Final report

Livestock export life cycle carbon assessment

Project code	LC.RDE.0032 – Undertaking a life cycle assessment of the livestock export supply chain
Prepared by	Integrity Ag
Date published	29 September 2025
Published by	LiveCorp PO Box 1174 NORTH SYDNEY NSW 2059
	Meat & Livestock Australia Limited Locked Bag 991 NORTH SYDNEY NSW 2059
In partnership with	IntegrityAg

LiveCorp and Meat & Livestock Australia acknowledge the contribution from the Commonwealth of Australia to research and development undertaken in the LEP RD&E Program.

This document is published by the Livestock Export Program (LEP), a collaboration between the Australian Livestock Export Corporation (LiveCorp) and Meat & Livestock Australia (MLA). Care is taken to ensure the accuracy of the information contained in this document. However, LiveCorp and MLA cannot accept responsibility for the accuracy or completeness of the information or opinions contained in the document. No person should act on the basis of the contents of this publication without first obtaining specific, independent professional advice. Any recommendations, suggestions or opinions contained in this publication do not necessarily represent the policy or views of LiveCorp and MLA. Reproduction in whole or in part of this publication is prohibited without prior written consent from LiveCorp.

Abstract

Demonstrating and improving supply chain sustainability is an increasing societal and regulatory expectation. The Australian government's greenhouse gas (GHG) reduction targets require all sectors to contribute, including the livestock export industry. Livestock export plays a vital role in global food security and nutrition, forming an essential part of the red meat supply chain- particularly in markets with processing constraints, limited cold-chain infrastructure, or a preference for locally processed fresh meat. This study updates the 2011 life cycle assessment (LCA) of Australian cattle and sheep exports, quantifying carbon footprint, fossil energy use, and freshwater consumption across major destination markets, and including, for the first time, air freight. The prior study was published in 2011 for the 2010 baseline year.

The assessment focused on emissions during livestock export, which includes quarantine yards to arrival at the destination port, upstream scope 3 emissions, and a downstream case study of Indonesian cattle feedlot finishing. Updated methodologies were used for GHG and water accounting.

Weighted average emissions during live export (quarantine to port of arrival) were 17.1 kilogram (kg) carbon-dioxide CO_2 equivalents (CO_2-e) head^{-1} day^{-1} (hdd^{-1}) for cattle and 4.8 kg CO_2-e hdd^{-1} for sheep), with shipping energy and animal emissions as primary contributors. Direct fossil energy use was 149.6 MJ (megajoules) hdd^{-1} for cattle and 56.3 MJ hdd^{-1} for sheep; freshwater consumption was 33.2 L (litres) and 8.3 L hdd^{-1} respectively. Air freight, which contributes a small portion of total livestock export volume, had substantially higher emissions and energy use, though similar water consumption to sea freight.

Compared to the 2010 baseline, GHG emissions for cattle decreased 30%, mainly as a result of reduced energy use. In contrast, sheep emissions increased 10%, mainly due to reduced ship stocking densities resulting in higher shipping emissions per head and higher reported production impacts. Freshwater consumption used a different measure which took into account the use of desalinated drinking water use during shipping and therefore showed lower water use than in 2010.

From primary production up until arrival to the destination port, supply chain impacts ranged from 15.3-21.1 kg CO_2-e kg liveweight^{-1} (LW^{-1}) for cattle and 10.5-13.1 kg for sheep, with energy use varying from 8.3-85.3 MJ kg LW^{-1} and 42.6-83.1 MJ kg LW^{-1} respectively. Air freight showed the highest impacts for cattle and sheep. The livestock export stage (quarantine to port of arrival) contributed 25% (sheep) and 4% (cattle) of total emissions at destination, but a larger share of fossil energy use. Water use during this stage was relatively minor.

Case study analysis showed that Indonesian feedlot finishing resulted in a carbon footprint of 14.3 kg CO_2-e/kg LW, which is approximately 12% higher than the Australian average for slaughter cattle (~12.8 kg CO_2-e/kg LW; Wiedemann et al. 2023). This comparison is indicative rather than direct, as the Indonesian figure includes the export leg while the Australian average does not. Transporting cattle to Indonesia via sea freight contributed marginally more emissions than long-distance trucking to southern Queensland, but this was not material, and full supply chain comparisons (to boxed product) are needed for robust evaluation.

Overall, live export remains a low-impact stage within the supply chain, enabling efficient market access particularly for cattle. Emission reductions may be achieved through feed supplements and improved energy efficiency of freight to destination.

