Final Report

Sustainability Reporting Uplift Project Final Report

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Contents

List of Tables

List of Figures

Glossary

Term	Definition
ABARES	Australian Bureau of Agricultural and Resource Economics and Sciences
ABS	Australian Bureau of Statistics
ACCU	Australian Carbon Credit Unit
ACCU Scheme	Australian Carbon Credit Unit Scheme
AFRC	Agricultural and Food Research Council
ALFA	Australian Lot Feeders' Association
AMPC	Australian Meat Processor Corporation
AWI	Australian Wool Innovation
CER	Clean Energy Regulator
CF	Carbon Footprint
CLUM	Catchment Scale Land Use of Australia
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CWD	Coarse Woody Debris
DAFF	Commonwealth Department of Agriculture Fisheries and Forestry
DCCEEW	Department of Climate Change, Energy, the Environment and Water
dLUC	Direct Land Use Change
DMI	Dry Matter Intake
DOM	Dead Organic Matter
FullCAM	Full Carbon Accounting Model
GHG	Greenhouse Gas
GHG Protocol	Greenhouse Gas Protocol
GW	Greasy Wool
GWP	Global Warming Potential
HIR	Human Induced Regeneration Method
ISO	International Organization for Standardization
LANCA	Land Use Indicator Value Calculation in Life Cycle Assessment
LCA	Life Cycle Assessment
LEAP	Livestock Environmental Assessment and Performance
LULUC	Land Use and Land-Use Change
LULUCF	Land Use, Land-Use Change, and Forestry: a reporting subsection in the NGGI

Term	Definition
LW	Live Weight
MLA	Meat & Livestock Australia
MSA	Meat Standards Australia
NGGI	National Greenhouse Gas Inventory
NIR	National Inventory Report
PEF	Product Environmental Footprint
SBTi	Science Based Targets initiative
sLUC	Statistical Land Use Change

Abstract

Sustainability reporting for Australia's red meat and wool industries is evolving rapidly in response to heightened stakeholder expectations for impact reduction, data transparency, and granularity. This study developed and beta-tested a new data framework integrating existing and novel data streams to enhance life cycle assessment (LCA) capability for beef, sheep meat, and wool. Key innovations included national-scale first-order estimates of Land Use (LU) and statistical Land Use Change (sLUC) emissions and removals; expanded carbon footprint (CF) reporting at state-level for beef, including dairy beef analysis; and the first national estimates of freshwater consumption for sheep products. Results for boxed beef and lamb product were also reported for the first time as a national average.

For beef, results showed a 4.7% reduction in CF from 2020 levels for cattle derived from the beef herd (12.1 kg CO_2-e kg^{-1} LW, excluding sLUC), which further reduced to 11.9 kg CO_2-e kg^{-1} LW when including dairy-sourced beef. A long-term trend analysis revealed a 25.3% decline in beef herd emissions over 44 years. First-order Land Use and sLUC results indicated this was either a source of removal or emission depending on whether a 10 or 20 year discounting timeframe was used. Using the standard 20 year discounting timeframe, impacts were 2.6 kg CO_2-e kg LW^{-1} or -1.1 kg CO_2-e kg LW^{-1} with 10 year discounting. This resulted either in an increase of the CF of beef by 21% or a decrease of 9%, highlighting the sensitivity of the method choice, and the transitional state of the industry where this source is moving from a net emission to a net removal. Boxed beef CF was estimated at 26.9 kg CO_2-e kg^{-1} boxed weight. LU and sLUC was estimated to be 5.7 kg CO_2-e kg boxed^{-1} under 20-year linear discounting and -2.4 kg CO_2-e kg boxed^{-1} with 10 year discounting. While some reporting systems mandate 20 year discounting, 10 year discounting may be more closely aligned with the biological loss processes involved in Australia, and further research is needed to improve and clarify the best approach for Australian conditions.

From 2020 to 2023, the sheep meat and wool CF decreased by 7% (from 7.3 to 6.8 kg CO_2-e kg^{-1} LW and from 26.3 to 24.5 kg CO_2-e kg^{-1} GW). First-order Land Use and sLUC results indicated removals were −1.3 kg CO_2-e kg^{-1} for sheep meat with a 20 year linear discounting time period, and –2.2 with a 10 year linear discounting period. Similarly, results were −4.6 kg CO_2-e kg^{-1} for wool with a 20 year linear discounting period and – 8.0 with a 10 year linear discounting period. Based on the 20 year discounting time period, Land Use and sLUC reduced total CF by 18% and this was greater with 10 year linear discounting. Boxed sheep meat results were reported for the first time at the national scale, and were 15.1 kg CO_2-e kg boxed^{-1}. LU and sLUC was estimated to be -2.8 kg CO_2-e kg boxed^{-1} under 20-year linear discounting.

Removals were predominantly from regeneration of native vegetation. These results were a contrast compared to beef and reflected the different regional distribution of sheep compared to beef in Australia, and the higher levels of removals associated with regenerating native vegetation in sheep producing regions. For both beef and sheep, the Land Use and sLUC values were subject to a high degree of uncertainty compared to other emission sources, and further research is required to improve the accuracy and measurement capability for these results.

Freshwater consumption was estimated at 400 L kg^{-1} LW for beef which was stable compared to the previous reporting period. Freshwater consumption was 145 and 520 L kg^{-1} for sheep meat and wool respectively, representing a 9% decline since 2020. National scale estimates for sheep were subject to higher uncertainty than the carbon results and should be interpreted with caution.

Despite high uncertainty—particularly in Land Use and sLUC and irrigation estimates—the framework successfully demonstrated capacity for more refined reporting. Further automation will provide the capacity for more frequent reporting to meet industry needs. Notably, the inclusion of Land Use and sLUC, adoption of state-based allocation, exclusion of carbon credit removals to avoid double counting, and GHG Protocol-aligned discounting improved methodological integrity. Future refinement is needed to enhance certainty and enable supply chain and market-specific reporting. This project marks a substantial advancement in emissions and resource use accounting for the

red meat and wool industries, supporting progress toward robust, standard-aligned sustainability reporting and provides extensive recommendations on industry data needs to maintain and enhance reporting into the future.

Executive summary

The need for sustainability reporting continues to expand for the red meat and wool industries. The expected frequency of reporting, breadth of indicators covered, granularity and specificity of results have increased over time. Further, industries operate in an environment where impact reduction is an expectation to meet customer and governmental targets. Reporting is facing increased scrutiny to better meet these expectations.

This project developed a data framework and implemented it in beta form, merging new data streams with existing data streams to provide new analysis capability for red meat and wool. New indicators included reporting of fresh water consumption for sheep and the product carbon footprint was expanded to provide state-level reporting for both beef and for the first time, to report the average for Australian beef inclusive of dairy beef. In a major enhancement, a first-order estimate of statistical Land Use and Land Use Change (Land Use and sLUC) emissions were reported per kilogram of beef, lamb and wool for the first time at national scale, with noted high levels of uncertainty.

The framework was developed in a period of unprecedented change in data management for agriculture in Australia, as a result of the ABS Data Modernisation program. This has decreased the availability of many key datasets used by industry and used in sustainability reporting, which was concerning to the industries. This has happened at a time of unprecedented demand for sustainability reporting, exacerbating the challenge for industries. Further, the National GHG Inventory (NGGI) has also entered a period of review of methods, data systems and data availability which will improve reporting capability over time. These initiatives will continue to occur over the next two to three years.

Developing the framework during this period of change had both advantages and disadvantages. It helped clarify industry data needs and prompted the search for new data sources to meet these needs in conjunction with similar efforts by the ABS and NGGI. However, it also led to decreased data availability and caused delays in accessing data during the project. The beta implementation focused on demonstrating the capability of the system. Some results displayed a high level of uncertainty and need to be interpreted with caution. For example, the Land Use and sLUC results were very important findings, but there were many methodological and data uncertainties. They are presented as first order results and will require refinement and revision in future years.

The results of the beta implementation for beef showed a reduction in CF of 4.7% compared to the five years to 2020 after baseline recalculation for cattle derived from the beef herd, resulting in a new benchmark of 12.1 kg CO_2-e kg LW^{-1} excl. Land Use and sLUC. Including beef derived from the dairy herd decreased impacts a further 1.7% to 11.9 kg CO_2-e kg LW^{-1} excl. Land Use and sLUC. The long term trend showed a decline in impacts of 25.3% over 44 years for the beef herd. Impacts varied between states and territories, from 10.9 to 14.8 kg CO_2-e kg LW^{-1}.

First-order Land Use and sLUC results indicated this was either a source of removal or emission depending on whether a 10 or 20 year discounting timeframe was used. Using the 20 year discounting timeframe, impacts were 2.6 kg CO_2-e kg LW^{-1} or -1.1 kg CO_2-e kg LW^{-1} with 10 year discounting. This resulted either in an increase of the CF of beef by 21% or a decrease of 9%, highlighting the sensitivity of the method choice, and the transitional state of the industry where this source is moving from a net emission to a net removal. Removals mainly arose from regeneration of forests. This result was subject to a higher degree of uncertainty and further research and development of the data system is required to improve certainty in the result. Nonetheless, the findings are aligned with the National GHG Inventory which has shown that removals have exceeded emissions in the major categories, forest and grassland for 10 years, giving confidence that LULUC represents a removal source for the beef industry, not an additional emission source. Having noted this, the NGGI continues to display variance between states, with QLD reporting ongoing emissions at a declining rate, while other states have substantial levels of removals.

The fresh water consumption for beef was subject to a higher degree of uncertainty in the current year because key irrigation data sources were not available. Nonetheless, the result for 23/24 was 400 L kg LW^{-1}, which was not substantially different to the result in 2020.

Carbon footprint results were reported for boxed beef for the first time as part of the beta implementation, as a first-order estimate. The CF was 26.9 kg CO_2-e kg boxed^{-1} for the national slaughter, excl. Land Use and sLUC. Reportable Land Use and sLUC impacts were 5.7 kg CO_2-e kg boxed^{-1} under 20-year linear discounting or -2.4 kg CO_2-e boxed^{-1} with 10 year linear discounting, resulting in either higher net emissions or lower net emissions pending the method chosen. Further data related to meat yield and co-product yields are needed to improve the accuracy and specificity of this result.

The CF of sheep meat (excluding Land Use and sLUC) decreased 7% from 7.3 to 6.8 kg CO_2-e kg LW^{-1} between 2020 and 2023, after baseline recalculations. Similarly, the CF of wool decreased from 26.3 to 24.5 kg CO_2-e kg GW^{-1} . First-order Land Use and sLUC results indicated removals were −1.3 kg CO_2-e kg^{-1} for sheep meat with a 20 year linear discounting time period, and –2.2 with a 10 year linear discounting period. Similarly, results were −4.6 kg CO_2-e kg^{-1} for wool with a 20 year linear discounting period and – 8.0 with a 10 year linear discounting period. Based on the 20 year discounting time period, Land Use and sLUC reduced total CF by 18% and this was greater with 10 year linear discounting. Removals mainly arose from regeneration of forests. As noted with the beef result, this value was subject to a higher degree of uncertainty and further research is required to improve the result. Nonetheless, it is significant to note Land Use and sLUC is estimated to provide a substantial source of removals for the sheep industry.

The CF of boxed sheep meat was 15.1 kg CO_2-e kg boxed^{-1}. Reportable Land Use and sLUC impacts were estimated as -2.8 kg CO_2-e kg boxed^{-1} under 20 year linear discounting, resulting in lower net emissions when these sources were included. As noted for the beef results, improved datasets are needed to improve the accuracy of this result.

Fresh water consumption was published for the first time for sheep meat and wool at a national scale. The first-order estimate was 145 L kg LW^{-1} and 520 L kg GW^{-1} respectively for 2023 and results were also published for 2020, for comparison. Results for 2023 decreased by 9% compared to 2020. National scale estimates for sheep were subject to higher uncertainty than the carbon results and should be interpreted with caution.

Major improvements in the data system enabled more granular reporting and will enable updates to be completed more cost-effectively at more frequent intervals. Future reporting is recommended to use a shorter averaging interval of two years for cattle and sheep to balance the contrasting benefits of stability and sensitivity to seasonal effects. Reporting may be done either annually or biennially.

The new Land Use and sLUC analysis completed was a major step forward in the completeness of assessment, and resulted in a new data release from DCCEEW for public use, disaggregating impacts for grazing and cropping sectors. Using state-based results for allocating between beef and sheep on a grazing density basis improved alignment and resulted in a more sophisticated allocation of impacts to sheep and beef. Removals associated with carbon credit generation were also excluded to remove the risk of double counting. Further, the results used a discounting approach following GHG Protocol, which is required for high integrity product level reporting and company reporting. This provided new results that are vital for presenting a more balanced understanding of the supply chain. The results were considered a first-order estimate in the present implementation, and further system development needs have been outlined to improve the certainty of these estimates and enable supply chain reporting in the future.

The beta system has demonstrated capability to report impacts for cattle at state-scale, though a wide range of considerations emerge when this is undertaken, including whether the most relevant measure is state-of-origin, or state-of-sale at the end point of production. In the present study, we provided results based on state-of-origin to demonstrate the capability. Further, the system has the capability to report results on a market specification basis (results not shown), but further work is needed to establish and confirm the appropriate means of separating cohorts of cattle into these different markets. It can be expected that significant differences will exist between market categories because of the relationship between market specifications for weight, age and length of time in grain finishing. This will become increasingly important for understanding the options available to the industry for producing the highest quality, lowest emissions red meat and wool.

The project opens the door to a wide range of possibilities for the industry to advance analysis and reporting capabilities. Progressing this project to automate data flows and calculations will provide the capacity for more frequent reporting to meet industry needs at lower cost and is a key need for the industries, government and society. A detailed set of recommendations has been included in the report to achieve the next advancement in agricultural sustainability reporting capability.

1.0 Introduction

The Australian beef and sheep industries have worked proactively over the past decade to understand and report environmental impacts through the Australian Beef (2024) and Sheep Sustainability Frameworks (2024). These documents set out the material impacts for each industry and track performance over time. Increasingly, companies in the beef, sheep and wool supply chains are moving to establish their own assessment and reporting frameworks, as they seek to engage producers and customers to improve sustainability outcomes. This trend is set to accelerate, with the introduction of mandatory Climate Related Financial Disclosure regulations in Australia in 2024. Because of the structure of this regulation, companies with high staffing levels and gross turnover, such as meat processors and to a lesser extent, wool brokers will need to report in the next 2 years.

These regulations, and a large proportion of the focus in supply chain reporting is on climate change impacts. However, it is recognised in the Sustainability Frameworks that other impacts such as water are also relevant for the industry, and that in the future more environmental indicators will need to be tracked and reported to support industries' sustainability claims.

Reporting complex environmental indicators at the national scale and attributing these two products is a challenging task. To-date, important indicators such as the carbon and fresh water consumption of beef, and the carbon footprint of sheep meat and wool, have been updated every five years, because of the large task required to calculate these results. Some 40 datasets form the input to this process, but changes in the collection and release of Agricultural Statistics have resulted in iterative changes to many key datasets in the past three years making the update process difficult.

In order to track progress against industry goals and provide a benchmark for supply chains, these numbers need to be reported more frequently, and the approach used needs to be methodologically similar to the approach used by industry for farm level or supply chain level reporting.

This project was established to develop a new beta data framework for the industries, and to test this by implementing the framework in beta mode delivery for an updated timestep for beef, wool and sheep meat. The project also coincided with a period of change in data collection and availability for agriculture and natural resources, prompted by ABS Data Modernisation program. This resulted in new challenges for the program and ongoing agricultural sustainability reporting. It also provided a new and unexpected opportunity to document the status of key datasets and new data needs. The objectives are outlined in the following section.

2.0 Project objectives

The project aimed to deliver:

1. an interoperable, streamlined credential reporting system (data framework) for the beef, sheep and wool industries,
2. an improved data collection and analysis system (data framework) for reporting key indicators, specifically carbon and water footprints for the beef and sheep sustainability frameworks, and
3. capability for an annual update of key indicators for the Australian Beef and Sheep Sustainability Frameworks, and reporting of national-scale results for beef, lamb and wool that are compliant with the EU PEF database, where they will underpin reporting for Australian products supplied to that market.

This report presents the data framework and an annual update of results for beef, wool and sheep meat which have been developed through a beta implementation of the framework.

3.0 Methodology

3.1 Data framework

A data framework was designed and implemented to store and transform data required to deliver the project objectives. This data framework is visually described in Figure 1.

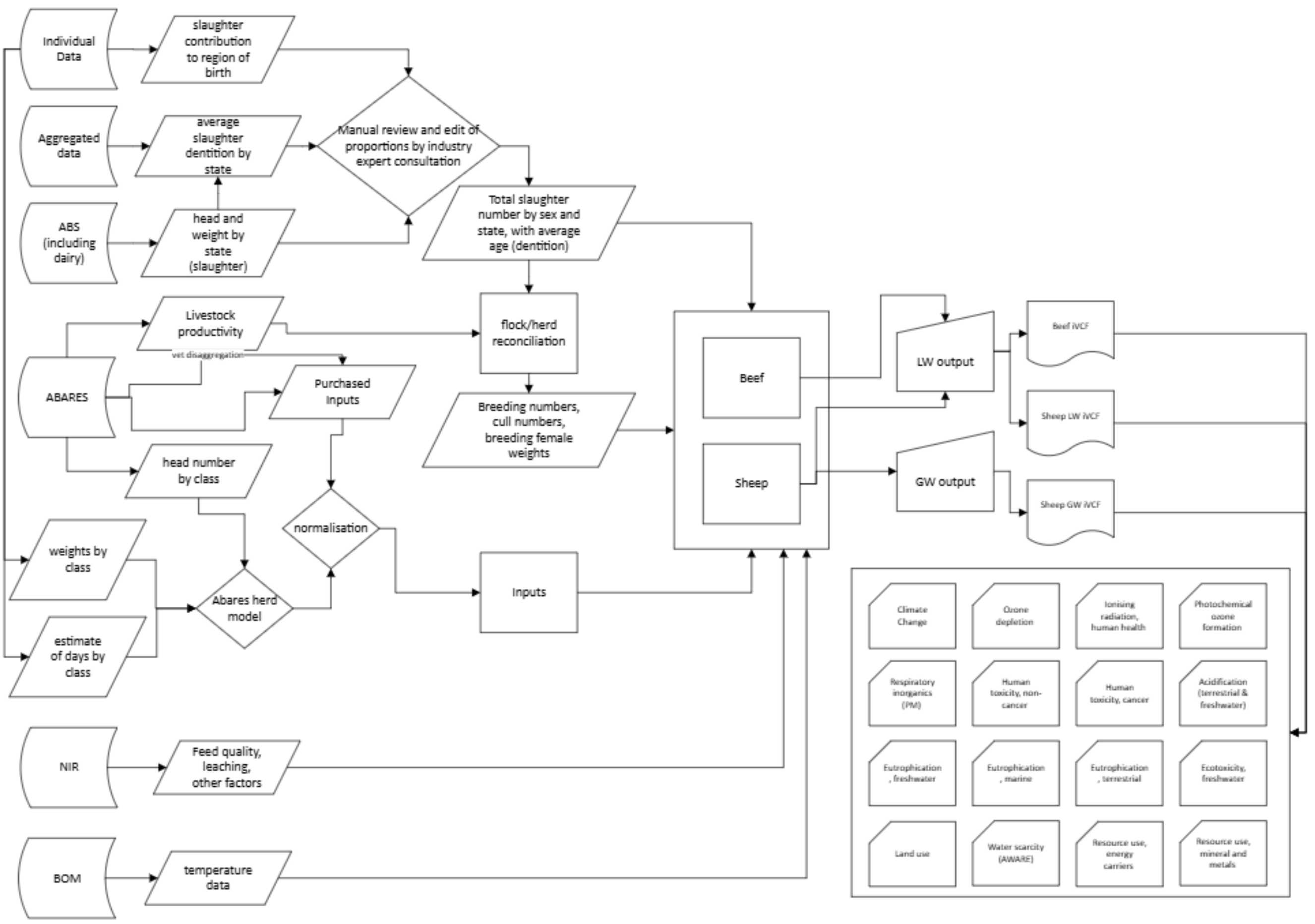


Figure 1. Data map and process diagram for beef and sheep databases

The data framework can be categorised into the following distinct but interoperable components:

3.1.1 Data storage and acquisition

A relational database model was developed to centralise and version the storage of input data. These data are categorised into "aggregate" and "transaction" data.

Aggregate data comprise > 90% of the tables that are used in the analysis, and are unstructured data that have been accessed from third party sources. Aggregate data have been pre-cleansed and analysed prior to access. Examples of aggregate data include data from ABS, ABARES, and derived data from these sources. Data in the "aggregate" database have a codependent and cyclical relationship with the data model (described below). The data model reads data from the aggregate database, generates outputs, and then stores these outputs back into the aggregate database.

Transaction data include individual animal data that provide highly stratified and granular information on the end of life of animals. Examples of transactional data include MSA data, feedlot induction data and third-party data on processed animals provided for the project.

API endpoints were developed for the aggregate and transaction data to allow access to these datasets programmatically. A database caching system was also developed to cache data in the aggregate portal, so that users could specify an expiry date on data provided through the aggregate API. The caching mechanism reduced analysis runtime caused by API latency and improved the speed at which the data framework could be tested and developed. The caching system was designed to work with vectorised computational methods. Specifically, it had local pandas (McKinney, 2010; The pandas development team, 2020) endpoints that allowed for efficient integration with the computational tech stack.

3.2 Inventory data

Following the recommendation of ISO 14044 (2006), inputs to the farming systems were first divided among farm sub-systems (sheep, beef and cropping) and were accounted separately. At national scale, no datasets were available that reported the total land area used specifically for beef or sheep production in Australia. Total land area used for livestock production was determined from data derived from ABS (2021), and estimates of stocking densities of sheep and cattle, respectively, were used to allocate Land Use between livestock systems on a state-by-state basis. Where inputs were not specific to a particular sub-system, such as administration overheads or fertiliser inputs to pasture land, inputs were divided based on predicted dry matter intake (DMI) as a measure of land occupation.

