years old.	Societal and farm; increased market access	Australian Government (2014)
Biodiversity	Remnant vegetation, large patches and corridors connecting blocks. Improves as vegetation matures.	Societal; protection of general biodiversity and threatened habitats Indirectly on farm; through pollination and pest control	Tucker and Simmons (2009), Nicholls and Altieri (2013), Gurr et al. (2003), Altieri (2004), Lundgren and Fausti (2025), Di Sacco et al. (2021)

4.2.2 Pasture

Tree planting can create benefits for pasture and grazing management:

- Pasture productivity is also likely to increase in a well-planned paddock and shelterbelt (Lynch and Donnelly 1980b; Bird 1998; Cleugh *et al.* 2002; Bennell and Verbyla 2008; Baker *et al.* 2021).
- Well-placed trees can improve grazing access by reducing salinity and/or water logging (George 1991).

4.2.3 Water

Tree planting helps to retain water loss and improve water quality:

- Water loss can be reduced when paddocks are sheltered (Lynch *et al.* 1980).
- Vegetation and trees in the riparian zone of dams can improve retention of runoff and reduce evaporative losses (Ryan *et al.* 2010).
- Trees and vegetation around dams improve water quality by reducing nitrogen,: turbidity, algal blooms, and bacteria (Ryan *et al.* 2010; Dobes *et al.* 2021).Live weight gain of cattle increases when they have access to better quality water.

4.2.4 Soil

Tree planting reduces soil damage by protecting soils from erosion and environmental damage:

- Soil retention improves when protected from high wind speeds and from reduced water runoff (Ryan *et al.* 2010).
- Soil nutrition and health can possibly improve when sheltered from high wind speeds (McKeon *et al.* 2008).

4.2.5 Biodiversity

Tree planting assist in maintaining and increasing biodiversity on farms:

- provision of habitat increases biodiversity on farm and in the wider landscape, this can benefit farming systems through increased pollinators (Phillips *et al.* 2010) and potentially reduced pests (Lumsden and Bennett 2005).
- opportunities to capitalise on natural capital assets that improve biodiversity, including earning credits through the Biodiversity Credit Exchange or the Nature Repair Market.

4.2.6 Carbon

- Carbon sequestration can be improved in denser forest and planted shelterbelts relative to woodlands (Australian Government 2014).

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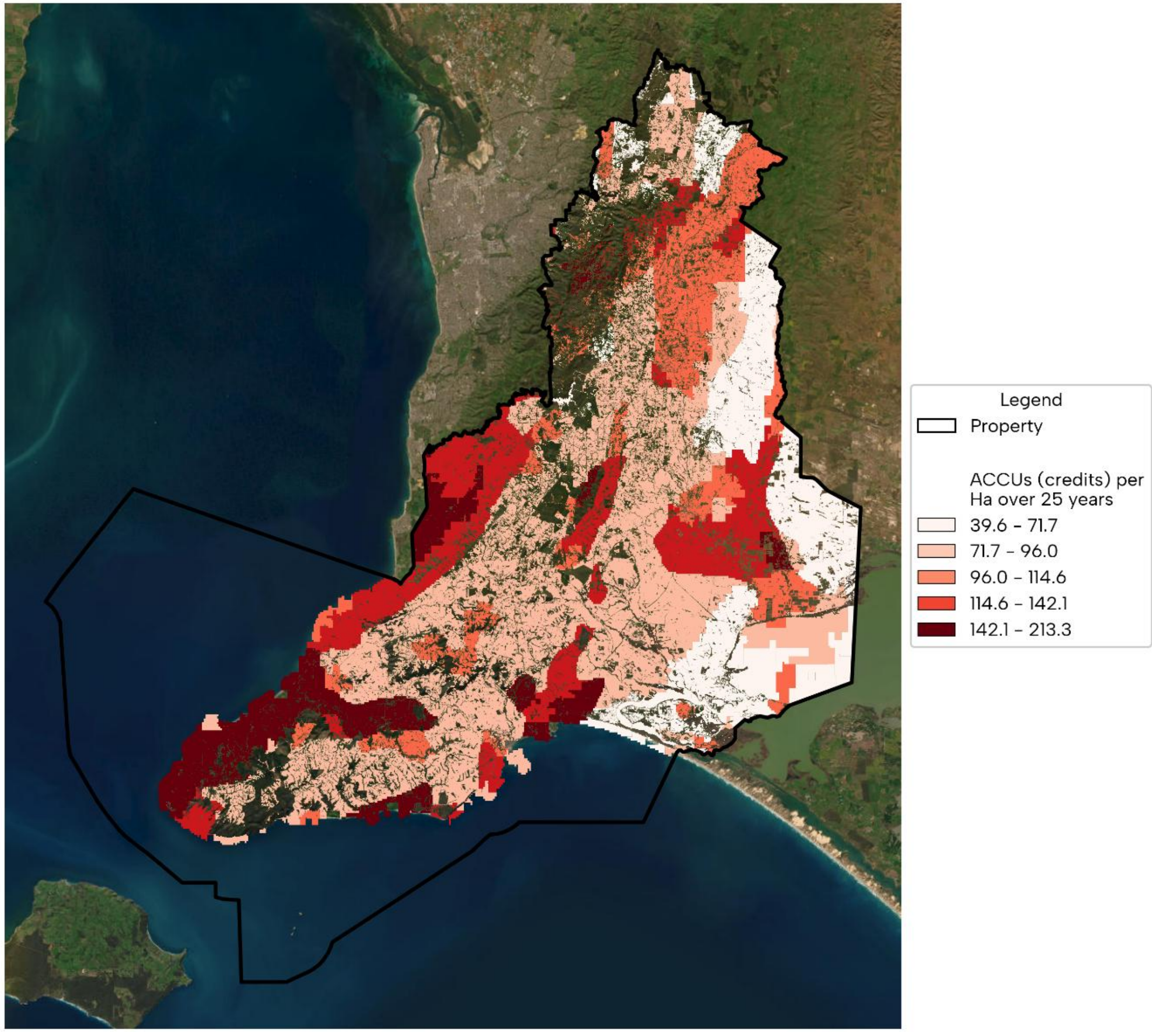
6. Appendix A Carbon Yields



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