3.2.1 Beef inventory data

A herd model was constructed to represent the Australian beef herd. This model was designed to determine impacts from the herd retrospectively, and was not intended to create an annual herd stock-and-flow inventory model. Instead, the herd model was designed to determine the production for a given year of cattle processed for beef.

This model relied on livestock processed and modelled the production herd. The ABS provide slaughter statistics at a state and national level. ABS data describes the total weight (HSCW) and head number of cattle processed in Australia. The ABS data were augmented with spatially specific and granular carcass data, including dentition, weight by sex and approximate region of origin. These data sources included:

- MSA carcass data
- Third party carcass data
- ALFA survey data.

MSA primary data were used to provide high granularity information relating to the weight and age of grain and grass fed cattle, separately. The MSA dataset was stratified on dentition at slaughter, sex and finishing type (grain vs grass). ALFA aggregated data were provided specifying total numbers being grain fed by market category. These head numbers were merged with the carcase data to provide a complete inventory of feedlot turnoff in Australia and categories based on number of days on feed.

Culled cattle (predominantly cows) were calculated using a recursive root finding algorithm that exploited the monotonic, convergent nature of the herd model. Original conditions were provided to the model and it was allowed to recursively compute the estimated cull numbers from the beef cattle herd.

The herd model (described below) was then applied to each iteration of the recursive root finding algorithm to predict the total herd turnoff and herd population. These turnoff estimates were compared with known turnoff values (ABS, ALFA, MSA, etc.,), and the algorithm was run until the relative error tolerance threshold was met. This advanced modelling technique allowed for new, highly granular results to be generated on an annual basis.

Breeder herd numbers were determined from slaughter data, estimated age and herd productivity indicators (branding/weaning rate and mortality rate). This enabled the estimation of the number of joined cows. Replacement heifers were assumed to be held in the herd to replace cows sold for slaughter (culled cows, as described above) and annual mortality. Herd numbers were calculated that provided an inventory reflective of a self replacing herd, in conformance with the requirements of LEAP (2015).

Purchased inputs

Purchased inputs on grazing farms, including livestock feed, services, fuel and fertilisers, were determined using the methods described in Wiedemann et al. (2015c). The inventory values used for energy and services used for the feedlot phase were from Davis et al. (2010), as applied in Wiedemann et al. (2017).

Background data for upstream processes such as generation and supply of energy and purchased products such as fertiliser were sourced from the Australian National Life Cycle Inventory Database (AusLCI, 2020). Feed grain inputs were modelled using inventory data from Wiedemann et al. (2017) and the Australian National Life Cycle Inventory Database (AusLCI) (ALCAS, 2017).

Water

Fresh water consumption was inclusive of cropping irrigation, pasture irrigation, livestock drinking water, and the associated supply losses, which were modelled using water use data from ABS and ABARES for irrigation water use. Drinking water use was predicted from the livestock inventory using the prediction equation derived from CSIRO (2007) by Ridoutt et al. (2012). Drinking water requirements for feedlot cattle were determined from feed intake and ambient temperature using Winchester and Morris (1956). Drinking water supply loss rates were determined for different sources, and evaporation losses from farm dams were estimated using methods outlined in Wiedemann et al. (2015c). Key water datasets including the ABS Farm water survey were ceased between the last trends analysis update (Wiedemann et al., 2023b) and the current study. This necessitated a revised method, where pasture irrigation was determined from ABARES irrigated land area data for beef production and irrigation rates from previous ABS reporting. This method was calibrated using reported water use from earlier ABS datasets to establish the estimation method. However, as there was no way to confirm updated irrigation rates (ML/ha) the results had a higher degree of uncertainty than previous studies. This method was also implemented for sheep for the first time in the present study.

3.2.2 Sheep inventory data

The national flock inventory was developed from livestock statistics of sheep on-farm, live export numbers and sheep processed, wool produced, and the annual ABARES survey for livestock productivity parameters. Sheep and lamb weights were determined from, and reconciled against, ABS slaughter statistics. Key flock production parameters used to determine emissions are summarised in Table 1. Farm input data such as farm fuel use, feed inputs, fertiliser, services and transport of sheep throughout the supply chain were estimated from ABARES dataset and cross-checked with case study data (Agriculture Victoria, 2020; Wiedemann et al., 2015a, 2016).

During the analysis period, ABS have changed methods for assessing the sheep flock and at the time of publishing this report had not released sheep numbers for the past two years. The project implemented an equivalent method to the cattle model, whereby the sheep flock was calculated proportionate to the processed sheep and wool.

The Australian flock was categorised into three groups: (1) Merinos, (2) dual-purpose and composite breeds (here described for simplicity as dual-purpose breeds), and (3) shedding sheep. The number of shedding ewes in the national flock was estimated to be 17% of the dual-purpose sheep in 2019 (MLA, 2020). It was assumed that negligible numbers of shedding sheep were present in the flock prior to 2000. Breed composition of the ewe base and ABS statistics on “ewes mated to a Merino ram” and “ewes mated to other rams” determined the composition of the lamb flock: Merino lambs, first cross lambs, second cross lambs and shedding lambs. The age of lambs at processing was determined from data collated from major meat processing plants and via analysis of annual lambing dates and corresponding lamb processing numbers, informed by a survey of industry experts. The flock inventory represented a self-replacing flock with a balanced opening and closing inventory, in conformance with LEAP (2015). By doing this, the effect of elevated sheep sales from a declining flock inventory was removed. Results were presented as an average of the total flock.

Table 1. Key beef herd production parameters showing the trend and most recent two year timestep

Production parameter	Units	1985 [A]	1990 [A]	1995 [A]	2000 [A]	2005 [A]	2010 [A]	2015 [A]	2020 [A]	FY23-24
Weaning rate	%	71.5%	77.5%	77.8%	81.4%	78.4%	77.2%	77.6%	79.3%	78.3%
Average mature cow weight	kg	388	407	426	445	463	482	501	520	569
Steer turnoff age	years	2.41	2.38	2.33	2.27	2.18	2.15	2.05	2.11	1.90
Steer turnoff liveweight	kg LW	437	489	492	527	545	524	591	651	651
Steer ADG (birth to slaughter)	kg / d	0.46	0.53	0.54	0.60	0.64	0.62	0.74	0.80	0.89
Heifer turnoff age	years	2.04	2.00	1.96	1.86	1.83	1.81	1.69	1.83	2.05
Heifer turnoff liveweight	kg LW	368	405	419	435	460	440	484	502	542
Heifer ADG (birth to slaughter)	kg / d	0.45	0.51	0.54	0.59	0.64	0.61	0.73	0.70	0.68

[A] each of the years from 1985 to 2020 represent a five year average with the stated year being the final year of the averaging period. I.e. 1985 is the 5 year average of 1981-1985.

Table 2. Key sheep flock production parameters showing results for the two most recent time steps

Parameter	2016	2017	2018	2019	2020	2021	2022	2023
Proportion of wethers > 18 months in flock (%)	12%	11%	13%	13%	12%	13%	12%	12%
Ewe Mature Weight (kg/head)	56	59	56	55	60	57	63	62
Sheep mortality rate (%)	5.6%	4.3%	5.1%	4.5%	4.4%	4.8%	4.7%	4.7%
Lambing rate (% at marking)	79%	89%	90%	85%	89%	94%	90%	90%
Average lamb sale weight (kg LW/head)	51	52	52	52	54	55	56	56
Average lamb sale age (days)	240	236	237	238	243	243	247	245
Wool cut per sheep shorn	3.3	4.6	4.3	3.7	3.9	4.4	4.6	4.5

3.3 Impact assessment

Outputs from the data framework were input to a separate model, the Integrity Ag iVCF model, to calculate impacts for sheep and beef. The methods used in the iVCF have been described in various previous publications (Wiedemann et al., 2023a, 2017, 2015c, 2015b, 2016). This model has been used for reporting in the Beef and Sheep Sustainability Frameworks to date. These methods are updated periodically in accordance with revisions in the science but were not fundamentally changed. The generalised methodological approach is outlined for beef and sheep in the following sections.

As part of the project scope, the intention of the model was to report annually, rather than using a five-year timestep. This prompted re-evaluation of the data averaging period for each reported timestep, and a change was proposed and implemented to move from a five-year average to a two-year rolling average. This change was made to improve the responsiveness of the model to interannual variability in flock and herd performance.

As stated in the project objectives, a key measure of the success of the beta data framework was its ability to deliver annual updates to the Beef and Sheep Sustainability Frameworks. This was a technical measure of success to demonstrate implementation practices. The methods below describe the LCA methods that were used in conjunction with the implementation of the data framework to generate these results. This information is included here for completeness. The project did not include modification of these methods.

The study assessed GHG emissions using the updated Intergovernmental Panel on Climate Change (IPCC) Sixth assessment report (AR6) (Table 3).

Table 3. IPCC GWP100 values for the Fifth Assessment Report and Sixth Assessment Report

Greenhouse Gas	AR5	AR6
Methane (biogenic)	28	27
Nitrous Oxide	265	273

Impact assessment modelling was conducted using the Integrity Ag Verified Carbon Footprint implemented in SimaPro™ 9.3 (Pré-Consultants, 2021).

While the primary goal of the model was to report results for the ABSF and SSF, a secondary goal was market readiness for reporting to overseas markets, as required. The EU market was considered, and the system was also designed to report impacts using the Product Environmental Footprint (PEF) impact assessment method. The impact categories are described in Table 26.

Results reported using this system were also reported in Appendix 2.

3.4 Beef model

3.4.1 System boundaries and reference flow

This study completed a cradle-to-farm gate analysis, using a reference flow of ‘one kilogram of liveweight (LW)’ on-farm, immediately prior to processing. The product carbon footprint used an LCA approach as required in the

International Organization for Standardization (ISO) 14067 (2018). LCA as referred to in ISO 14044 (2020) is a primary tool for the assessment of environmental impacts and environmental efficiency within supply chains, and typically assesses impacts relative to the functional output of the system (typically, one unit of output, termed the 'reference flow' or 'functional unit'). Carbon and water footprinting, when following the LCA approach, are a comprehensive means of assessing carbon and water impacts for a product, using a defined system boundary which is shown for the cattle herd in Figure 2. The analysis covered the entire beef cattle industry, including breeding cattle processed from the dairy and live export industries, but did not include cattle exported from Australia as part of the live export trade because these cattle were produced to different market specifications to the slaughter herd.

The system boundary included pre-farm and on-farm emission sources from farm services (e.g., purchased feed, diesel, petrol, electricity, administration) and other purchased inputs (e.g., herbicides and pesticides). Impacts were reported for cattle exiting the production system at the point where cattle were ready for transport for meat processing. Impacts at this point were reported using a reference unit of 'one kilogram of LW'.

As part of the current project, the system boundary included meat processing, and results were reported per kilogram of boxed beef, with the system boundary ending at the load-out dock prior to meat being transported from the processing plant.

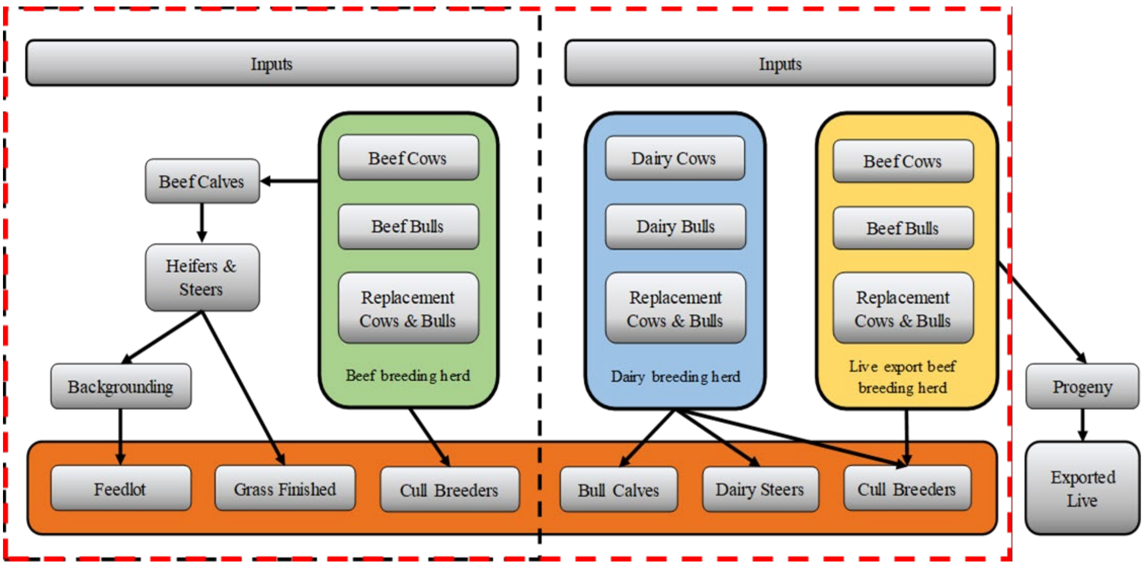


Figure 2. System boundary diagram showing coverage of the cradle-to-farm gate primary production system producing beef cattle processed in Australia (black dashed line) and included production systems (red dashed line) – live export cattle, and beef from dairy herds

3.4.2 Greenhouse gas emission calculations

This study conducted livestock GHG emission modelling using Australian National Greenhouse Gas Inventory (NGGI) methods (Commonwealth of Australia, 2025a) with state-specific activity data using the general approach previously described for grazing systems (Wiedemann et al., 2015b) and grain finishing (Wiedemann et al., 2017). Within the NGGI, emissions from grazing cattle are estimated based on relationships between dry matter intake (DMI) and methane production derived from analysis of Australian respiration chamber data (Charmley et al., 2016). The estimation of DMI was based on Australian derived relationships that rely primarily on the animals' weight, weight gain and milk production (Commonwealth of Australia, 2025a). For feedlot cattle, enteric methane was determined using the equation of Almeida et al. (2025) as applied in the NGGI. This method for feedlot cattle was revised in 2025 in the NGGI and as a result, impacts over the trend period were recalculated.

The methods comply with the international guidelines for conducting livestock LCA (FAO, 2016). The enteric methane equation of Charmley et al. (2016) produced similar methane yields per kilogram of DMI as the IPCC (2019) for grass fed cattle.

The study methods were not able to differentiate methane yields between suppliers that grazed cattle on pastures or forages that have recently been shown to reduce enteric methane, such as Chicory (Loza et al., 2021; Waghorn et al., 2002), plantain (Durmic et al., 2016) or forage brassicas (Storlien et al., 2015; Sun et al., 2016). Where these pastures were grazed, the study results would be conservative.

The data model enabled segregation of cattle that had been fed low methane supplements such as Bovaer (Dijkstra et al., 2018; Patra et al., 2017) or Asparagopsis (George et al., 2024; Wasson et al., 2022). Data reporting the number of cattle fed these products were not available but to test the framework, a case study was implemented where emissions from a known sample of animals that had been fed Bovaer were assessed.

3.4.3 Handling co-production

With respect to handling co-products, this was avoided by separating sub-systems at the farm level to divide impacts associated with beef from other agricultural products (i.e., sheep and cereals), The functional unit of the study did not differentiate between beef from different animal classes, and no allocation was performed. Manure nutrients from the grazing herd were assumed to return directly to the pasture and were considered a biological feedback loop without the need for allocation. Manure nutrients from feedlot manure were treated as residuals, following guidance from LEAP (FAO, 2016). Farm services and purchased inputs associated with multiple enterprise systems (beef, sheep and cropping) were subdivided, and inputs associated with crop production and sheep were excluded following recommendations from ISO 14044 (ISO, 2006).

The carbon footprint of boxed beef was estimated using allocation methods described in Wiedemann and Yan (2014), and a sensitivity assessment was done to assess the impact of a variation in meat yields and allocations, which were uncertain estimates.

Recent national scale data of retail meat, edible offal, hides and other co-product yields were not available and as a result, a sensitivity analysis was undertaken with a range of plausible assumptions. This is an area requiring further data development in the framework for subsequent years.

3.4.4 Boxed meat

Inventory data for meat processing were taken from Ridoutt (2025). Only a national value was reported for boxed meat pending sufficient data at state level to provide meaningful estimates.

3.5 Sheep model

3.5.1 System boundaries and reference flow

This study examined the primary production system (i.e., cradle to farm gate) of the Australian sheep flock, using a reference flow of ‘one kilogram of liveweight (LW)’ and ‘one kilogram of greasy wool’ on-farm, immediately prior to sale for live export, processing or in the case of wool the point at which wool leaves the farm (Figure 3). This study did not differentiate between sheep meat or wool types.

Sheep destined for live export were included in the system boundary. This differed to cattle, because sheep destined for live export arise from more similar production systems and are sold at similar weights to animals for processing.

The sheep flock contained a class that contributed to meat, but not wool (shedding sheep). This class was subdivided, and impacts were only attributed to meat. The system boundary included farm services (e.g., purchased feed, fuel, electricity, administration) and other purchased inputs (e.g., herbicides and pesticides).

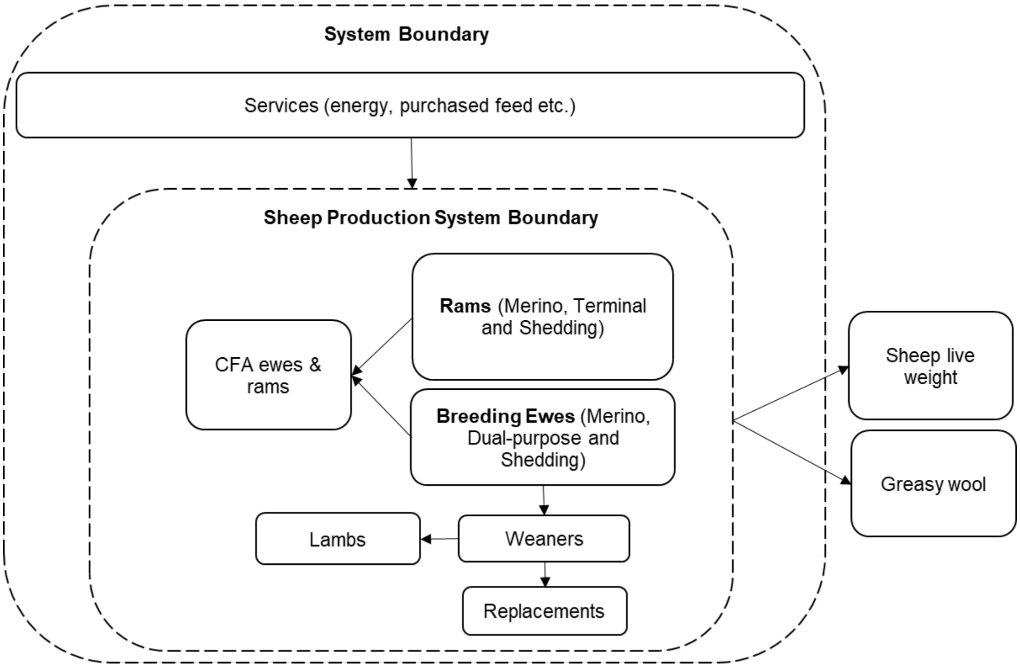


Figure 3. National system boundary and sheep production sub-system boundary (dashed line). The outputs of the sheep production sub-system are sheep liveweight and greasy wool

3.5.2 Greenhouse gas emission calculations

Feed intake was calculated using the AFRC (1990) method as applied by the Australian National Greenhouse Gas Inventory (NGGI) (Commonwealth of Australia, 2025a). Livestock GHG emissions were determined by applying methods outlined in the NGGI for enteric methane and manure emissions (Commonwealth of Australia, 2025a) Inventory data related to dietary crude protein, dry matter digestibility and dry matter availability used regional assumptions from the NIR (Commonwealth of Australia, 2025a, p. 285).

3.5.3 Handling co-production

As described for the beef model, farming systems were subdivided to avoid multi-functional systems where possible. Handling co-production of wool and LW (for meat) was modelled using protein mass allocation (Wiedemann et al., 2015a). The protein mass for greasy wool was estimated by multiplying the greasy wool by clean wool content, with clean, dry wool being 100% protein and protein from LW being assumed to be 18% (Wiedemann et al., 2015a).

A boxed sheep meat carbon footprint was estimated using the same methods as described in section 3.4.4 with sheep specific data from AMPC and Wiedemann and Yan (2014). Retail yields were increased 2.5% on account of changes in breed type since the previous study, and a sensitivity assessment was done noting this was an uncertain estimate. Inventory data for meat processing taken from Ridoutt (2025).

3.5.4 Boxed Meat

Recent national scale data of retail meat, edible offal, hides and other co-product yields were not available and as a result, a sensitivity analysis was undertaken with a range of plausible assumptions. This is an area requiring further data development in the framework for subsequent years.

3.6 Land Use and Land Use Change (LULUC) GHG assessment

Land Use and Land Use Change emissions and removals are an important impact and are recommended inclusions in ISO 14067 (2018) and GHG Protocol. This assessment has not been done in previous studies, because of the high degree of uncertainty in attributing impacts to sheep and cattle.

This assessment has a high degree of uncertainty, related to both the calculation of emissions and removals over millions of hectares of grazing land, and in the attribution of these emissions to beef, sheep and wool. With this higher uncertainty noted, the beta implementation of the model included LULUC emissions and removals for beef and sheep systems using the methods outlined in the following sections. The result was a statistical analysis determined at state scale and reported at national scale.

This study established and utilised a new data release from the NGGI, which disaggregated LULUCF impacts (that included non-grazing land uses such as cropping and forestry) and reported these as at industry scale for “grazing” industries. This data release was subject to predetermined methodological decisions and processes, which are explained in NGGI reporting (see the annual National Inventory Report and attachments). One key methodological decision taken by the NGGI is the selection of the emission boundary and land area assessed for anthropogenic emissions or removals, which has not been disclosed publicly. Providing clarity on these boundaries would greatly assist the grazing industries to understand the attribution of both emission and removal sources.

3.6.1 Grazing area assessment

A spatial boundary layer was developed to determine land areas for sheep and beef grazing, state-by-state. This formed the geographical boundary of the assessment. To achieve this, areas unsuitable for agricultural purposes including national parks, state forest etc were removed. Areas where landholders lack full operational control were identified and excluded. These areas where producers lack full operational control include areas that have been protected for biodiversity purposes or similar. These were excluded from the assessment, because landholders did not have the full authority to introduce and implement changed management practices that would influence emissions and removals and any change in these areas would be deemed biogenic rather than anthropogenic. Additionally, areas within urban regions where the Australian Collaborative Land Use and Management Program’s (ACLUMP) Catchment Scale Land Use of Australia (CLUM) dataset identified land as not attributable to agriculture were removed.

The Grazing Area was further partitioned to identify areas producing cattle and sheep. The Australian Bureau of Statistics (ABS) Commodities data, specifically the 2021 release, were used because it was the most recent release that provided high granularity, SA2 level distribution of sheep and cattle. Areas with inconsequential numbers of sheep or cattle were excluded.

For areas of mixed sheep and cattle grazing, the stocking densities of sheep and cattle were calculated from ABS livestock numbers and were used to determine the fraction of land used for cattle and the fraction used for sheep. Areas for each species were then aggregated and implemented at state scale.

3.6.2 Emission and removal sources excluded from the system boundary

Land categories not attributable to sheep and cattle were excluded from the GHG inventory. This included commercial Forestry, which is separately accounted in the NGGI and was excluded. Other non-grazing agricultural sectors were also removed. Emissions and removals attributable to grazing land were assessed. It is possible this included some land used for grazing other livestock types such as horses, goats or dairy cattle. This may have resulted in slight over-attribution to red meat of either emissions or removals, but it was not possible at the scale of the current assessment to separate these impacts and the error was expected to be <5% based on the size of these industries compared to extensive beef and sheep. Further work is needed to accurately remove these impacts from the account.

3.6.3 State scale Land Use and sLUC assessment

Due to the scale of the study area, direct Land Use (dLUC) and Land Use Change were not practical and therefore a statistical Land Use (sLUC) and Land Use Change approach was used, complying with GHG Protocol requirements (Greenhouse Gas Protocol, 2022a).

Source emissions and removals data were taken from the National Greenhouse Gas Inventory (NGGI) at state-scale, which is reported annually by the Commonwealth of Australia (2025a). For the purposes of this report, NGGI data (emissions and removals) were used as foundational data for reporting LULUC relevant to the beef and sheep industry. The methods implemented by the Commonwealth of Australia (2025a) are not repeated here in detail. Briefly, LULUC accounting undertaken by the NGGI team and reported with sectoral disaggregation for ‘grazing’ which was dominated by sheep and beef. This excluded “Forestry” which is designated as plantations for harvest and were not attributable to grazing. These emissions and removals are modelled using Tier 3 models; integrating spatially referenced data with the Full Carbon Accounting Model (FullCAM). Spatial datasets identify key disturbance events and apply a comprehensive modelling approach to the estimation of carbon stock changes (Commonwealth of Australia, 2025a, p. 285). The method aims to only account for anthropogenic emissions and removals.

In order to disaggregate specific Land Use and impacts for sheep and cattle, the following steps were undertaken by the NGGI team for the project. The 2023 NGGI LULUCF’s sources and sinks were split according to Economic Section (NIbES) categories: Agricultural land, Forestry Land, and Other Land. The agricultural land was further split into “cropping”, “grazing”, and “conservation and other land uses”. The proportions of emissions and removals assigned to these subclasses were based on FullCAM simulation results within the Catchment Scale Land Use of Australia (ALUM) land cover. These “grazing” estimates were then proportioned between cattle and sheep using the spatial extent generated by the Grazing Area Assessment.

3.6.4 Exclusion of removals from carbon credits

The National Inventory accounts for removals on land areas where ACCU Scheme regeneration projects are operated, resulting in double-counting between the ACCU Scheme and national inventory. Within the purposes of reporting national emissions and removals, this is accepted, because ACCUs are not legally able to be traded outside Australia and contribute to meeting Australia’s international emission targets.

However, when determining impacts for a sector of the economy – beef and sheep, double counting of ACCU Scheme credits with removals attributable to beef and sheep reduces the integrity of the carbon account and is not accepted under business or product based accounting. As the present study aimed to develop Land Use and sLUC factors for product and value chain accounting, ACCU credits needed to be removed from the account.

To achieve this, methods were refined to remove the potential double counting of removals that were sold from the beef and sheep sector to other sectors in the economy. No method has been developed previously to achieve this, and the methods carried out in the present study are outlined in the following sections.

A range of guiding assumptions were made to conduct this work. Firstly, the ACCU Scheme represents the most utilised system for development and retirement of carbon credit units in Australia, and no international registers were evaluated. This was expected to create minimal error because few projects have been registered under other schemes in Australia. It was acknowledged that ACCUs could be traded multiple times before being retired, and that ultimately companies operating within the supply chain could buy and retire these credits to reduce net emissions of red meat or wool. While this was technically possible, there was no data to describe the trade of ACCUs for retirement against red meat or wool and a scan of retailers was made to confirm that any credits retired were negligible. As a result of this scan, no credits were accounted to the sector via this mechanism.

The following ACCU Scheme vegetation-related methods were assessed as most relevant: Human Induced Regeneration; Regrowth Methods and Tree Planting Methods. The Savanah Burning Method was not considered because this was a removal method and wildfire emissions were excluded from the system boundary in the present study, being considered part of the biogenic carbon cycle.

Soil-based ACCU scheme methods were excluded because no credits were sold from these methods in the period of assessment. Plantation methods were excluded because forestry was outside the system boundary. Avoided clearing / deforestation methods were excluded because these were avoided emissions methods not removal methods.

It was possible to separate Government purchases of carbon credits from those sold directly to other sectors. These were accounted separately, but in the present study both were removed from the beef and sheep carbon account. ACCUs sold to other sectors were removed for obvious double-counting reasons between sectors and businesses. Government purchased credits could be argued to be valid sources of removals for beef and sheep if the Government retired these. However, recent Government policies indicate that contracted or purchased ACCUs by the Federal Government may be sold to other entities, such as those covered by the Safeguard Mechanism. As a consequence, a conservative position was taken where all credits contracted or sold to the Federal Government were removed from the beef and sheep carbon account to avoid the risk of double counting.

There is no dataset available in Australia that clearly quantifies these removals or transfers from one sector to another. The present study developed a method to conservatively account for and exclude ACCU Scheme removals from the carbon account. The method is briefly described here. Firstly, ACCUs retired outside of CACs (Carbon Abatement Contracts with Commonwealth government) were calculated. Using Clean Energy Regulator (CER) ACCU Scheme data (CER, 2024a), the total number of retirements for relevant vegetation methods (noting CACs are excluded from this dataset) were calculated. An assessment was made to determine if any retired credits remained within the red meat and wool industries (for example, were retired to support a market claim for red meat). There was no information regarding credits retired for market claims and as a result, a conservative estimate was made assuming there were no credits retired that were attributable to beef or sheep.

To determine the overlap in project areas with livestock grazing, the ratio of total project areas across relevant land-based project extent mapping (CER, 2024b) was overlayed with the grazing area determined for sheep and beef. The proportion of land area that overlapped relative to total area of ACCU projects was used to determine the volume of abatement to be removed from the livestock carbon account. For the purposes of partitioning removals across the beef and sheep-based pastoral extents, ACCU Scheme-related project area was assumed equal or proportionate to CEA areas for such projects. Credits were also assumed to be generated proportionately across projects based on their size and yield per hectare (using the total issued credits as a surrogate).

Using statistics for relevant methods outlined in CER data (CER, 2024a), the total amount of credits retired were determined. CER data (2024a) combines all vegetation methods, including non-relevant vegetation methods. To determine the proportion of ACCUs retired for relevant methods, the CER CAC data (CER, 2024c) were reviewed for vegetation projects that were active within the reporting period. The total volume of ACCUs delivered for relevant and non-relevant methods was calculated to determine a ratio which was then applied to the total amount of vegetation method ACCUs. To determine the proportion of credits attributable to sheep / beef land, the total credits retired were divided proportionately for relevant project mapped extents based on project size and then apportioned to sheep and beef based on Land Use mapping created as part of the grazing area assessment.

This method was then repeated for CACs by using the CAC register (CER, 2024c), the relevant project types that delivered CAC-based ACCUs in 2022, and the volume of CACs sold. These were attributed to beef and sheep using the aforementioned methods.

Lastly, ACCUs retired outside the beef and sheep industry were combined with CAC-based ACCUs to determine the total amount of ACCUs retired outside of the beef and sheep industry.

3.6.5 Handling emissions and removals

The NGGI and the underlying FULLCAM model does not separate emissions and removals that are occurring within the same system; for example emissions and removals that may be constantly arising from natural carbon cycles in forests or agricultural soils. Instead, the NGGI reports net values. This makes compliance with GHG Protocol difficult, because of the discounting approach required for emissions (see next section). There was no clear way to overcome this limitation in the present study because of the limitations of the NGGI modelling approach. Two approaches were taken to more closely follow GHG Protocol, but neither was completely able to comply with GHG Protocol requirements (discussed in following sections).

3.6.6 Allocation and discounting approach

The LULUC dataset was further processed to implement the discounting requirements of GHGP (Greenhouse Gas Protocol, 2022a, pp. 23, 103, 112).

The NGGI does not use an arbitrary discounting period for emission sources as required by GHG Protocol. Instead, when an LUC event occurs, for example through conversion of forest to grassland, approximately 90% of the carbon within biomass is counted as an emission in the reporting year, with the remaining proportion decaying and contributing to emissions over a 50 year period. This is a simplified reflection of the biophysical system. It is biologically implausible for ~90% of emissions from an LUC event to arise in the first year. Even where land is cleared, raked and burned, it still takes time for biomass to dry sufficiently to burn. It is likely that 2-3 years is the fastest decay curve possible, and that in many instances where trees are not burned, decay happens over a long period of time under natural processes.

It is reasonable to believe under the current mix of management activities, that the majority of losses are likely to occur over the first 5-10 years as trees decay or are burned as part of land clearing activities.

The GHGP guidance states that when accounting for Land Use Change emissions an assessment period of 20 years or greater must be used (Greenhouse Gas Protocol, 2022a, p. 110). This is applied to emissions, but not removals, and was therefore challenging to implement using the Inventory data which combined emissions and removals. For reported results, the discounting was applied to the years where the net results were a total emission. Correspondingly, years where reported net results were a total removal, no discounting / amortisation was applied for that year (i.e. the removal was applied to that year only). This was a necessary simplification considering the format the data were received in, but should be improved in the future.

Either a linear or equal discounting approach can be used to distribute emissions across the assessment period (see Figure 4 (Greenhouse Gas Protocol, 2022a, p. 112). In the present study, linear discounting was applied because this most closely aligned with likely emission sequences close to the timing of the LUC event.

The GHGP guidance states that the results of net LUC emissions can be allocated between industries based on a Shared Responsibility Approach (Greenhouse Gas Protocol, 2022a, p. 113). Therefore, the Shared Responsibility approach can be used to allocate LUC emissions based on the land area to sheep and beef and this was undertaken in the present study.

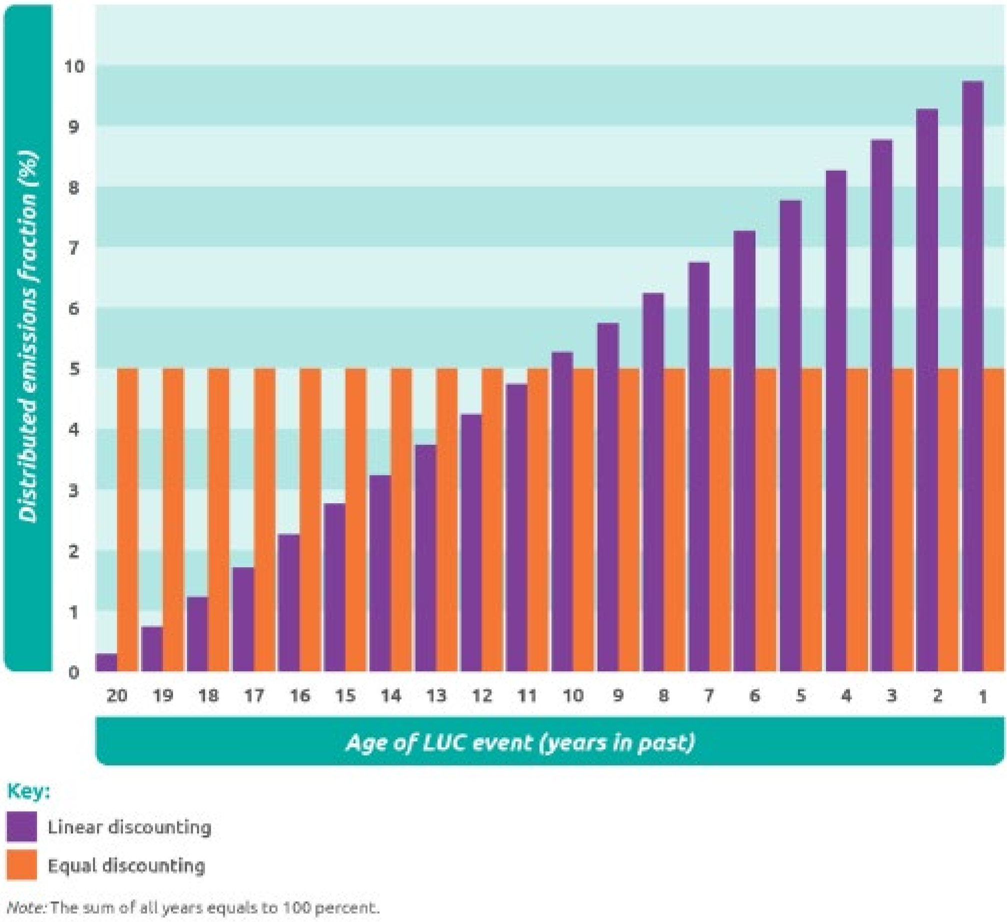


Figure 4. Illustration of the linear and equal discounting approaches across 20 years. The Linear discounting approach applies heavier weighting to more recent years in the lookback period (Greenhouse Gas Protocol, 2022a, p. 112)

Results were sensitive to the discounting time period and discounting method (linear or equal) applied. Linear discounting was the preferred approach as this most closely resembles the biomass transitions occurring after an LUC event.

The 'discounting' time requirement is explicit in GHG Protocol and derived methods such as SBTi. However, ISO 14067 (ISO, 2018) is less clear and recommends a discounting period of "decades". The smallest unit for such an approach could be 10 years and this was therefore implemented as part of a sensitivity analysis, along with comparison of the linear and equal discounting method. This time period was considered more likely to reflect the actual loss rates from land clearing where reasonably rapid decay or burning would result in almost all emissions having occurred within 10 years.

3.6.7 Data years and projections

At the time of completing the analysis results were only available from the NGGI up to 2022. Results for 2023 were released close to the date of completion of the project and showed a similar trend in removals at national scale. Because the emissions assessment was completed for 2023/24 for beef, and 2023 for sheep, a projection was used to include emissions for 2023 and 2024. This was done by projecting the 2022 result to 2023 and 2024. This was a simplification but was reasonable, considering the national scale 2023 result released in May 2025.

4.0 Project outcomes

4.1 Data framework

The beef and sheep data frameworks have been developed and successfully delivered an interoperable, streamlined data system for the beef, sheep meat and wool industries. This enhancement meets shared cross-sector data requirements for both national and international sustainability reporting. The system includes an improved data collection and data processing mechanism, providing required input data for carbon and freshwater consumption analysis as required for the beef and sheep sustainability frameworks and value chain reporting needs such as reporting against SBTi targets. By developing a 'tell it once' data collection system, the project has successfully reduced the burden on industry by enabling reporting capabilities at industry wide scale, and providing a system that can be implemented by ‘supply chain aggregators’ such as meat processing plants or wool buyers, who need a system to determine impacts from large numbers of individual producers without the difficulty of engaging in very large data collection activities. Further, the system was tested to deliver results for an overseas market reporting scheme, the EU PEF, which required reporting against 16 environmental indicators. This ensures compliance with detailed guidelines and supports the future competitiveness of Australian agricultural exports.

By implementing the beta framework, an annual update was conducted, and reporting was expanded for beef, sheep meat and wool. The framework and conceptual approach may also be adopted by other similar sectors to promote cross-commodity uniformity in reporting for sustainability frameworks. The following sections present the results of implementing the beta data framework combined with the iVCF model for beef, sheep meat and wool.

4.2 Beef model

4.2.1 Herd productivity

Total beef production from the Australian beef herd increased over entire trend period from 1985 to 2024 by 66%. Production was 5% higher in the most recent period at 2.2M tonnes, compared with the 5 years to 2020. This was achieved via an improvement in the weight for age of slaughter cattle, which has almost doubled since the five years to 1985 in response both to heavier carcase weights (increased 49%) and younger age at slaughter. Beef production per cow joined increased substantially over the past 40 years (Figure 5), with more beef turnoff from fewer breeder cows and a smaller livestock inventory.

In the most recent two-year period, the increase in carcase weights moderated compared to previous time periods, reflecting the greater sensitivity of the two-year averaging period. Growth rates in young cattle were estimated to have increased by 11%, despite the proportion of feedlot turnoff remaining static, which was a good outcome reflecting higher growth rates in grass finished cattle. Because of the moderation in carcase weight, beef produced per joined cow also decreased marginally.

The primary drivers of this moderation in carcase weight increase were the stabilisation of the proportion of feedlot cattle relative to grass finished cattle, which had increased in every previous time period. This was also influenced by the shorter assessment period of two years (2023 and 2024) when more cattle were finished on grass than may have been expected, possibly because good rainfall conditions across cattle producing regions resulted in excess pasture growth that could be utilised for grass finishing. Looking forward into 2025, it is apparent that the number of cattle on grain has increased, meaning the long-term industry shift to grain finishing is likely to continue in the next reporting period.

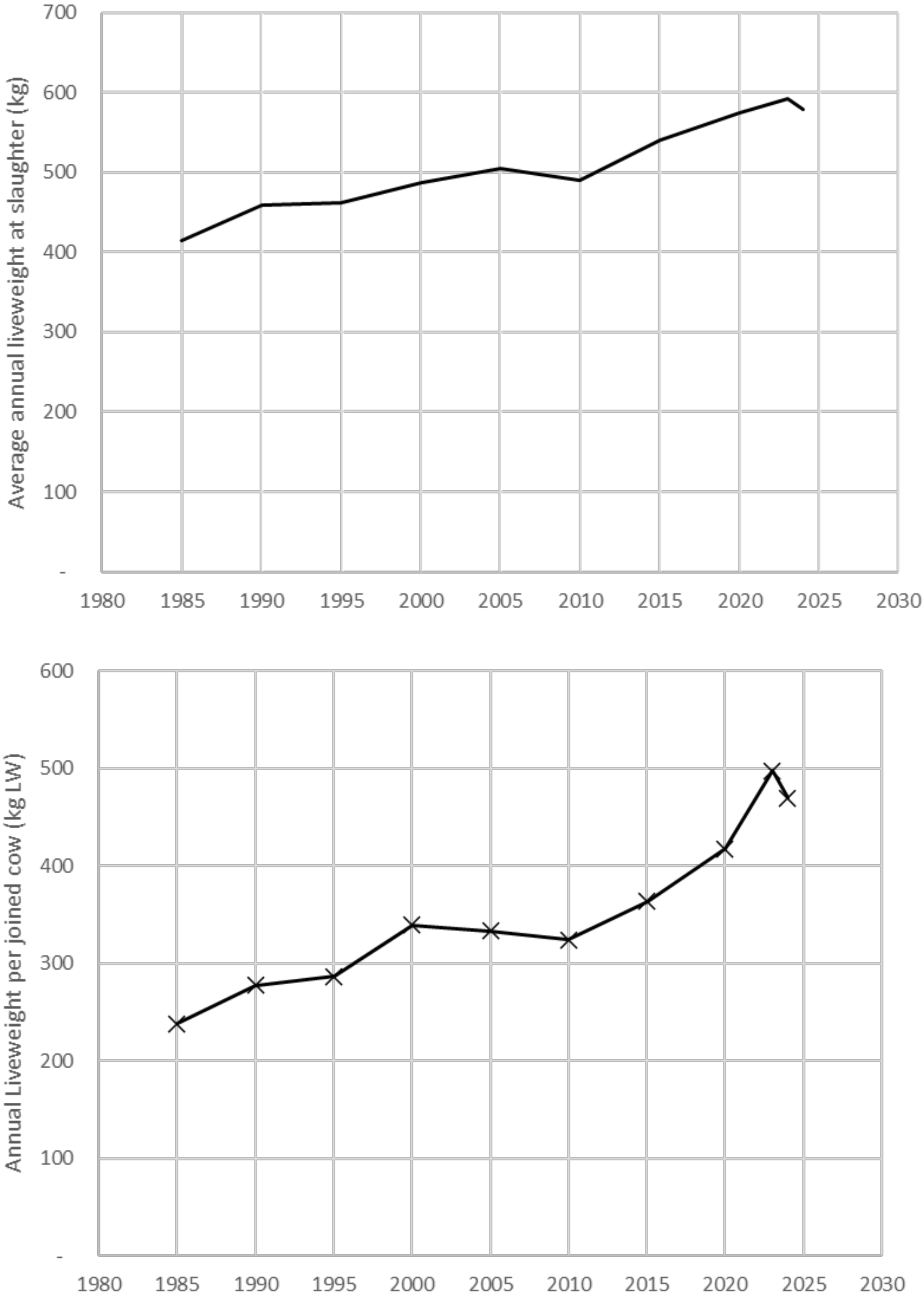


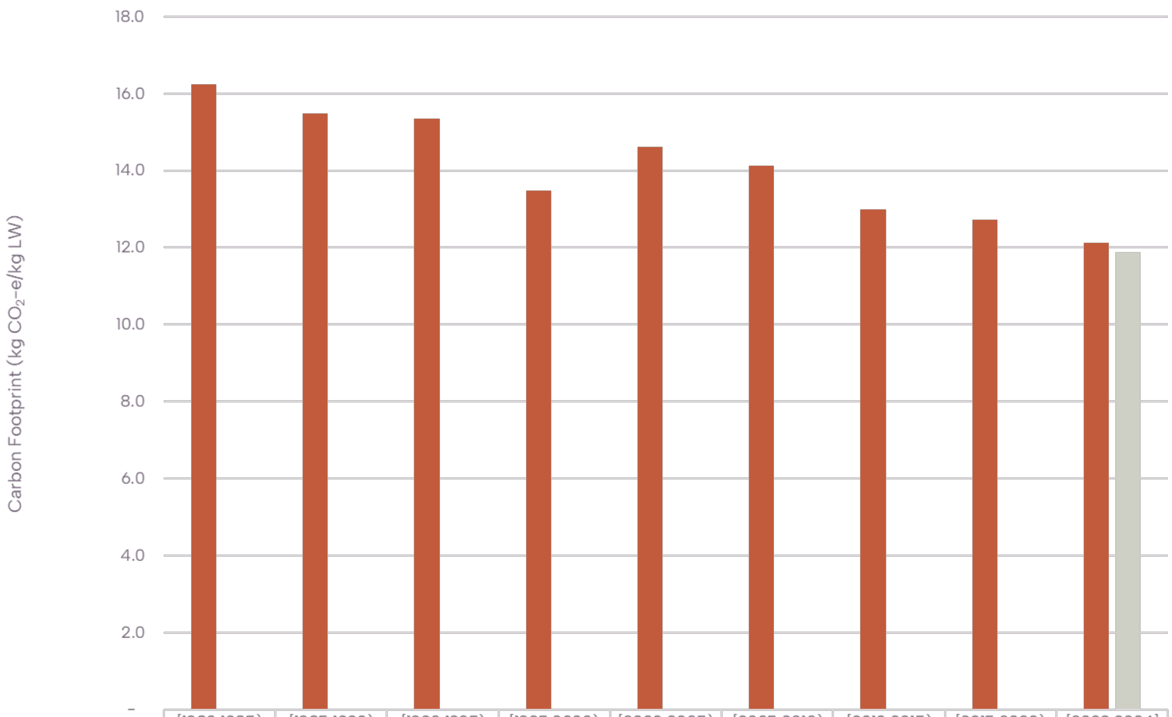
Figure 5. Changes in A) average live weight at slaughter and B) liveweight produced per joined female over the period 1985 to 2024

4.2.2 Product carbon footprint

Historical and current results were updated to align with the IPCC AR6 GWP factors (Figure 6). In response to herd productivity improvements and specifically weight for age, the analysis revealed a 4.7% decline in GHG carbon footprint (excl. LU and dLUC) in the most recent period and a 25.3% decline from 16.2 kg CO_2-e kg LW^{-1} in the five years to 1985 to 12.1 kg CO_2-e kg LW^{-1} in the two years to 2024 (Figure 6) for cattle derived from the beef herd. The reduction in emissions was primarily associated with decreased enteric methane emissions, which declined in absolute terms from 14.7 kg CO_2-e kg LW^{-1} to 10.4 kg CO_2-e kg LW^{-1}. The proportion of methane in the emission profile declined from 90% of total impacts in 1985 to 83% in 2024, partly in response to better herd efficiency reducing methane contributions, and partly because the intensity of production increased, resulting in larger contributions from carbon dioxide associated with energy use and purchased inputs.

The revised feedlot enteric methane formula had the effect of reducing emissions from feedlot cattle, accelerating the emission reduction in the national herd, because the proportion of feedlot finished cattle increased over the trend period. Feedlot cattle generated <50% of the enteric methane emissions of grass fed cattle per kilogram of DMI. Combined with the higher weight gain on grain diets, emission intensity during feedlot finishing was much lower than comparative grass finishing, contributing to the ongoing trend towards lower CF in the national herd. This demonstrated the role of grain finishing as a mitigation strategy for the herd, despite the higher inputs required for grain production, grain milling and transport, which were all included in the analysis.

For the first time in this analysis period, results were also calculated inclusive of beef from dairy herds. This resulted in a lower reported carbon footprint of 11.9 kg CO_2-e kg LW^{-1} (Figure 6, grey bar) with the difference caused by the lower carbon footprint of beef from dairy systems compared to beef from purpose grown beef breed herds. Noting the small volume of beef from dairy, the reduction was relatively modest. For comparison with the trend, the result for the beef herd only was also reported (Figure 6, red bar) and the CF was 12.1 kg CO_2-e kg LW^{-1}. When interpreting these results, it would be most meaningful to use the beef-breed only result to compare with markets or production systems, and to use the results inclusive of dairy when assessing impacts for commodity markets where cow beef from dairy herds contribute to the market.



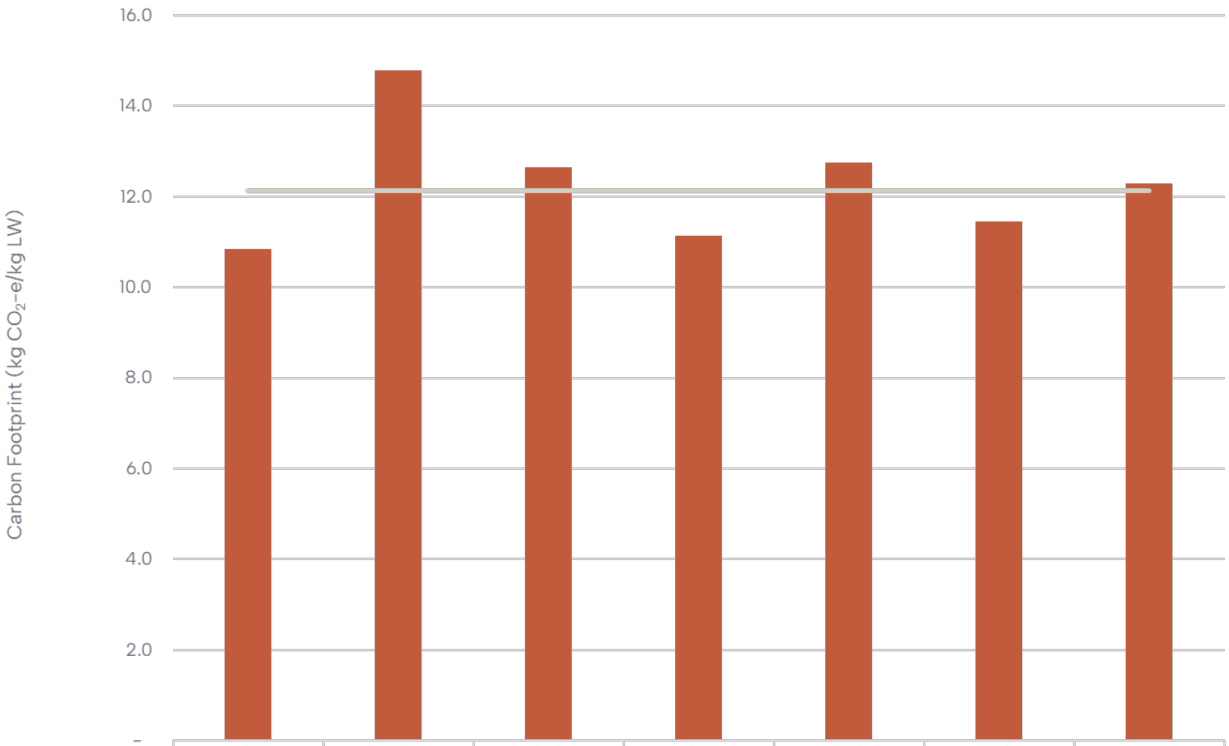
	[1980,1985)	[1985,1990)	[1990,1995)	[1995,2000)	[2000,2005)	[2005,2010)	[2010,2015)	[2015,2020)	[2023,2024]
Beef breeds	16.2	15.5	15.4	13.5	14.6	14.1	13.0	12.7	12.1
Incl Dairy, Live Ex									11.9

Beef breeds   Incl Dairy, Live Ex

Figure 6. Carbon footprint (excl. LULUC) for the production of 1 kg of liveweight beef ready for slaughter over the period 1985 to 2024 reported using AR6 GWP_{100} values. Red bars represent cattle from beef breeds. Grey bar in 2023/24 is inclusive of beef from dairy herds

For the first time in the current analysis, results were also reported for beef based on the state in which the cattle were bred. This did not reflect whether cattle were subsequently moved interstate for growing or finishing, which commonly occurs, particularly for regions such as the Northern Territory. The results were first order estimates and were produced to demonstrate the capability of the data framework for generating more granular results. The state-based results were influenced by two dominant trends; firstly, differences in herd performance (data not shown) explained part of the difference between the states, with QLD and NT showing higher impacts than NSW, SA and VIC. Secondly, the proportion of young cattle finished in feedlots influenced the result and contributed to lower impacts.

Because of the role of feedlots which aggregate cattle from many farms into very large cohorts, the national and state averages will be difficult to compare to 'farm gate' results from many producers. Further to this, farm-gate results will differ from slaughter ready results, particularly for producers of feeder cattle for feedlots. Feeder cattle entering feedlots with a CF of 13.5 or 14 kg CO_2-e kg LW^{-1} may exit with a CF of 8.5-9.5 kg CO_2-e kg LW^{-1} depending on the performance in the feedlot and the time on feed. This has a profound effect on the national average and emphasises the importance of like-for-like comparisons. Where producers sell livestock prior to slaughter weight, either as weaners or feeder weight cattle suitable for entering a feedlot, the CF will typically exceed the national average, but this is explained through the different stage in the life cycle of these cattle, which results in the higher carbon footprint.



	NSW	NT	QLD	SA	TAS	VIC	WA
State Mean	10.9	14.8	12.7	11.1	12.8	11.4	12.3
National mean	12.1	12.1	12.1	12.1	12.1	12.1	12.1

Figure 7. Carbon footprint (excl. LULUC) on a state basis for the production of 1 kg of liveweight beef ready for slaughter reported using AR6 GWP_{100} values

4.2.3 Land Use and sLUC impacts

The impact of Land Use and sLUC on beef was reported for the first time this year as a first-order result (Table 4) which was either a source of removal or emission depending on whether a 10 or 20 year discounting timeframe was used. Using the standard 20 year discounting timeframe, impacts were 2.6 kg CO_2-e kg LW^{-1}, increasing the CF by

21%. This result was heavily influenced by historical emissions from land clearing, and then in more recent years by regeneration of native forest on previously cleared agricultural land used for beef grazing. The national inventory has reported removals in the most recent 3 years for grazing sector – see Table 19 of Appendix 1 (Commonwealth of Australia, 2025a), after historical land clearing had previously been a net emission source. With a shorter linear discounting period of 10 years, which was more consistent with likely emission rates over time, removals were -1.1 kg CO_2-e kg LW^{-1}, which resulted in a 9% lower CF than the emissions-only result. This change in the sign of the result highlighted the sensitivity of outcomes to methodology choices (discussed in later sections).

These results should be treated with caution, as a range of limitations exist around the analysis and assumptions required to calculate the results. Furthermore, the base datasets had a one year delay in the present analysis, meaning the data used in the present analysis was for 2023 resulting in a one year lag between Land Use and sLUC and emissions data and an implicit assumption that results were reasonably representative for 2024. Data will be available to update these results in April-May 2026 with new data which will provide insight on the year-to-year variation in results and the impact of this variation on reporting. As a consequence the results were considered a 'first order' analysis and may vary widely from this result when data quality is improved. Because of the complexity of the method and limitations on access to historical datasets, baseline recalculations were not done to determine impacts across the full trend period back to 1985. This should be investigated to provide more insight in future years.

Table 4. Carbon footprint (AR6) and Land Use and sLUC impacts for 1 kg of beef LW produced in 2024

	Carbon footprint reported on live weight basis (kg CO_2-e kg LW^{-1})	
	excl LULUC	Land Use and sLUC
20 year linear discounting	12.1	2.6
10 year linear discounting		-1.1

Sensitivity analysis results using equal discounting are shown in Table 24 of the Appendix.

4.2.4 Fresh water consumption

Water consumption in 2023-2024 was slightly higher than 2020 and indicated a moderation in the trend of water reductions that have occurred over the trend period. Total freshwater consumption was 71% lower in the two years to 2024 than in the five years to 1985 and reported a value of 400 L kg LW^{-1}. Over the 44 years, the dominant trends were the decline in losses associated with drinking water supply and the substantial decline in pasture irrigation, which was partly countered by an increase in irrigation requirements for feedlot ration production.

In the most recent period, declines were observed in irrigation water for pasture production and drinking water relative to beef production, the latter of which declined in response to improved herd efficiency. Losses associated with irrigation water supply were also found to decline compared to the previous analysis period, but losses from on-farm drinking water supply was estimated to have increased.

As discussed in the methods, changes in data availability resulted in a new methodological approach being adopted for calculating some water sources, meaning there was discontinuity in the trend particularly with respect to irrigation water use. The result should therefore be treated with some caution as new data releases in the next two years may result in recalculation of these results.

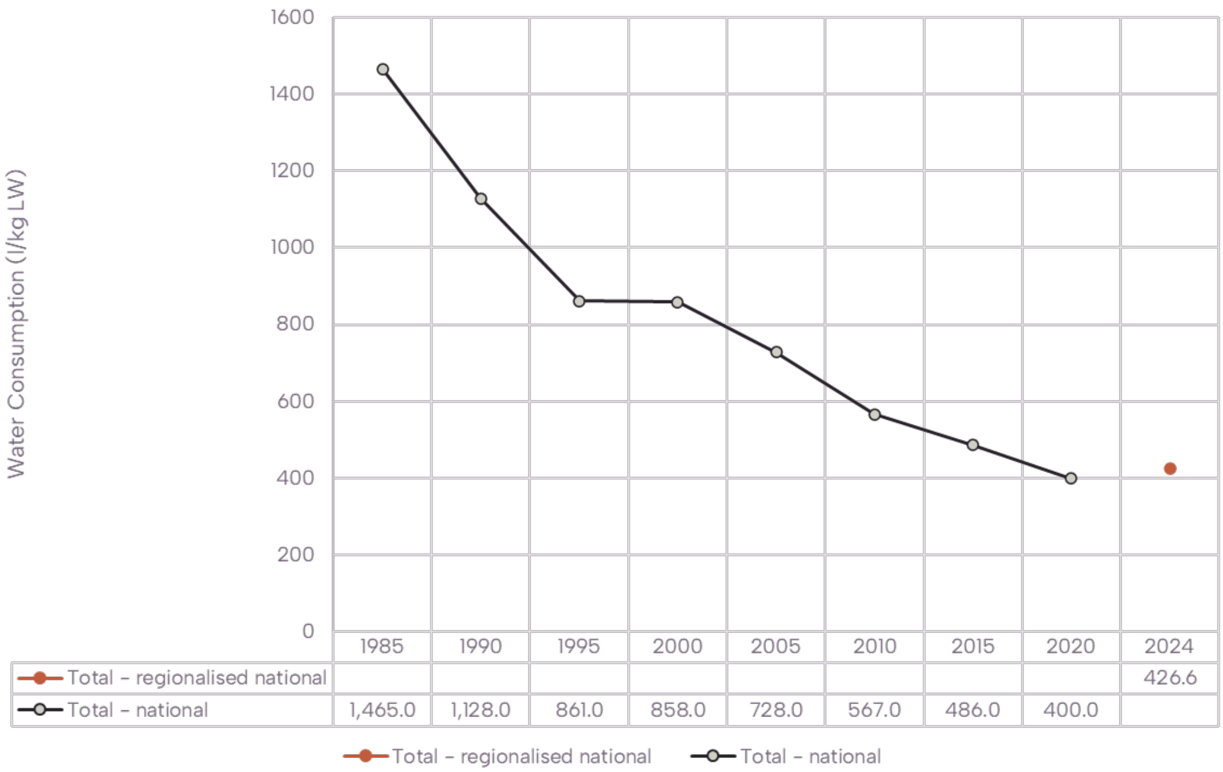


Figure 8. Changes in freshwater consumption from the production of 1 kg liveweight beef over the period 1985 to 2024

4.2.5 Boxed meat

The national average boxed beef carbon footprint was estimated to have 98.5% of emissions arising from primary production (to farm or feedlot gate). While emissions contributed by primary processing were relatively low in the supply chain, the product transformation during meat processing resulted in a very significant increase in reported emissions, from 11.9 kg on a live-weight basis, to 26.9 kg on a boxed meat basis, because of the mass losses that occurred during processing. Proportionally, similar emissions from Land Use and sLUC occurred for boxed product as for live weight, resulting in 5.7 kg CO_2-e kg boxed^{-1} under 20-year linear discounting. Under 10 year discounting, this was -2.4 kg CO_2-e kg boxed^{-1}. Results from processing also implicitly include other products such as tallow, pet food and hides. These were not reported in detail, but results for hides were included for reference in Appendix 2 (Table 28). Default values for co-product mass and value were used in the present study to develop the framework and the boxed result should be updated with recent industry data to provide a more representative result that can be used for benchmarking purposes.

Table 5. Boxed beef carbon footprint for the weighted average of FY2023-2024. Scope boundaries are presented as a guide only, and are based on an emission boundary where the business owns the meat processing facility only, and does not own livestock prior to slaughter

	National Average
Primary Processing – energy and waste water (scope 1)	0.8%
Primary processing – energy (scope 2)	0.7%
Primary production – livestock and farm inputs (processor scope 3)	98.5%
Carbon Footprint (kg CO_2-e kg boxed^{-1}) excl. LU, sLUC	**26.9**

4.3 Sheep model

4.3.1 Flock productivity

There have been significant productivity improvements in the national sheep flock in recent years. Protein production per DSE increased by 24%, showing a substantial increase in flock productivity since 2016, which was driven by a 30% increase in LW production per head while wool production was relatively stable (Figure 9). The productivity improvements were partly the result of a change in flock structure to produce more sheep meat (Figure 9). There was a 10% and 15% increase in mean lamb sale weights and lamb marking rates, respectively over the short-term trend. Other productivity improvements within the flock included reduced mortality rate, cull rate and lamb age. Wool production increased slightly, but this was also masked by increased production of wool from dual purpose breeds, which is lower quality, compared to Merino wool.

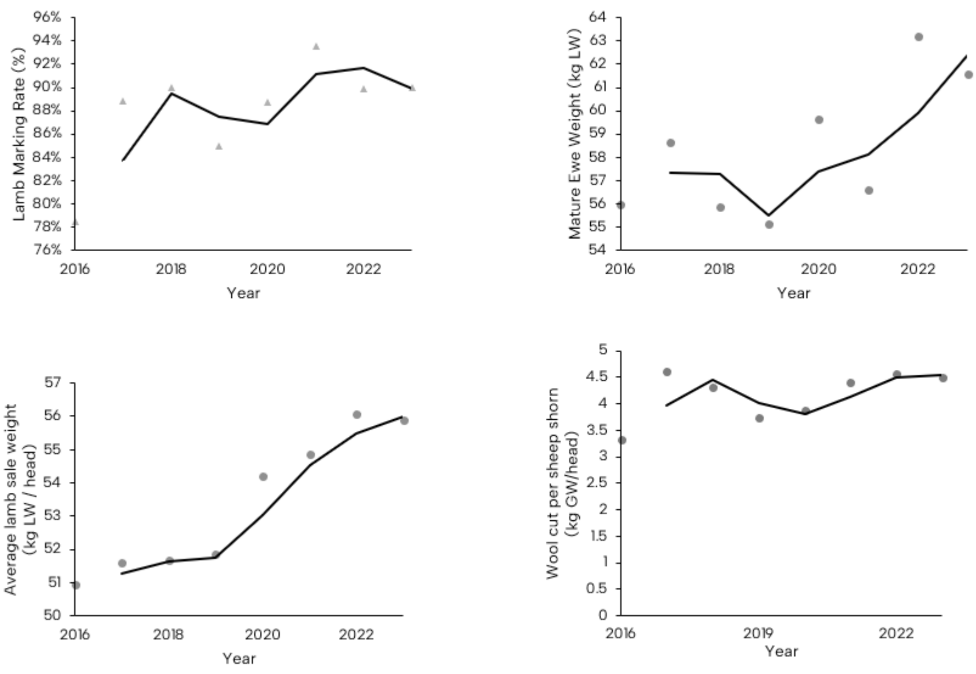
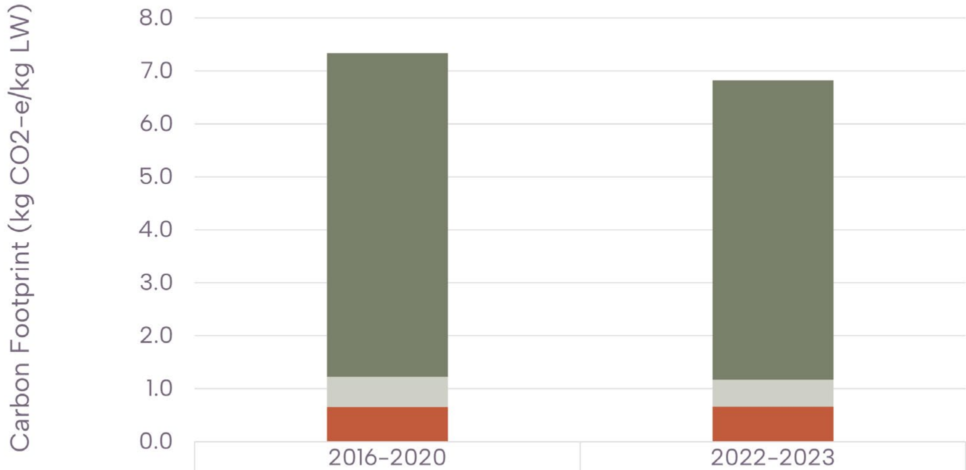


Figure 9. Flock performance changes in the Australian sheep flock over the period 2016 to 2023

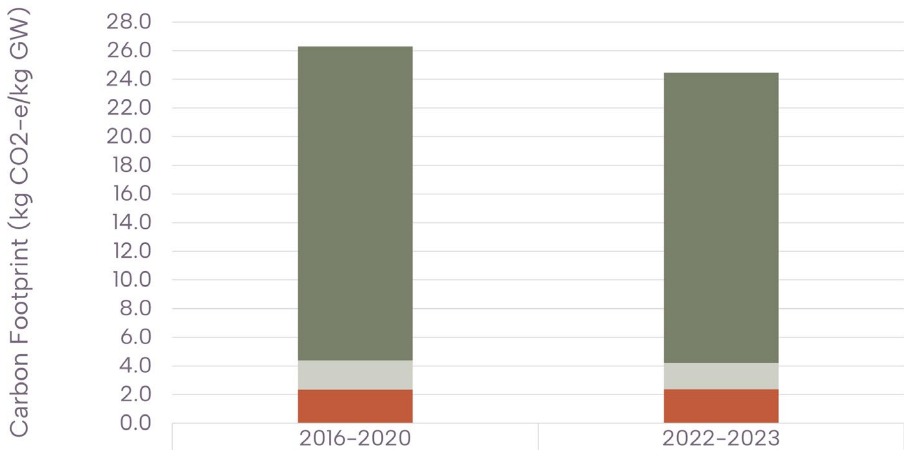
4.3.2 Product carbon footprint

From 2020 to 2023 the carbon footprint of sheep meat (excluding LULUC) decreased 7% from 7.3 to 6.8 kg CO_2-e kg LW^{-1} (Figure 10). The carbon footprint for wool decreased 7% from 26.3 to 24.5 kg CO_2-e kg GW^{-1} over this time period (Figure 11).



	2016-2020	2022-2023
Total	7.3	6.8
Methane (CH_4)	6.1	5.7
Nitrous Oxide (N_2O)	0.6	0.5
Carbon dioxide (CO_2)	0.7	0.7

Figure 10. Carbon footprint (excluding Land Use and sLUC) from live weight production over the years from 2016 to 2023



	2016-2020	2022-2023
Total	26.3	24.5
Methane (CH_4)	21.9	20.3
Nitrous Oxide (N_2O)	2.0	1.8
Carbon dioxide (CO_2)	2.4	2.4

Figure 11. Carbon footprint (excluding Land Use and sLUC) from greasy wool production over the years from 2016 to 2023

4.3.3 Land Use and sLUC impacts

The impact of Land Use and sLUC on sheep meat and wool was reported for the first time this year as a first-order result (Table 6).

The reported removals for sheep differed to the emissions reported for beef, because removals were much greater in southern states where sheep are grazed in larger numbers. As noted for the beef results, these results should be treated with caution, as a range of limitations exist around the analysis and assumptions required to calculate the results.

Table 6. Carbon footprint (AR6) including LULUC for 1 kg of sheep LW and GW produced in 2022-2023

	Live weight (kg)		Greasy wool (kg)	
Carbon footprint	**excl LULUC**	**LULUC only**	**excl LULUC**	**LULUC only**
20 year linear discounting	6.8	-1.3	24.5	-4.6
10 year linear discounting		-2.2		-8.0

4.3.4 Fresh water consumption

Water consumption results were reported for the first time in the present study. From 2020 to 2023, fresh water consumption for sheep meat decreased 9% from 160 to 145 L kg LW^{-1} (Figure 12, Figure 10). Water consumption for wool decreased 10% from 575 to 520 L kg GW^{-1} (Figure 13).

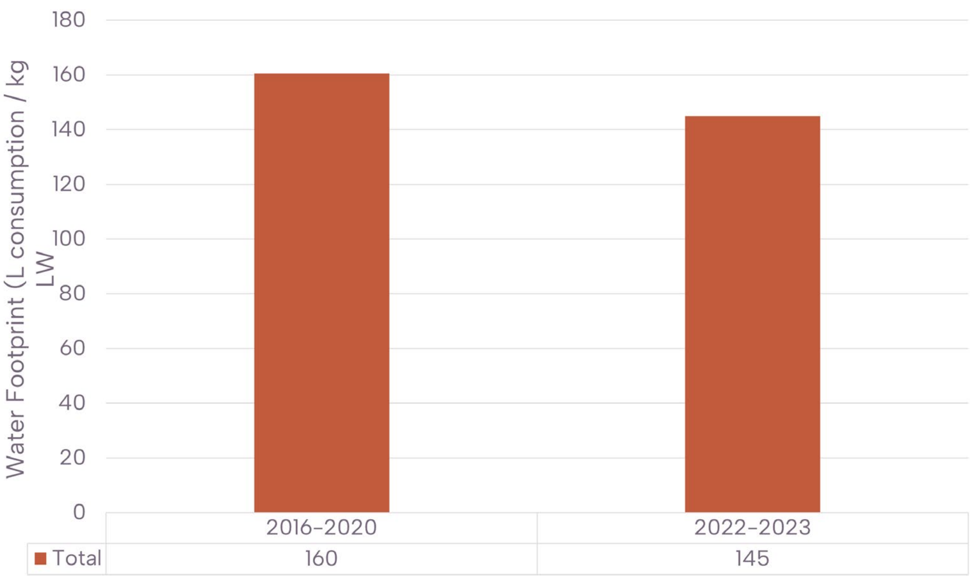


Figure 12. Fresh water consumption footprint for sheep meat from 2016 to 2023

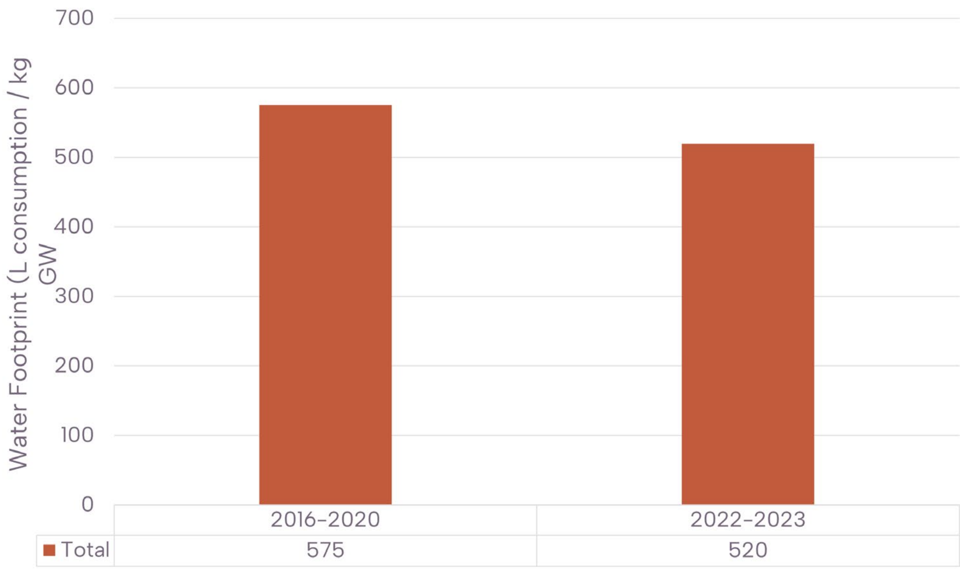


Figure 13. Water consumption footprint for greasy wool produced from 2016 to 2023

4.3.5 Boxed Meat

The national average boxed sheep meat carbon footprint was estimated to be 15.1 kg CO_2-e kg boxed^{-1} excl. Land Use and sLUC, with 98.3% of emissions arising from primary production (to farm gate). The impacts from LU and sLUC for boxed sheep meat was estimated as -2.8 kg CO_2-e kg boxed^{-1} under 20 year linear discounting. With 10 year discounting, the result was -6.5 kg CO_2-e kg boxed^{-1}. Proportionally, similar reductions from Land Use and sLUC occurred for boxed product as for live weight, resulting in a 18% lower CF for boxed lamb at national scale with 20 year discounting. While emissions contributed by primary processing were relatively low in the supply chain, the product transformation during meat processing resulted in a substantial increase in reported emissions, from 6.8 kg on a live-weight basis, to 15.1 kg on a boxed meat basis, because of the mass losses that occurred during processing. Default values for co-product mass and value were used in the present study to develop the framework and the boxed result should be updated with recent industry data to provide a more representative result that can be used for benchmarking purposes.

Table 7. Boxed sheep meat carbon footprint for the weighted average of FY2022-2023. Scope boundaries are presented as a guide only, and are based on an emission boundary where the business owns the meat processing facility only, and does not own livestock prior to slaughter

	National Average
Primary Processing – energy and waste water (scope 1)	0.9%
Primary processing – energy (scope 2)	0.8%
Primary production – livestock and farm inputs (processor scope 3)	98.3%
Carbon Footprint (kg CO_2-e kg boxed^{-1}) excl. LU, sLUC	**15.1**

5.0 Discussion

5.1 Data framework

The beta data framework has delivered a significantly improved capability to generate sustainability results for the wool, sheep meat and beef industries. The development of the data framework successfully enabled the disaggregation of national-level insights to state resolution for cattle, providing stakeholders with a higher level of granularity previously unavailable in the literature. This methodological approach necessitated the generation of market-based analysis (i.e. analysis of impacts relative to the market specifications of different sale classes) as intermediate computational products, which, while essential for accurate regional aggregation, remain insufficiently validated for direct reporting. None-the-less, the framework has the potential to report by market category with improvements to source data quality.

Given the potential value of market based and individual animal productivity metrics for livestock management, we recommend that future research efforts be specifically commissioned to address the validation challenges inherent in these granular estimates. Such work would require targeted data collection at processor or wool broker level, and statistical frameworks designed to handle the increased uncertainty and heterogeneity present at higher analytical resolutions. The ultimate goal is to enable the enhancement of the framework to report on different markets and at different scales up and down the supply chain from primary production to customer.

To enable integration of earlier time steps, previous sheep and beef models were combined and programmed into a python model. This python model is loosely coupled to the database developed in the data framework using a dependency injection model. This dependency injection model allows for greater flexibility in future updates to data, including updates to data structure.

In this instance, loose coupling is a desirable outcome, as it allows for more flexible updates to the data within the framework at a later stage.

One challenge for the project was data availability. During the project, the collection and availability of agricultural data diminished dramatically as a result of changes in ABS survey practices. Some of these impacts are expected to be short term but others, such as release of water statistics, is uncertain. Further, ABS statistical releases in smaller land parcel units (such as SA2) may be difficult to achieve, but are highly valued for projects such as this. These changes have come at a time when agricultural industries are facing more scrutiny than ever over environmental performance. Specific instances are noted in the following section and detailed recommendations have been developed and provided in the following section.

5.1.1 Ongoing framework development

The framework was developed in a period of unprecedented change in data management for agriculture in Australia, as a result of the ABS Data Modernisation program. Further, the National GHG Inventory (NGGI) has also entered a period of review of methods, data systems and data availability which will improve reporting capability over time. These initiatives will continue to occur over the next two to three years. Developing the framework during this period of change had both advantages and disadvantages. It helped clarify industry data needs and prompted the search for new data sources to meet these needs in conjunction with similar efforts by the ABS and NGGI. However, it also led to decreased data availability and caused delays in accessing data during the project. The beta implementation focused on demonstrating the capability of the system. At the finalisation of the project, there was an ongoing program of work that would significantly enhance capability of the framework and allow more seamless integration with other data sources and programs. The beta data framework is reliant on a number of third party data sources. The most recent versions of these data sources were cloned into the data framework, but many of these will need to be updated for updates to sustainability reporting. The data requirements are listed in Table 8, which lists the data sources used in the present study, and notes any required improvements to data quality in future assessments.

Table 8. Data requirements for operation of the beta data framework

Indicator or measure	Data Source Used	Current Data Source	Notes	Requirements
Beef and sheep water use	CLUM	ABS	Currently this does not pick up on northern irrigation development.	To adequately assess this, the framework requires CLUM data specifying irrigated land area for grazing purposes Australia wide and specifically in northern Australian regions where data gaps currently exist.
Beef production – dairy fraction	Dairy slaughter numbers	Predicted from ABS/ ABARES	With a list of PICs, and buy in from cow processors, we could more accurately estimate the contribution of dairy – this will improve the analysis by including the correct number of low-emissions cattle in the Australian market mix.	PIC level identification of dairy producers vs beef producers. Alternatively another means of separating dairy and beef carcases could be used.
Beef production	MSA grading data	MSA	This is essential to deliver state based insights, and future insights which are more granular.	The MSA data sharing agreement needs to be renewed after the close of each financial year.
GHG mitigation – beef and sheep	Bovaer feeding records	N/A	The data framework was beta tested with a sample of known cattle. Inventories of livestock numbers fed on methane reducing supplements nation wide were not available.	A full register of Bovaer and other methane reducing supplement use is required to report emission reduction in future analyses.
Beef and sheep production	ABS slaughter data	ABS	More information required on dentition at slaughter and weight by sex.	ABS to consider collecting data on male and female cattle and sheep. Cattle to be recorded by dentition as 0, 2, 4, 6, >7. Sheep to be recorded as 0, 2, >3.
Beef production	ABS herd statistics	ABS	ABS have reconstructed their data system to model the beef herd. The purpose is different for the ABS model and it will not give exactly the same results as the present model. Interchange of data between the ABS model and the current project would be beneficial for both projects.	Disaggregated ABS cattle model results provided to the Framework annually.
Beef Production	ALFA survey information	ALFA		We require the non-public, disaggregated survey data, which specifies aggregate performance data by feedlot DOF. This was provided in the beta framework and is required going forward for reporting.
Beef Production	Cow kill sheets	Specialised cow processors		Individual animal kill sheets for culled cows are required to properly assess regional herd characteristics. A partial sample was delivered for the beta implementation, but confirmed

				access and data sharing agreements must be established in perpetuity to ensure the framework can deliver consistent trends.
Beef production	Dairy calf slaughter numbers	Dairy Australia	Currently dairy number have been estimated from summary statistics, raw data from DA would be beneficial to improve estimation of dairy calves in the beef supply chain.	No. dairy calves x beef breed. Dairy calves sold.
Beef, sheep and LULUC emissions and removals	NIR data	NIR	This needs to be accessible via API for faster updates. Currently it is an extremely cumbersome process to extract updated factors in a timely manner.	Full set of emission equations relevant to beef and sheep. Full set of default assumptions used for beef and sheep. Disaggregated land sector emissions and removals in table and map format (see following section).
Sheep production	ABS sheep population statistics	ABS	Updated values were not available at the time of completion of this project. This will likely be available for future assessments The purpose is different for the ABS model and it will not give exactly the same results as the present model. Interchange of data between the ABS model and the current project would be beneficial for both projects.	Disaggregated ABS sheep model results provided to the Framework annually.
Sheep (wool) production	Aus sheep wool production	ABS, AWTA, ABARES, DAFF	Currently these sources do not reconcile, and do not use consistent units.	
Beef and sheep meat and co-products	AMPC survey	AMPC/processing sector	The framework was established with default factors for meat yield, edible offal, pet food, rendering materials and hides, and economic values. Updated values are needed annually to provide accurate boxed beef and lamb results and results for other co-products such as hides.	Survey of industry covering: Boxed meat, edible offal, pet food, hides, tallow, renderables (reported as mass or % of total products). Economic value of primary product and co-products (as a %).

Progressing this project to automate data flows and calculations will provide the capacity for more frequent reporting to meet industry needs at lower cost. A business case is needed to underpin the next phase of development and for the upkeep of the model. Further development work is needed to maximise the effectiveness of the system. Beyond that, there will be a maintenance requirement for annual upkeep. The outputs of the framework have the potential to be a benefit to the AMPC and its members, AWI and its members, MLA and its members, the Federal DCCEEW and ABS. It is possible that ongoing upkeep could be maintained through a combination of stakeholders investing. This requires exploration and development into a business plan following completion of the project.

5.1.2 Beef model

The data framework was beta tested to deliver an update to the water and carbon footprints on a liveweight production basis. This update was done on years where the required data were available, viz, 2021-2024. MSA data were not provided for historical assessment periods, and this meant that a full, data driven baseline recalculation could not be completed. We recommend that the data framework be implemented in a future project on all historically available carcass feedback data. This would require buy in from the processing sector to provide confidential data, as cleansed MSA data represents a decreasing proportion of the national turnoff, as the trend extends into the past.

Sensitivity analysis was performed on the two most sensitive and uncertain input parameters to the boxed beef model, namely the fraction of edible product, and the allocation of emissions to this product. The result of this sensitivity analysis is shown in Table 9.

Table 9.Sensitivity analysis of product yield and economic allocation for boxed beef. Highlighted yellow values show the values used in this study

		Mass fraction to boxed beef and edible offal							
		40.0%	41.0%	42.0%	42.1%	43.0%	44.0%	45.0%	46.0%
Economic allocation to boxed beef and edible offal	87.0%	26.4	25.7	25.1	25.1	24.5	24.0	23.4	22.9
	89.0%	27.0	26.3	25.7	25.6	25.1	24.5	24.0	23.5
	91.0%	27.6	26.9	26.3	26.2	25.7	25.1	24.5	24.0
	93.5%	28.3	27.6	27.0	26.9	26.4	25.8	25.2	24.6
	95.0%	28.8	28.1	27.4	27.4	26.8	26.2	25.6	25.0
	97.0%	29.4	28.7	28.0	27.9	27.4	26.7	26.1	25.6
	99.0%	30.0	29.3	28.6	28.5	27.9	27.3	26.7	26.1

The mass fraction to boxed beef and edible offal, here reported relative to live weight, is the most sensitive parameter, and has a hyperbolic relationship to CF. This relationship is shown in Figure 14. The framework was established with default values and methods from Wiedemann & Yan (2014). Considering the sensitivity of results to both the data and the methods, further work is needed in this area. Research and consensus building is required regarding the methods used for handling co-products. This can lead to a guideline or industry standard for best practices in analysing impacts between meat and co-products. With increasing interest in the impact of co-products such as tallow and hides, this an increasingly important task. As an example, there has been growing interest in tallow for producing low-emissions biofuel, and prices have risen for tallow recently. However, the environmental claims of biofuel from tallow depend on receiving 0% allocation to tallow from primary production. The present study did not assume zero allocation, but allocated some impacts to tallow based on dollar value. This is an important matter to resolve, and the industry will need to consider that the outcomes affect other sectors in the economy such as biofuel and leather.

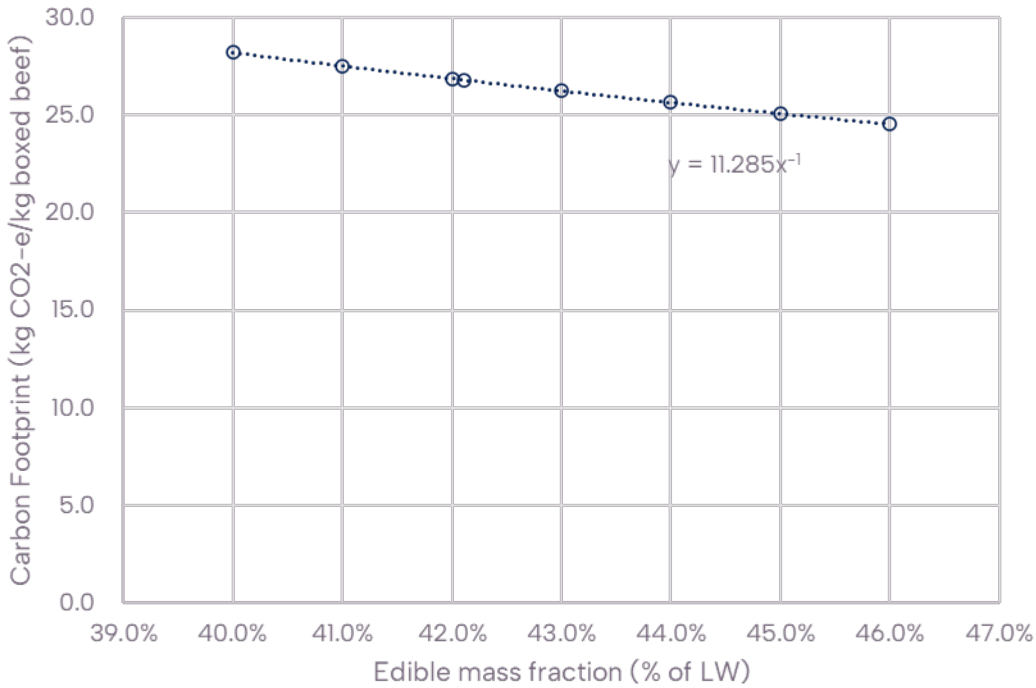


Figure 14. Relationship between boxed beef carbon footprint and retail mass fraction of LW

5.1.3 Sheep model

There was a large degree of uncertainty in the meat flows and allocation data used in the present study. We relied on historical published data (Wiedemann and Yan, 2014), recognising these values need to be revised to match current industry performance by acquiring additional processor level data. A sensitivity analysis was performed on the meat flow and allocation factors, which showed a standard deviation of 0.95 kg CO_2-e kg boxed meat^{-1}. A histogram of these footprint results is shown in Figure 15.

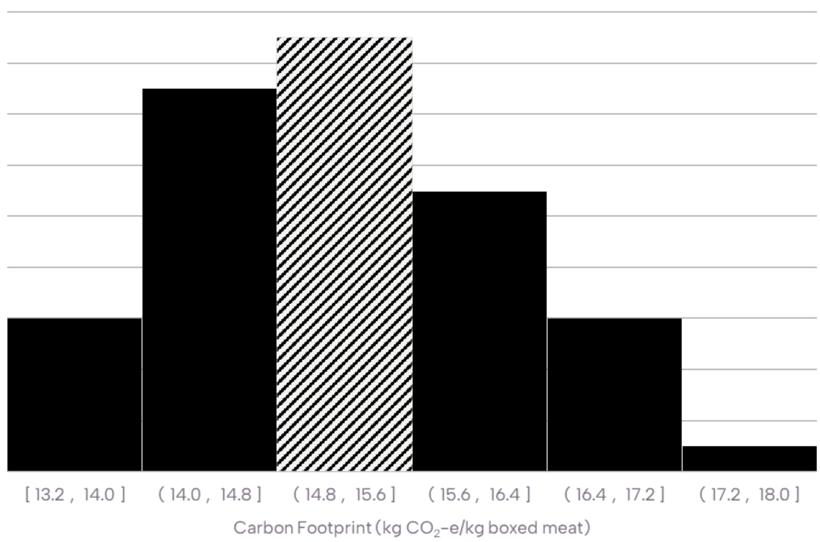


Figure 15. Boxed sheep meat distribution from sensitivity analysis on meat yield, and allocation factor. The dashed bin indicates the mean and median results

5.1.4 Water assessment

Whilst the data framework is complete, and able to deliver beta results for water; the source data that feed the framework are not robust enough to deliver final results. Notably, on farm survey data for water use on sheep and beef farms needs to be provided.

Additionally, ABS and CSIRO are redeveloping a water balance model that will update the water use estimates at a national scale.

The present study could not deliver results appropriate for public dissemination without these key input data.

5.2 Land Use and Land Use Change GHG assessment

The present study implemented for the first time a method of accounting Land Use and sLUC emissions that could be reasonably allocated to Australian beef, sheep meat and wool at the national scale. This required establishment of a more detailed land and emission boundary at state-scale, and development of a means of attributing impacts between sheep and beef in mixed grazing regions. At the scale of implementation, the method was imprecise and is best considered a ‘first order’ estimate. None-the-less, it importantly indicated Land Use and sLUC was a net source of removals not emissions for the sector, with the quantum of removals being heavily influenced by the time period over which discounting was applied. This reflects a long-term trend where land sector processes have changed from a net emission to a net removal source.

While the results presented the same general trend as the sectoral red meat study trends analysis (Mayberry, 2024) the quantum of removals was much less in the present study. Four major methodological differences exist between the present study and Mayberry. Firstly, additional work was undertaken in the present study to allocate impacts between sheep and beef at state level resulting in a different, regional allocation of impacts between the species. Secondly, emissions or removals that were outside the system boundary such as those from commercial Forestry, cropping or other sectors were excluded, but may not be fully excluded from the Mayberry study because of the methods used. Thirdly, removals that were associated with ACCU Scheme projects, where the abatement was sold were excluded in the present study but have not been excluded in Mayberry (2024). Lastly, linear discounting was applied as required by GHG Protocol and secondary users such as SBTi. In contrast, Mayberry uses the NGGI values, which report ~90% of emissions from LUC as occurring in the year the LUC took place, which is not biologically correct.

The different methodological approach was required in order to meet the requirements of GHG Protocol value chain and ISO 14067 accounting. Further, they are required for company level emission reporting or benchmarking with SBTi. In the case of SBTi, 20 year discounting must be used.

Conceptually, it would be more aligned with actual emission rates if this time period was shortened to 10 years, because most losses typically occur in a shorter time period (refer 5.2.1). This would also have the effect of reducing the historical burden of LUC impacts on businesses and supply chains.

Reporting at state-level showed variation with some states showing a net emission while others showed net removals. This variation is expected to occur to an even greater extent at property scale, where historical land clearing events up to 20 years ago may contribute very significant emissions to carbon accounts, or products leaving the farm today. This method will present a significant challenge for supply chain and business scale reporting. Accounting for LUC emissions and removals remains one of the most difficult aspects of carbon footprinting for supply chains. Considering the difficulty and barrier to calculating Direct Land Use and Land Use Change (LU, dLUC), creating regionalised Land Use and sLUC factors may assist industry to integrate these emission and removal sources into supply chain level reporting.

It can also be expected that LU, dLUC assessment will be required for carbon accounting and supply chain purposes. This will pose further challenges because of the additional compliance requirements for removals accounting. Based on the GHGP Land Sector and Removals Guidance (Greenhouse Gas Protocol, 2022a, pp. 246–247, 2022b, pp. 53–72) the following points indicate key GHGP removal requirements:

- Removal calculations: The GHGP (Greenhouse Gas Protocol, 2022b, pp. 53–72) notes requirements around remote and field-based requirements and the use of primary data. This can't be achieved using regional scale analysis such as the results from the NGGI.
- Independent validation. The GHGP stipulates requirements for independent validation (Greenhouse Gas Protocol, 2022a, pp. 19–30) for dLULUC assessment. This is a higher level of validation than can be achieved at national scale with the NGGI results.
- Monitoring and reversals: In the GHGP, if an organisation loses the ability to monitor carbon stocks associated with previously reported removals, companies shall assume previously reported removals are emitted and report reversal (Greenhouse Gas Protocol, 2022a, pp. 93–100). This stipulation will be very difficult to handle in supply chain accounting because of the frequent movement of producers between supply chains. Implementation of these requirements will require sophisticated systems and a degree of flexibility to manage the effects.

As evidenced by the large shifts in emissions / removals between the last two years of NGGI reporting (Commonwealth of Australia, 2025a, 2024a) reliance on the NGGI accounting for Land Use and sLUC results is also problematic, especially from a forecasting perspective, as shifts in methodological approaches can change historical estimates and forecasts.

5.2.1 Vegetation-based Land Use Change emissions approach

As evidenced in the result of this report, the discounting period timescale and approach to 'discounting' is one of the key sensitivities in modelling vegetation-based LUC emissions derived from land-clearing.

Several key factors influence the transfer of woody biomass into the atmosphere as CO_2 or other gases:

- Nature of the clearing (including pulling / pushing with no burn or with a subsequent burn when material is dry enough)
- The age of the vegetation (from young, thin secondary forest through to large older growth trees)
- The rainfall gradient and decay rates.

This is represented in a range of studies on clearing practices and coarse woody (CWD) decay. In an analysis of a global dataset on decay rates of CWD, mean annual temperature and rainfall were found to be the primary driver of decomposition, although wood density and log diameter at the start of decay were also determining factors (Mackensen et al., 2003). Termite activity has also been discussed as an important driver in areas that it occurs (Mackensen et al., 2003; Shorohova et al., 2021). Studies have shown a wide range of decay rates for different species and regions, from 10 years in tropical forests to over 100 years in temperate forests globally, and in Australia, decay rates for various Eucalyptus species range from 7 to 375 years (Brown et al., 1996; Garrett et al., 2007; Harmon et al., 1995; Janisch et al., 2005; Mackensen et al., 2003; Mackensen and Bauhus, 1999; O'Connell, 1987; Thornton et al., 1991, 1983; Threlfall et al., 2019; Woldendorp and Keenan, 2005).

In Australia, land clearing practices vary regionally, which in turn influences the rate of emissions resulting from land clearing events. In the wetter eastern and coastal parts, clearing is extensive, particularly on flatter, more fertile soils (Scanlan and Turner, 1995). Historically, burning was widely used after clearing, although its frequency decreased since the 1960s, leading to increased density of woody species (Scanlan and Turner, 1995). However, burning is still common in tropical areas with reliable rainfall to remove bulky dry matter (Scanlan and Turner, 1995). In contrast, land clearing practices in the drier central parts of Australia, such as the Brigalow and Mulga belts, typically involve using two bulldozers to pull vegetation with a chain (Cowie et al., 2007; DLRM, 2021). The felled timber is then sometimes (but not always) allowed to dry in situ before being burnt to maximize timber control over time, with residual unburnt timber often raked and burnt again (Back et al., 2009; Cowie et al., 2007; DLRM, 2021). In semi-arid areas, there is a reluctance to burn standing fodder due to concerns about exacerbating drought conditions if subsequent rain is insufficient (Scanlan and Turner, 1995). Retention of mulga for fodder is also a common practice in mulga country (Scanlan and Turner, 1995).

For LULUCF modelling, the NGGI uses FullCAM, which simulates decay processes over time for different carbon pools, such as Dead Organic Matter (DOM) which includes CWD (Commonwealth of Australia, 2025a, p. 328). FullCAM models the decay of DOM pools based on site conditions and monthly climate data including temperature and rainfall (Commonwealth of Australia, 2025b, p. 232). The decay of deadwood is modelled using simple single-pool decay functions with rates calibrated from empirical data, and specific decay rates for deadwood are used as model inputs (Commonwealth of Australia, 2025b, p. 232).

Carbon from decaying woody debris is released as a gas, primarily CO_2, and is also transferred into the soil carbon pool (Commonwealth of Australia, 2025b, pp. 230–231). The FullCAM model dynamically simulates the specific proportions and rates of these processes (Commonwealth of Australia, 2025b, p. 211). Specifics on the rates or proportion of dead organic matter transferred to the soil carbon pool is not provided.

These slow decay rates are recognised and accommodated in the FullCAM 2024 HIR model as evidenced in Figure 16 and Figure 17. Running simulations in FullCAM for a HIR method model in a wetter location (above 500 mm annual rainfall) for regrowth that is cleared (CWD left in place) after 10 years in the one simulation, and 80 years in the other, indicate decay rates of approximately 16 years for both the former and the latter for the CWD to reduce by 80% (Figure 16). The same simulations, but in a drier location (below 500 mm annual rainfall), showed decay rates of 14 years for both regrowth cleared after 10 years and 80 years for the CWD to reduce by 80% (Figure 17). Considering these decay rates and the prevalence of burning to reduce the amount of CWD left after clearing, it is reasonable to assume a shorter 10 year discounting period would more closely align with the biological decay curve in Australia.

Figure 16. FullCAM simulation results for a HIR method project in a higher rainfall region with regrowth that is cleared after 10 years (top graph) and 80 years (bottom graph)

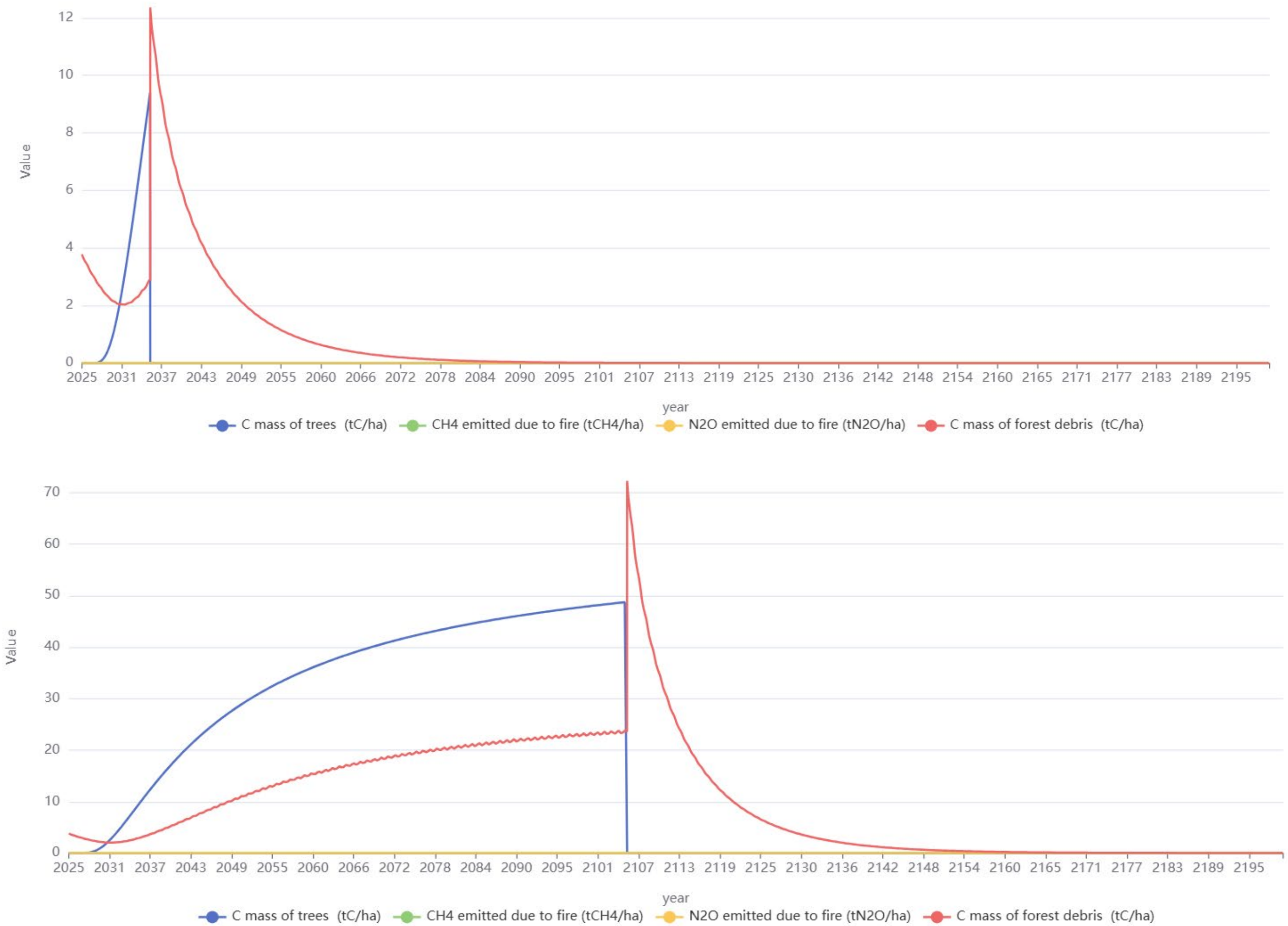


Figure 17. FullCAM simulation results for a HIR method project in a low rainfall region with regrowth that is cleared after 10 years (top figure) and 80 years (bottom figure)

Anthropogenic emission boundaries

The present assessment was bounded by the emission boundaries established by the NGGI, which determine where in Australia emissions and removals are accounted. This is the first step towards attribution of emissions to industry sectors. This step is described in the NGGI, but spatial boundaries have not been disclosed to the research team or publicly. The methods, and the detailed spatial boundaries, are key information gaps for the agricultural sector to understand attributable emissions. Considering the significance of Land Use and LUC results in the present study and likely trajectory of removals in Australia, disclosure of the key spatial dataset and review of the methods and rationale for determining this boundary is important for the industry.

Limitations

The method applied was limited by the following factors:

- The current grazing area assessment likely overestimates the land used for grazing of cattle and sheep as it identifies only regions which cannot be used for grazing and does not include localised areas that are not suited to grazing on individual farms. However, the data required to accurately assess the grazing areas at scale is not publicly available, and clearing is unlikely to occur in these areas if they are not considered productive for grazing.
- The analysis currently provided by the NGGI provides an annual net change in carbon stock and does not differentiate between emissions and removals. The analysis was limited by the assumptions used to separate emissions and removals from the net emissions result (i.e. ratios of emissions to removals, and rations of emissions with discounting already applied).
- The assessment of credited removals was limited to the 2022 assessment year, whereas the assessment periods include other years where removals were credited. Therefore, the current analysis will overestimate removals in years other than 2022.
- The assessment of credited removals could only be done with high-confidence at national scale. Therefore, the discounting of credited removals could only be completed for the national assessment and could not be completed for the state-based results.
- The inclusion of removals in an account requires a greater level of verification than emissions. The headline results in this study assumed that the NGGI analysis meets the requirements of the GHGP and ISO 14067 guidelines for Land Use and sLUC, and fully accounts for reversals of removals within their emissions calculations.
- The method relies on a spatial boundary that determines where anthropogenic emissions and removals are accounted. This layer and the method and rationale for setting this boundary was pre-set and not able to be modified as part of the project. This is a limitation to the study.
- The requirement for verification of removals is a sensitive consideration for the industry. As removals begin to have a larger effect on net emissions (see section 7.1.1) scrutiny and requirements for verification should be expected to increase and is a key need for the future. While not an objective of the project, an additional outcome to come from this section of work was a new public data release from DCCEEW, which now report LUC emissions for “grazing and cropping” making industry attribution in the future less time consuming and not subject to special approvals. Accounting for abatement

The beta framework was developed with capability to measure reductions in emissions from abatement interventions. This was tested using Bovaer, with a case study based on actual feeding programs developed and implemented at commercial scale. There was not sufficient data available to implement the framework with a nationally representative amount of Bovaer or other anti-methanogenic supplements, consequently, the framework was not able to generate measurable or material emission reduction results at national or state scale. In future assessments, with nationally representative data, the framework will be able to deliver results which demonstrate a material and measurable reduction in the carbon footprint of cattle in Australia. Further work is needed to provide complete inventory data to fully realise the GHG implications of low methane supplements. We note that this is an administrative data inventory barrier, requiring the appropriate data sharing agreements with industry partners.

To demonstrate the capability of the data framework, an example of the effect of feeding anti-methanogenic supplements has been developed and shown in **Figure *18***.

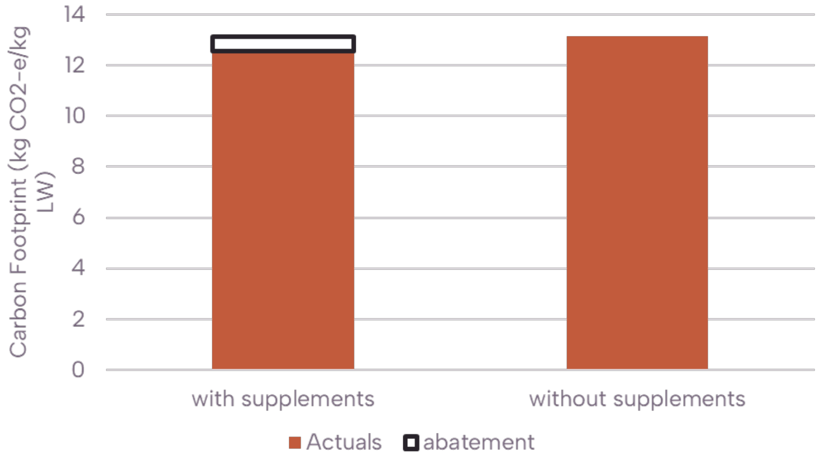


Figure 18. Case study example showing implementation of data framework, comparing impact of anti-methanogenic supplements in cattle

5.3 PEF assessment

Impact assessment results using the European PEF indicator set and methods were generated to demonstrate the capability of the beta model. Results were generated for sheep meat and wool as the most relevant products for this market (see Appendix 2, Table 27). The beta framework provided inventory data for livestock, energy use, water and Land Use, which provided most of the input data required for the larger set of indicators required for PEF through the resolutions of data to support modelling of toxicity and eutrophication was generally lacking, resulting in high uncertainty on these estimates. National scale reporting has been used to support the wool industry with industry reporting requirements in the EU and this may become more important over time. However, supply chain scale assessment is also likely to emerge as an industry need. While the framework was able to provide that data requirements for implementing the method, a range of enhancements would be beneficial, including regionally specific Land Use and impact assessment, improved data related to chemical use for the toxicity assessment, and improved data for the nutrient loss assessment. The land impact assessment in the present study was implemented using the current Land Use Indicator Value Calculation (LANCA) method, but the developers have indicated this will be revised in the near term to operate with different inputs. Once new details have been released, it may be possible in subsequent iterations of the framework to create spatial layers with LANCA scores using GIS data inputs in the system.

The PEF analysis required use of PEF approved processes, and no PEF approved Australian processes were available for sheep feed. All approved processes, which were based on European production, assumed irrigated crops, greatly increasing the water consumption of sheep meat and wool. Most feed types commonly used for sheep in Australia have relatively low amounts of irrigation, and if these were approved for use, the water consumption could be reduced by approximately 30% - as shown below. As such, we believe the water consumption was overestimated in the PEF analysis.

Table 10. Analysis of water consumption in EU PEF approved feed processes compared to Australian processes

Process	Factor	Water consumption using EU PEF processes	Water consumption with Aust. processes
Lupin (3.3) -> Broadbean (196)	0.017	182.5	3.1
NSW Wheat (0) -> Wheat Germ (910)	0	51	0
Total		**768**	**537.6**

Acknowledged flaws and weaknesses exist in the PEF method when implemented in Australia, and while resolving these was not directly in-scope for the project, the beta implementation was influenced by these factors. For example, results for three impact categories, atmospheric acidification, terrestrial eutrophication and particulate matter, were strongly influenced by ammonia lost from animal manure and urine. Regional characterisation factors are needed to improve interpretation of these impact categories and the role of ammonia in Australia. Generally, diffuse sources of ammonia occurring in vast grazing areas, combined with the nutrient deplete status of much of Australia's land mass, suggest the importance of this emission source is over-estimated. Regional characterisation factors are also needed for nutrient loss factors. These further development tasks constitute a large program of work and it remains to be seen if the PEF program will become an important feature of trade to the EU or not. Notwithstanding these serious limitations, the framework and beta implementation has demonstrated the capability to report results for this system. The system could rapidly be modified to ingest new data to support more robust analyses in the future.

6.0 Conclusions and recommendations

6.1 Reporting

Sustainability reporting needs continue to expand for the red meat and wool industries. The expected frequency of reporting, breadth of indicators covered, granularity and specificity are all increasing. Further, in an environment where impact reduction is an expectation to meet customer and Governmental targets, reporting must have the specificity and capability to account for quite small changes over time.

This project developed a data framework and implemented it in beta form, merging new data streams with existing data streams to address these new expectations. New indicators such as fresh water consumption for sheep were added. The product carbon footprint was expanded to include a measure of the impact of Land Use and sLUC, with noted high levels of uncertainty. The granularity of results was improved substantially by reporting with a more frequent time step, a shorter averaging period and at state scale in the case of beef. This improves the capability of the system to provide benchmarks and track performance.

The system provided Land Use and sLUC results for the first time, which was a major improvement in the completeness of the result. For all industries, this represented a source of removals, which was a positive outcome. Future research would be beneficial to include this in the historical trend, showing the large change recorded in carbon footprint over time because of changed land management practices. Projections also suggest further reductions will occur over the next 5 years, though this is uncertain and depends on the rate of removals and/or reversals. None the less, this trend is influential for the whole industry in reaching targets expected by customers through programs such as SBTi.

6.2 Data framework – business case for ongoing development

Progressing this project to automate data flows and calculations will provide the capacity for more frequent reporting to meet industry needs at lower cost and is a key need for the industries, government and society. A business case is needed to underpin the next phase of development and for the upkeep of the model. Further development work is needed to maximise the effectiveness of the system. Beyond that, there will be a maintenance requirement for annual upkeep. The outputs of the framework have the potential to be a benefit to the AMPC and its members, AWI and its members, MLA and its members, the Federal DCCEEW and ABS. It is possible that ongoing upkeep could be maintained through a combination of stakeholders investing. This requires exploration and development into a business plan following completion of the project.

6.2.1 Value proposition

The data framework has delivered a significant improvement on previous sustainability reporting outcomes. There are extensive opportunities for further development to enhance the system and capitalise on the unique capability. These include the expansion of high granularity data coverage, and the increased granularity for improved national scale benchmarking. Ongoing development opportunities have been highlighted below:

Market-based reporting enhancements

- Enable reporting by market type, including distinctions such as grass fed vs grain fed, and long fed vs short fed cattle to provide market-level benchmarks for industry and to track improvement over time. This will also provide industry with knowledge to 'shift the market' towards cost-effective and lower emissions products.

Expand state-based reporting for sheep

- Expand the framework to operate at state-scale. This will be enabled through new reporting of sheep by PIC, provided large scale datasets can be accessed. This will provide more meaningful benchmarks for the industry and enable tracking of improvements at a finer scale.
- Introduce breed-specific reporting (e.g., Merino, crossbred, shedding sheep) to enhance granularity and benchmarking.

Historical baseline recalculation

- Recalculate baselines using MSA data back to 2010 to better understand the relationship between product quality and environmental performance would provide key insights for the industry, and would help to determine cost-effective strategies for reducing carbon footprint into the future. This would be a high-value research investigation.

More frequent and granular reporting

- A shift is recommended to annual or biennial reporting of the key carbon footprint indicator with shorter averaging intervals (two years) to provide more sensitive results that will be effective for benchmarking. Noting this, data agreements are required to be able to achieve this at minimum cost.
- Develop operational capability for reporting from producer to customer level using the same method platform.

Water use data improvements

- Address current gaps in national irrigation statistics and on-farm water use data, especially for sheep farms.
- Integrate updated results from water surveys or modelling (currently under investigation by ABS). This should be reviewed in the next 12 months.

Boxed meat carbon footprint refinement

- Update meat flow and allocation data to reflect current industry practices.
- Reduce uncertainty in boxed meat carbon footprint estimates through improved data.
- Review allocation methods and establish industry best practice guidance for handling meat and co-products.

Statistical Land Use and Land Use Change (Land Use and sLUC) methodology

- Refine methods for allocating Land Use and sLUC emissions and removals between beef and sheep. The beta reporting from this project demonstrates the very significant importance of these impacts and the positive role that removals will have into the future for beef and sheep. This is viewed by producers as a key gap in current reporting and release of this information is recommended with caveats. There is a large amount of method development needed both with respect to biophysical modelling, attribution between biogenic and anthropogenic sources, attribution to cattle and sheep, and discounting. Each is a major area of focus. The benefit in completing this work is enabling accounting that accounts emissions and removals, which in the present study revealed lower net emissions than if Land Use and sLUC impacts were omitted. This is discussed further in section 6.4.

- Test the validity of a 10-year discounting period for emissions to better reflect biological decay rates in preparation for developing Australian-specific guidelines in the future.
- Work with NGGI to improve access to spatial and emissions data for validation and refinement and create automated data flows to the framework. Promote the NGGI to release the spatial layer used to determine where anthropogenic changes in LUC are assessed.
- Review, update and harmonise the methods from this study into the annual carbon account trends analysis done by MLA to the maximum extent possible, to harmonise the assumptions between the two studies.
- Noting LULUC is an emerging area that is not well understood, a communications exercise would be warranted to explain to processors and producers what the results mean and how/why they have changed over time between different industry publications. The large difference in methods between the results from this study, and the industry trends study will need to be addressed to avoid confusion.

Accounting for abatement

- Expand data collection on low-methane feed supplements (e.g., Bovaer) to quantify abatement impacts.
- Develop inventory systems to track and report abatement at supply chain scale.

Product Environmental Footprint (PEF) readiness

- Improve data for toxicity and nutrient loss assessments.
- Develop regionally specific Land Use impact assessments.
- Monitor updates to LANCA methodology and adapt GIS layers accordingly.

New indicators and reporting areas

- Explore inclusion of biodiversity and other natural capital indicators in future reporting.

6.3 Data requirements

During the project, the collection and availability of agricultural data diminished dramatically as a result of changes in ABS survey practices. Some of these impacts are expected to be short term but others, such as release of water statistics, is uncertain. Further, ABS statistical releases in smaller land parcel units (such as SA2) may be difficult to achieve, but are highly valued for projects such as this. It is noted that these changes have come at a time when agricultural industries are facing more scrutiny than ever over environmental performance. Action is needed to ensure data availability and quality do not permanently decline as a result of these changes, noting the very significant trailing impacts this has on many forms of reporting, including this data framework for sustainability reporting.

The beta data framework is reliant on a number of third party data sources. The most recent versions of these data sources were cloned into the data framework, but many of these will need to be updated for updates to sustainability reporting. The data requirements are listed in Table 8, which lists the data sources used in the present study, and notes any required improvements to data quality in future assessments.

6.4 Land Use assessment and external retirements

While not an objective of the project, an additional outcome to come from this project was a new public data release from DCCEEW, which now reports LUC emissions for “grazing” making industry attribution in the future less time consuming and not subject to special approvals.

The following broad recommendations aim to assist in the creation of a repeatable method for the Land Use and sLUC assessment:

- Work with CER to confidentially disclose externally retired abatement from relevant land-based projects, plus provide relevant project annual abatement in an easy to use, annually updated format.
- Work with the CER to provide traceability of credits retired so that accounting can remove only those credits that are retired against other sectors.
- Consortium to request the change / change boundary data / model parameters from NGGI due to uncertainty.
- Work on options to separate emissions from removals.
- Confirm an appropriate discounting period for Australia (with a ten year period recommended). This may need to be supported via more detailed investigation of LULUC practices and the likely decay rates. The best outcome for industry would be that the inventory also adjusts their methods to more closely reflect actual decay rates so that the two are closely aligned. It is plausible for Australian accounting to use a different discount time period (10 years) if this is supported, but data should also be available from the NGGI in such a way that this can be readily recalculated for reporting to international supply chains.
- Given their experience with broad-scale land-use change assessment, the NGGI team are well positioned to provide primary data of direct use to this project. To facilitate this, the following needs to be confirmed with that team to enable better accounting and validation processes:
  - Provision by the NGGI team of the spatial layer determining the assessment area for anthropogenic emissions and removals, and further explanation of the methods and rationale used to determine anthropogenic emissions and removals.
  - Ability to use the Eligible Grazing Area to delineate and calculate Land Use and sLUC-based emissions and removals.
  - Methods to account removals from primary forest that has remained forest (in particular areas that have never been cleared) that may be regenerating because of historical forest degradation.
  - Separate reporting of emissions and removals from land-clearing data.
  - Revision and clarification of methods that transfer biomass carbon to gas (emissions) ,as well as to the soil pool (a general transfer of carbon), noting that FullCAM may not be appropriately calibrated for CWD decay (discounting).
  - Mapping indicating where forest loss and gain detections has been targeted, and where such change occurred.
  - Release of the land area assessment layer used for tracking anthropogenic emissions and removals.

    - Investigation of anthropogenic and biogenic emissions and removals outside the current land area assessed by the NGGI. For example, examination of the role of woody thickening in northern Australia and the potential relationship between this and grazing.
- After understanding these elements better, a clear program of works for the NGGI team and beef and sheep industry representatives can be developed, which could include:
    - Maintenance and provision to NGGI team of grazing extent boundary.
    - Provision of suitable data and assumptions for use that meet industry objectives, but does not exceed the NGGI team's reporting scope.
    - Ongoing program of work to refine methods for assessment and testing of the scalability of these solutions to industry, supply chain and individual business (property) level.

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Appendix 1

Land Use and Land Use Change analysis

Grazing area assessment

Figure 19 shows the regions in Australia which were identified to be eligible for cattle or sheep grazing. The cattle grazing area extended further to the North and Central Australia regions than the sheep grazing areas. Whereas the eligible grazing area for sheep overlapped with cattle. Therefore, the mixed-use regions demonstrate the areas which both cattle and sheep had eligible grazing areas. The total eligible grazing area for cattle was 361,254,023 ha, and for mixed use grazing the total eligible area was 218,656,070 ha.

Based on internal practitioner review, the extent of grazing and mixed / cattle only areas were in general realistic and reflected grazing limits, though some areas on the outer threshold of grazing practice in the arid lands are included.

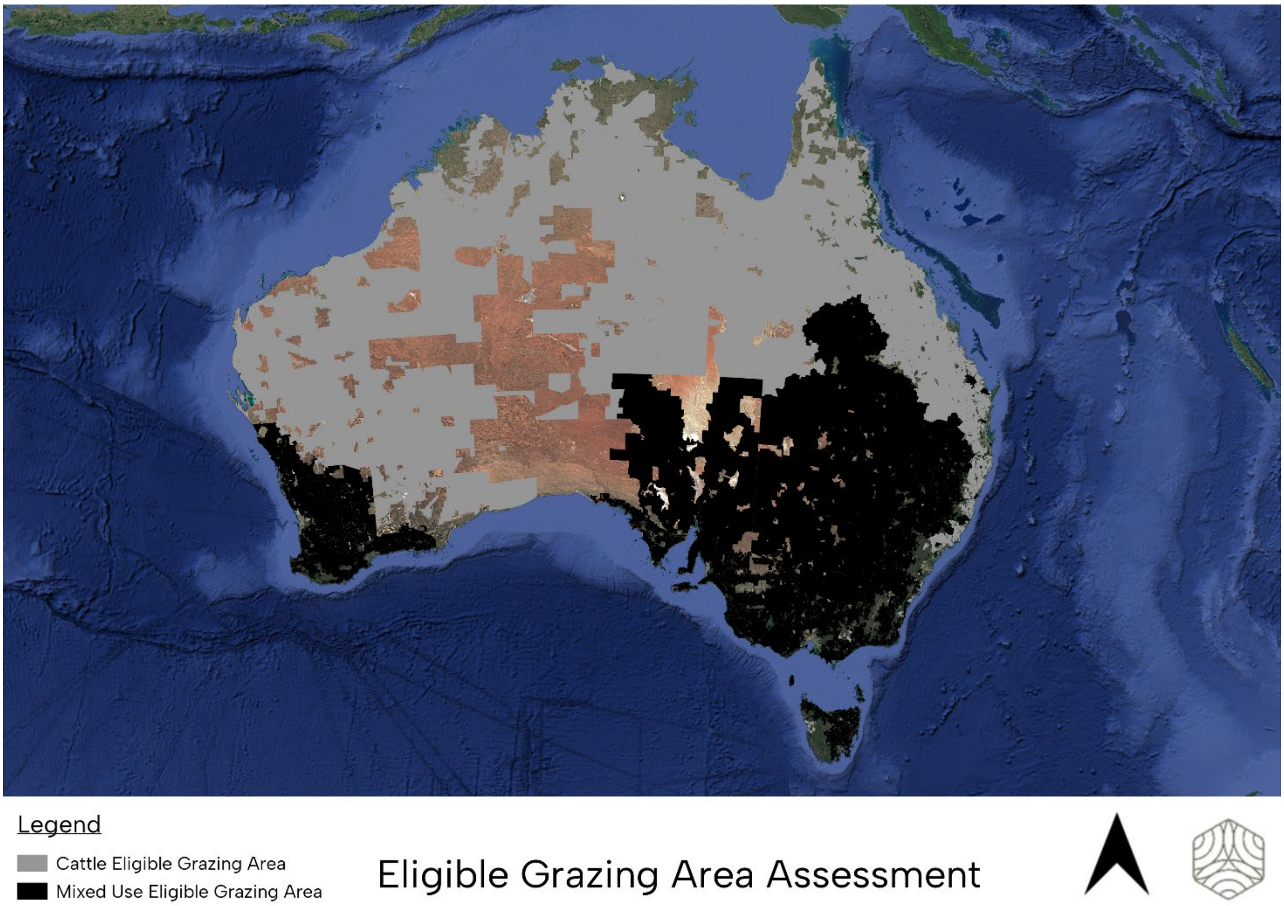

Figure 19. Eligible grazing area for cattle and sheep. As the sheep grazing regions were also used for cattle production these regions are referred to as "mixed use" areas

Table 11 shows the Dry Sheep Equivalent (DSE) proportions at both a national and state scale. These proportions were used to partition the "mixed use grazing area" and generate the eligible grazing area. These regions were in turn used in the allocation of the discounted LULUC assessment.

Table 11. Dry Sheep Equivalent (DSE) proportions assigned to cattle and sheep at both a state and national scale

Region	Beef DSE	Sheep DSE
Australian Capital Territory	0.52	0.48
New South Wales	0.52	0.48
Northern Territory	1	0
Queensland	0.966	0.034
South Australia	0.363	0.631
Tasmania	0.556	0.444
Victoria	0.499	0.501
Western Australia	0.538	0.462
National	0.692	0.308

2022 Credited removal accounting

ACCUs retired outside of CACs

Based on analysis of CER ACCU Scheme data (CER, 2024a):

- 9.8 million ACCUs were issued to vegetation methods during reporting period (refer Figure 20, **Table *12*** and Table 13). Based on this, vegetation methods made up 55% of the total ACCUs issued for 2022.
- 1.8 million ACCUs were retired in 2022 reporting period, with vegetation methods making up 1.1 million / 60.7% of these. It is important to note that based on these data, it can be assumed that approximately 8 million ACCUs (generated by vegetation methods in this period), were either sold as part of CACs or were not retired, and are being held in ANREU accounts for future retirement.
- Table 15 summarises the volume and broad demand sources of retirements, with Table 16 classifying the demand sources themselves, noting that it is currently assumed that as of 2022 there were no material retirements of ACCUs into the beef and sheep industry
- As only 60.7% of retirements were applicable to all vegetation-based methods, a further reduction of 39.3% was applied to this amount to obtain a total of 939,024 ACCUs derived from all vegetation methods, that were retired outside of the beef and sheep industry.
- Based on CAC data (CER, 2024c), and application of the ratio of ACCUs delivered under all vegetation methods compared to methods relevant to this assessment, 55.6% of vegetation method-based CACs

active during 2022 were attributed to the vegetation methods relevant to this assessment. This proportion-based reduction was applied to the volume of retired ACCUs from all vegetation methods, with the final number of ACCUs likely generated within, but retired outside of the beef and sheep industry being 616,873.

- Based on the extent of relevant projects live as of 2022, the proportionate volume of relevant retirements within the beef herd is 494,085 and within the sheep flock is 122,788.
- It is important to note that much of the abatement generated in 2022 within grazing properties may not have been retired yet and is likely to be retired in the future outside the beef and sheep industry, making this volume an underestimate.

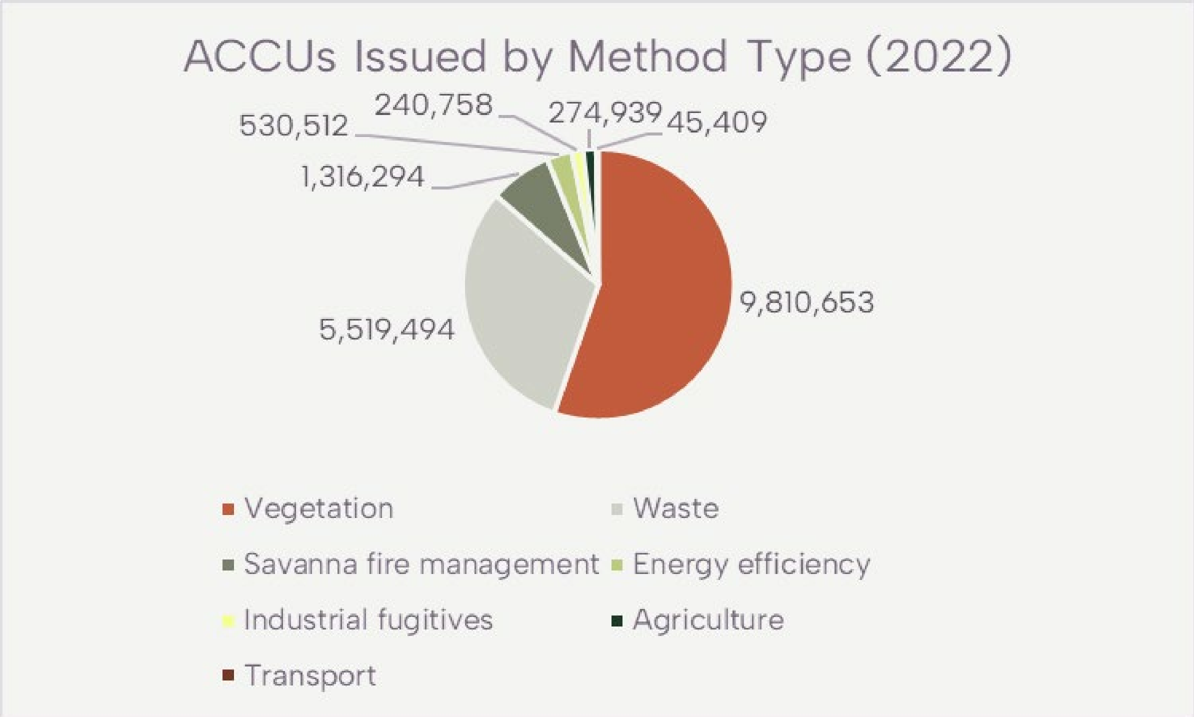

Figure 20. ACCUs issued (not retired) by method type (2022) Source: (CER, 2024a)

Table 12. ACCUs issued (not retired) by all method types for 2022

Method type	ACCUs
Vegetation	9,810,653
Waste	5,519,494
Savanna fire management	1,316,294
Energy efficiency	530,512
Industrial fugitives	240,758
Agriculture	274,939

Transport	45,409
Annual total	**17,738,059**

Source: (CER, 2024a)

Table 13. ACCUs issued (not retired) by all land sector method types for 2022

Land sector method type	Q1	Q2	Q3	Q4	Annual total
Vegetation	2,099,793	2,631,819	2,129,636	2,949,405	9,810,653
Savanna fire management	17,753	1,130,902	123,304	44,335	1,316,294
Agriculture	160,812	30,401	73,592	10,134	274,939
Total	**2,278,358**	**3,793,122**	**2,326,532**	**3,003,874**	**11,401,886**

Source: (CER, 2024a)

Table 14. ACCUs retired within 2022 reporting period, by method type

Land sector method type	Q1	Q2	Q3	Q4	Annual total
Savanna fire management	77,510	122,358	66,238	126,510	392,616
Vegetation	208,547	352,580	412,559	136,374	1,110,060
Waste	180,953	4,165	46,684	11,658	243,460
Agriculture	0	0	0	13,114	13,114
Transport	0	0	0	0	0
Energy	64,339	0	1,424	565	66,328
Industrial	2,238	0	0	0	2,238
Total	**533,587**	**479,103**	**526,905**	**288,221**	**1,827,816**

Source: (CER, 2024a)

Table 15. ACCUs retired within 2022 reporting period (2024a) by demand source, with relevant adjustments

Demand source	Q1	Q2	Q3	Q4	Annual total	Veg method adjustment*	Final relevant veg method adjustment**
Voluntary	161,020	295,784	166,294	231,983	855,081	410,439	288,583
Local, state and territory	1,118	5	448	2,542	4,113	2,468	1,388
Compliance	85,925	117,670	288,987	17,240	509,822	305,893	172,061
Safeguard	250,809	37,726	50,000	10,000	348,535	167,297	37,214
Other	34,715	27,918	21,176	26,456	110,265	52,927	117,628
Total	**533,587**	**479,103**	**526,905**	**288,221**	**1,827,816**	**939,024**	**616,873**

** Including all vegetation methods (39.3% reduction)*
*** Incorporating a further 55.6% reduction based on relevant vegetation methods*

Table 16. Retiree classification summary

Classification	Covered activities
Voluntary demand	Cancellations made against voluntary certification programs such as Climate Active, and any sort of organisational emissions or energy targets.
Local, state and territory government demand	Cancellations on behalf of local, state and territory governments, for example to offset emissions from state fleets or meet emissions reduction targets.
Compliance demand	Cancellations by private organisations and corporations for compliance or obligations against municipal, local, state and territory government laws, approvals, or contracts. For example, to meet Environmental Protection Authority requirements.
Safeguard demand	ACCUs surrendered to meet Safeguard Mechanism compliance.
Other demands	All activity not covered in the previous categories, primarily due to a lack of available information.

Source: (CER, 2024a)

ACCUs sold to Australian government as part of CACs

Based on analysis of CAC-based ACCU purchases in the year 2022 (CER, 2024c):

- The CAC database (CER, 2024b) was merged with the ERF project register (CER, 2024b) where a common ERF project was shared. The resulting CAC-ERF project dataset was filtered to remove projects that had the following status following close of 2022: Revoked and/or contract finalised and/or no issuance
- For the remaining CACs/projects, the contract years delivered up until the close of 2022 and the proportionate contract amount was calculated for CACs with multiple projects. The average ACCUs sold per annum was then calculated for each project by dividing the total amount of credits issued by the number of the project's operational years
- Based on the total of these results, 3,309,176 ACCUs were sold into CACs for relevant vegetation method based-projects active in 2022. Note that many CACs did not have a confirmed start or finish date so it was assumed that these were selling credits during 2022.
- Based on the extent of relevant projects live as of 2022, the proportionate volume of relevant retirements within the beef herd is 2,270,753 and within the sheep flock is 1,038,422.

Combined results

Based on the total of relevant non-CAC ACCU retirements (616,873 ACCUs) and CAC-based ACCU retirements (3,309,176 ACCUs), 3,926,049 ACCUs (tonnes of CO_2-e) were likely derived from land containing beef and sheep related activities, but sold outside the beef and sheep industry in 2022.

Based on the extent of relevant projects live as of 2022, the proportionate volume of relevant retirements within the beef herd is 2,674,839 t CO_2-e and within the sheep flock is 1,161,210 t CO_2-e.

Table 17. Total retirements attributable to the beef and sheep industry, 2022

	CAC-based ACCUS	Non-CAC ACCUS	Total ACCUs
Sheep	1,038,422	122,788	1,161,210
Beef	2,270,753	494,086	2,674,839
Total			**3,926,049**

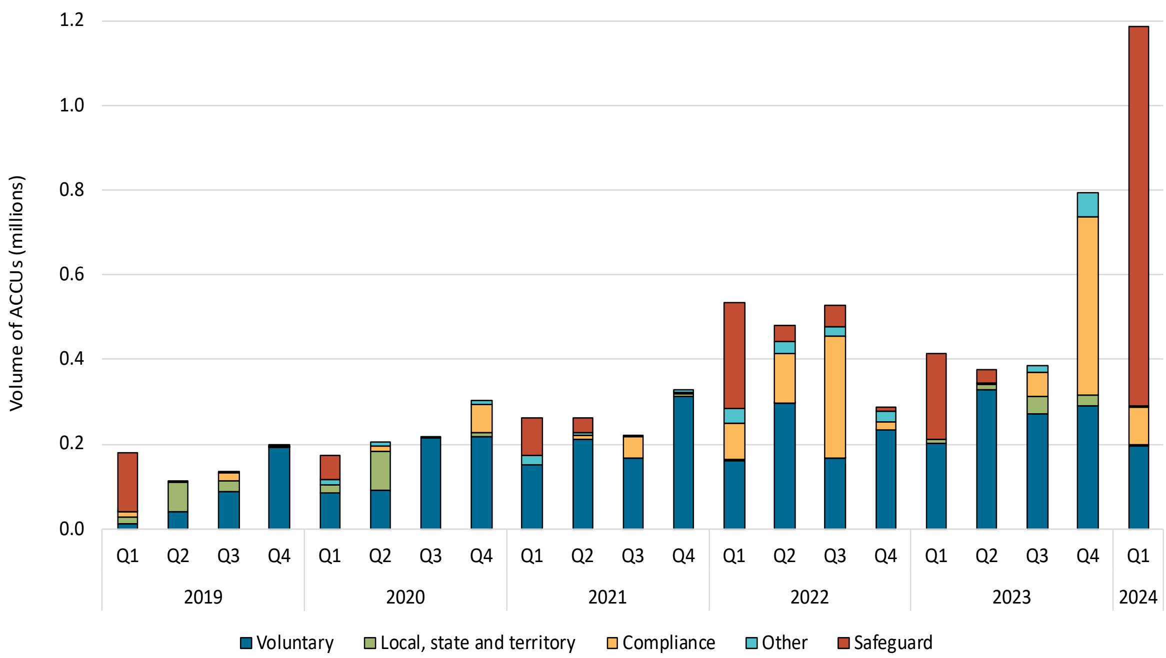

Figure 21. ACCU retirements by demand source over time. Source: (CER, 2024a)

The results from the NGGI team's analysis, shown in Table 18, demonstrate that removals appear to offset any LULUC emissions at a national scale for the 2022 reporting year. The exclusion of Credited Removals for 2022, while significant, do not change the significance of removals at a national scale. However, Table 19 shows that this net shift towards removals occurs around 2021, and is a recent shift both nationally and within the states most grazing occurs in, in particular Queensland. In all other assessment years there has at least been a net emission for key grazing states. This highlights the importance of discounting (or carrying forward) emissions from previous years.

It is also important to note that outputs from the NGGI team do not include layers showing forest cover loss or gain, or even the areas assessed for such change, making validation of this data impossible.

Table 18. Net Grazing emissions for 2022 (Land Use & Land Use Change (LULUC) emissions (mt CO_2 -e) for grazing sector generated by the NGGI team), results with credit removal and allocation to cattle and sheep

Region	Net grazing emissions 2023 (mt CO_2-e)	Credited removals 2023 (mt CO_2-e)	Net grazing emissions 2023 (mt CO_2-e) minus credited removals	Cattle Results with no discounting (mt CO_2-e) minus credited removals 2023	Sheep Results with no discounting (mt CO_2-e) minus credited removals 2023
Australian Capital Territory	0.0	0.0	0.0	0.0	0.0
New South Wales	-9.3	1.2	-8.0	-4.2	-3.9
Northern Territory	10.0	0.0	10.0	10.0	-
Queensland	-12.8	1.4	-11.4	-11.0	-0.4
South Australia	-3.3	0.1	-3.3	-1.2	-2.1
Tasmania	0.6	0.0	0.6	0.3	0.3
Victoria	-4.6	0.0	-4.6	-2.3	-2.3
Western Australia	1.6	1.2	2.9	1.5	1.3
National	-17.8	3.9	-13.8	-6.8	-7.1

Table 19. The Land Use & Land Use Change (LULUC) emissions (mt CO_2-e) for National grazing areas, as produced by the NGGI. The results for each assessment year in the past 20 years are included to show the recent shift towards net removals

Assessment year	National emissions (mt CO_2-e)
2023	-18.03
2022	-22.60
2021	-25.12
2020	1.68
2019	2.14
2018	23.80
2017	38.28
2016	11.08
2015	42.23
2014	56.04
2013	49.08
2012	35.75
2011	44.76
2010	70.95
2009	71.04
2008	88.29
2007	106.57
2006	130.98
2005	108.49
2004	79.73

State scale LULUC assessment

Sensitivity analysis

Different discounting methods and time periods were assessed to examine the sensitivity of the results to these method differences. Removals accounted using the linear method were greater than the equal method, because of the relatively higher emission rates in the early phase of the historical accounting period. When the time period was changed from 20 years, to a more biologically likely 10-year period (see Table 19 in the appendix), the removal rates increased.

State by state trends were clearly evident, and contributed to a different profile of emissions and removals for beef and sheep meat/wool, because of the different distribution of the species between the states. Sheep were predominantly located in southern states where removals were greater.

In some regions such as Queensland, Land Use and sLUC remained an emission source when assessed over 20 years with linear discounting. While beef and lamb results were not reported for Land Use and sLUC at state level, it is evident that results would vary if this was done. These results were too uncertain to present because the state-scale PCF result was based on state of origin, not total lifetime. This lack of traceability made it more uncertain to allocate state-level Land Use and sLUC results. None the less, the results are instructive of the likely findings from supply chain level analysis which may show distinctly different regional trends.

Table 20. The Land Use & Land Use Change (LULUC) emissions (mt CO_2-e) for each state after discounting and allocation of emissions applied

	Cattle results			Sheep results		
Region	Results with no discounting (mt CO_2-e) minus credited removals	GHG Protocol (20-year) linear discounting (M CO_2-e)	10-yr linear discounting	Results with no discounting (mt CO_2-e) minus credited removals	GHG Protocol (20-year) linear discounting (M CO_2-e)	10-yr linear discounting
	Projected 2023/2024	Projected av. 23/24	Projected, av. 23/24	Projected, 2023	2023	2023
Australian Capital Territory	0.0	0.0	0.0	0.0	0.0	0.0
New South Wales	-4.2	-3.3	-3.7	-3.9	-3.0	-3.3
Northern Territory	10.0	5.0	5.5	0.0	0.0	0.0
Queensland	-11.0	6.9	-4.8	-0.4	0.3	-0.1
South Australia	-1.2	-1.1	-1.1	-2.1	-1.9	-1.9
Tasmania	0.3	0.6	0.3	0.3	0.5	0.3
Victoria	-2.3	-1.9	-2.3	-2.3	-1.8	-2.3
Western Australia	1.5	2.3	1.0	1.3	2.1	0.8
National	-6.8	8.6	-5.0	-7.1	-3.8	-6.6

The requirement for verification of removals is a sensitive consideration for the industry. As removals begin to have a larger effect on net emissions (see section 7.1.1) scrutiny and requirements for verification should be expected to increase. To examine the most conservative scenario, where removals were taken out of the account (in the situation where they were not considered verifiable) this would have an extreme impact on reportable emissions, resulting in ongoing emissions from land sector beyond 2030. This is demonstrated in Figure 22, which shows excluding net results currently in a removals state will result in significant net emissions in both the current and future projected Land Use and sLUC accounts.

Figure 22. Projections of Land Use and sLUC results to 2030 in the scenario where net values currently in a removal state are treated as a net 0 state, partially reflecting the impact of excluding the contribution of removals on the account

7.1.1 Projections of Land Use and sLUC impacts to 2030 for beef and sheep

Future trends in Land Use and sLUC are expected to result in an increasing level of removals attributable to sheep and beef. With the discounting approach used, this trend has been delayed in the present analysis, but is evident in the NGGI since 2019 when LULUC became a net removal source for the grazing sector (see in Appendix 1). To examine potential trends, projections were done with a range of assumptions with static or decreasing rates of removals, and both 20-year and 10-year discounting (**Figure *23***). All demonstrated removals to 2030 at national scale with different rates, with the maximum change being Scenario 1's GHGP projection.

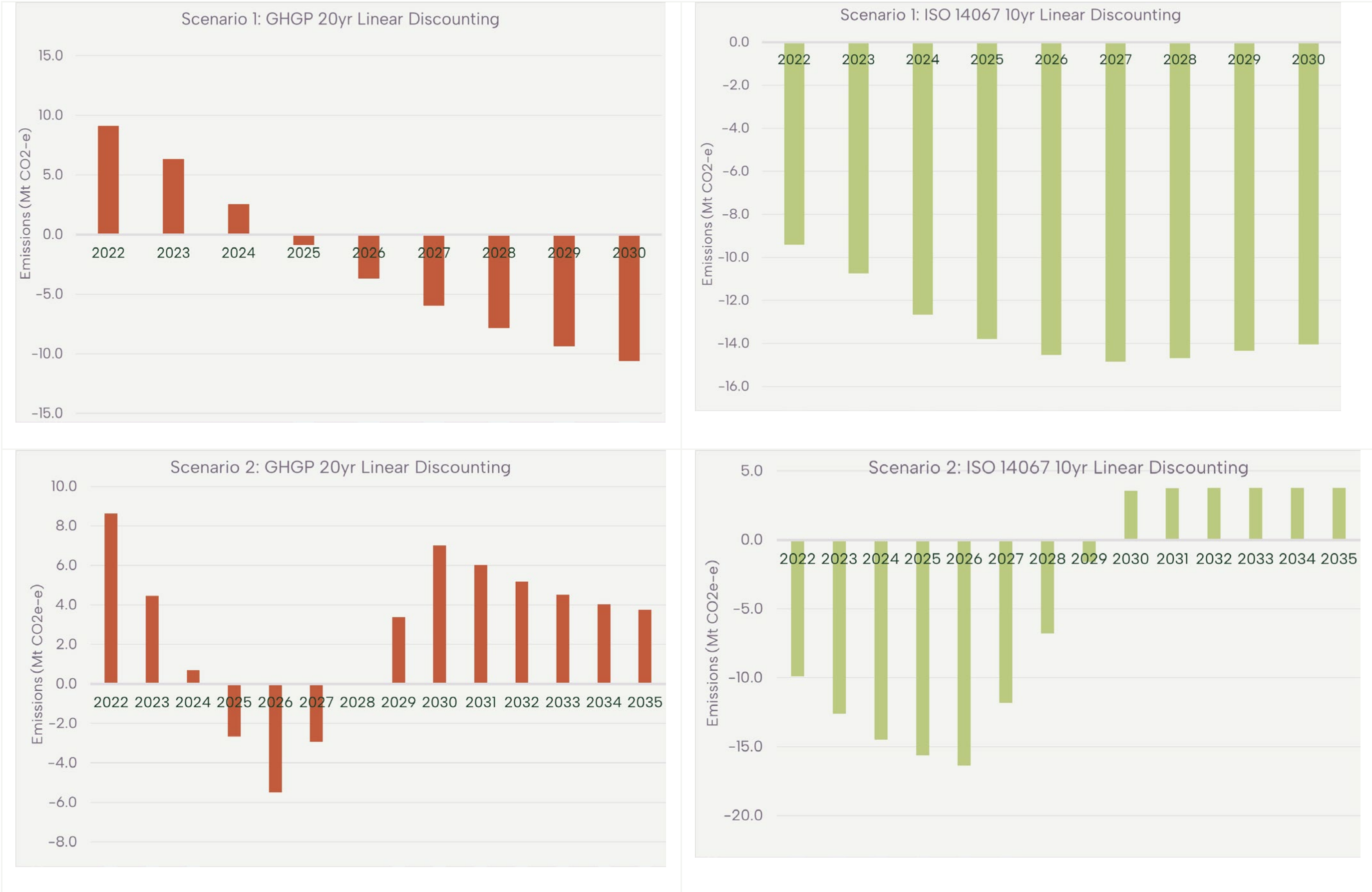

Figure 23. Projections of Land Use and sLUC results to 2030 with different scenarios showing varying rates of removals. S1a and S1b show static removals projected from 2022 to 2030, with either 20 or 10-year discounting. S2a and S2b show reducing rates of removals with a slowing rate of regeneration to approximately 1/3rd of current net removal rates

Table 21. Scenario 1 future projected annual accounts for the red meat grazing domain. The projected values are calculated on the assumption the net removals recorded in 2023 remain constant until 2030

	20-year discounting		10-year discounting	
Year	Equal discounting ($mt\ CO_2$-e)	Linear discounting ($mt\ CO_2$-e)	Equal discounting ($mt\ CO_2$-e)	Linear discounting ($mt\ CO_2$-e)
2022	28.8	9.1	0.3	-9.4
2023	25.6	6.3	-2.1	-10.8
2024	22.2	2.5	-6.6	-12.7
2025	17.4	-0.8	-9.7	-13.8
2026	11.4	-3.7	-10.7	-14.5
2027	6.7	-6.0	-13.8	-14.9
2028	2.9	-7.8	-15.6	-14.7
2029	-0.1	-9.3	-15.5	-14.4
2030	-3.1	-10.6	-15.3	-14.0

Table 22. Scenario 2 future projected annual accounts for the red meat grazing domain. The projected values are calculated on the assumption the net removals recorded in 2023 remain constant only until 2026. After 2026 there is a linear reduction to a third of existing removals, resulting in an approximate reduction in removals from 30mt to 10mt

	20-year discounting		10-year discounting	
Year	Equal discounting ($mt\ CO_2$-e)	Linear discounting ($mt\ CO_2$-e)	Equal discounting ($mt\ CO_2$-e)	Linear discounting ($mt\ CO_2$-e)
2022	28.4	8.6	-0.1	-9.9
2023	23.8	4.5	-3.9	-12.6
2024	20.4	0.7	-8.4	-14.5
2025	15.6	-2.7	-11.5	-15.6
2026	9.6	-5.5	-12.6	-16.4
2027	9.7	-2.9	-10.8	-11.8
2028	10.7	0.1	-7.7	-6.8
2029	12.6	3.4	-2.8	-1.6
2030	14.5	7.0	2.3	3.6

Table 23. Scenario 3 future projected annual accounts for the red meat grazing domain. The projected values are calculated on the assumption that removals cannot be applied during the calculation of accounts due to the higher level of validation required

	20-year discounting		10-year discounting	
Year	Equal discounting (mt CO_2-e)	Linear discounting (mt CO_2-e)	Equal discounting (mt CO_2-e)	Linear discounting (mt CO_2-e)
2022	60.2	40.4	31.7	21.9
2023	55.6	36.2	27.8	19.2
2024	52.2	32.5	23.4	17.3
2025	47.4	29.1	20.3	16.1
2026	41.4	26.3	19.2	15.4
2027	36.7	24.0	16.2	15.1
2028	32.8	22.1	14.4	15.3
2029	29.9	20.6	14.5	15.6
2030	26.9	19.4	14.7	16.0

Table 24. Carbon footprint (AR6) and LU, sLUC results for 1 kg of beef LW produced in 2024 showing different discounting methods and time periods

	Carbon footprint reported on live weight basis ($kg\ CO_2\text{-}e\ kg\ LW^{-1}$)	
	excl LU, sLUC	LU, sLUC only
20 year linear discounting	12.1	2.6
20 year equal discounting		6.5
10 year linear discounting		-1.1
10 year equal discounting		0.9

Table 25. Carbon footprint (AR6) and LU, sLUC results sheep meat LW and greasy wool produced in 2023 showing different discounting methods and time periods

	Live weight (kg)		Greasy wool (kg)	
Carbon footprint	excl LU, sLUC	LU, sLUC only	excl LU, sLUC	LU, sLUC only
20 year linear discounting	6.8	-1.3	24.5	-4.6
20 year equal discounting		0.0		-0.1
10 year linear discounting		-2.2		-8.0
10 year equal discounting		-1.9		-6.7

Appendix 2

European Commission Environmental Footprint (PEF)

Impact assessment methods

The environmental impact of the products was assessed using the EF method, which is the official impact assessment method of the Environmental Footprint initiative. The implementation was based on EF method version 3.1. Normalisation and weighting factors were based on Annex A of the Product Environmental Footprint Category Rules Guidance version 6.3 (Table 26). During the EF pilot phase, the European Commission (EC) gave instructions to remove the toxicity impact categories from normalised and weighted results. Therefore, an additional weighting set without toxicity impact categories is provided. However, all single score calculations in this study were conducted using the full weighting set comprising all 16 impact categories. At the time of writing this report, the EF3.1 method has been published by the EC, and is being developed for implementation in SimaPro LCA modelling software by PRé-Sustainability (developers of SimaPro proprietary software). Revisions to results will be expected for impact categories undergoing review (e.g. toxicity impact categories).

In the present study, impact assessment results were generated to demonstrate the capability of the beta model. Results were generated for sheep meat and wool as the most relevant products for this market. The beta framework provided inventory data for livestock, energy use, water and Land Use, which provided most input data required for the larger set of indicators required for PEF. However, a range of enhancements would be needed to implement the system at supply chain level, including regionally specific Land Use and impact assessment, improved data related to chemical use for the toxicity assessment, and improved data for the nutrient loss assessment.

Table 26. PEF normalisation and weighting factors based on the PEF guidelines v6.3

		Weighting	
Impact categories	**Normalisation**	**With toxicity**	**Without toxicity**
Climate change	0.0001289	0.2106	0.2219
Ozone depletion	42.82	0.0631	0.0675
Ionising radiation, human health	0.000237	0.0501	0.0537
Photochemical ozone formation	0.02463	0.0478	0.0510
Respiratory inorganics (PM)	1571	0.0896	0.0954
Human toxicity, non-cancer	2106	0.0184	0
Human toxicity, cancer	25969	0.0213	0
Acidification (terrestrial & freshwater)	0.018	0.0620	0.0664
Eutrophication, freshwater	0.3918	0.0280	0.0295
Eutrophication, marine	0.03536	0.0296	0.0312
Eutrophication, terrestrial	0.005652	0.0371	0.0391
Ecotoxicity, freshwater	0.00008464	0.0192	0
Land Use	7.49E-07	0.0794	0.0842
Water scarcity (AWARE)	0.00008719	0.0851	0.0903
Resource use, energy carriers	0.00001532	0.0832	0.0892
Resource use, mineral and metals	17.28	0.0755	0.0808

PEF impact results are presented in Table 27. Climate change and water results differ to the headline results for the SSF, because of differences in the impact assessment method. Note water scarcity is a fundamentally different result to fresh water consumption presented earlier in the report.

Table 27. PEF impact assessment for the year 2023

Impact category (PEF)	Unit	Greasy wool	Sheep LW
Climate change excl. Land Use and sLUC	kg CO_2 eq	27.6	7.7
Climate change Land Use and sLUC	kg CO_2 eq	-7.55	-2.11
Ozone depletion	kg CFC-11 eq	0	0
Ionising radiation, human health	kBq U-235 eq	0.05	0.01
Photochemical ozone formation	kg NMVOC eq	0.02	0.01
Respiratory inorganics (PM)	disease inc.	0	0
Human toxicity, non-cancer	CTUh	3.6×10^{-8}	1×10^{-8}
Human toxicity, cancer	CTUh	9.3×10^{-10}	2.6×10^{-10}
Acidification (terres. & freshwater)	mol H+ eq	0.65	0.18
Eutrophication, freshwater	kg P eq	0.002	0.001
Eutrophication, marine	kg N eq	0.03	0.01
Eutrophication, terrestrial	mol N eq	2.87	0.8
Ecotoxicity, freshwater	CTUe	178.64	49.83
Land Use	Pt	10665	2975
Water scarcity (AWARE)	m3	43	12
Resource use, energy carriers	MJ	8.9	2.48
Resource use, mineral and metals	kg Sb eq	0	0

Hides carbon footprint

The national average carbon footprint for hides was calculated using the same allocation and mass flow methods and data sources as described in 3.4.4. The results for this estimated hides carbon footprint is shown in Table 28.

Table 28. Carbon footprint of hides for the national average of Australian beef production in the weighted average of financial years 2023 and 2024

	National Average
Scope 1	1.0%
Scope 2	0.8%
Scope 3	98.2%
Carbon footprint (kg CO_2-e kg raw hides^{-1})	8.0