Executive summary

Background

Over the past century, the rise of globalisation, population expansion and associated economic growth has increased food demand and shifted dietary patterns. Australia's livestock export industry provides nutrition and food security to key markets around the globe, particularly those with specific meat processing requirements, limitations around cold chain boxed meat transport and storage, or where consumers have a preference for locally processed fresh meat. However, climate change constitutes a risk to the livestock industry, where food production has been identified as a contributor to global GHG emissions, and there is widespread agreement that reducing GHG emissions is a global priority to mitigate climate change (IPCC, 2021).

The Australian red meat industry aims to contribute to Australia's net-zero emissions through reducing industry emissions (MLA, 2020, 2025; RMAC, 2019). This study provided an LCA for cattle and sheep exports in 2023, assessing industry changes since a previous LCA study (Eady, 2011) and providing an updated benchmark for industry which can be used to track progress. The LCA also assessed energy and freshwater consumption. Impacts were reported on a product basis (e.g. per kilogram [kg] of liveweight [LW]), providing industry with comparable results across enterprises and supply chains of different sizes. Contributions from both direct emission sources (scope 1) and indirect emissions sources (scope 2 and 3) were used to quantify GHG emissions along the supply chain, although were not reported in absolute terms.

The LCA provided in this study will serve as a key platform for the industry to communicate its environmental performance, while also enabling the use of baseline data for self-assessment and performance benchmarking against other industries, ensuring ongoing progress and accountability.

Objectives

This study had the following objectives:

1. Review the findings from the 2010 assessment (Eady, 2011) focusing on carbon emissions and GHGs.
2. Recalculate baseline data to allow like for like comparisons between the 2010 LCA and 2023.
3. Provide baseline data for self-assessment and performance benchmarking against other industries.
4. Quantify the industry's carbon footprint. Incorporate sensitivity and uncertainty analysis from farm to in-market.
5. Develop an updated LCA focusing on carbon and GHGs, targeting the livestock export industry.
6. Understand and assess the scope 1 & 2 emissions for the livestock export supply chain.
7. Assess scope 3 emissions including the primary production phase upstream scope 3 emission sources from cradle to destination port. Include a case study analysis of downstream scope 3 emissions with specific focus on feedlot 'finishing' in market.

Methodology

The study included cattle and sheep production from major representative production regions across Australia, throughout the whole supply chain to the point of distribution to retail overseas. A large, integrated dataset based on case study farms and regional surveys was used to model cattle and sheep from major representative production regions across Australia. The functional unit was chosen as one kg of product sold, with a case study investigating Indonesian quarantine yards to processor using a reference unit of one kg of LW. The system boundary included on-farm primary production, quarantine yards, shipping to international market, transport to feedlot or market, and distribution to the point of retail. To facilitate comparisons with the previous study, results were updated to use the same global warming potential (GWP) values, and primary production methods were revised to standardise the calculations to the extent possible. Enteric methane predictions for cattle were revised to use up-to-date equations.

Results/key findings

The key result for the study was the benchmark of GHG emissions, freshwater consumption and energy for Australian cattle and sheep live exports from the point of arrival at the quarantine yards and during sea freight, shown in *Table 1*.

Table 1. Scope 1 and 2 GHG emissions, direct energy and freshwater consumption per hdd^{-1} for the livestock export sector from quarantine yards and sea freight

Animal	Scope 1 and 2 GHG (kg CO_2-e hdd^{-1})	Direct Freshwater Consumption (L hdd^{-1})	Direct Energy (MJ hdd^{-1})
Cattle	**17.1**	**33.2**	**149.6**
Sheep	**4.8**	**8.3**	**56.3**

Carbon footprint, freshwater consumption and energy use results for cattle and sheep from the whole supply chain to the point of arrival at destination port are provided in *Table 2* and *Table 3*. When the supply chain was extended to include results for cattle exiting the Indonesian feedlot, the carbon footprint decreased to 14.3 kg CO_2-e kg LW^{-1} which provided a result more comparable to Australian finished cattle supply chains.

Table 2. Life cycle assessment results for cattle at port in destination countries with results for carbon footprint, freshwater consumption and energy use

	Portland to China - Breeder cattle (Sea)	Fremantle to Israel - Feeder cattle (Sea)	Darwin to Indonesia - Feeder cattle (Sea)	Townsville to Vietnam (Sea)	Sydney to Malaysia - Breeder cattle (Air)
Carbon footprint (kg CO_2-e kg LW^{-1})	**15.3**	**16.4**	**17.1**	**16.1**	**21.1**
Freshwater consumption (L kg LW^{-1})	**143.8**	**160.4**	**186.0**	**169.6**	**176.0**
Energy (MJ LHV kg LW^{-1})	**23.5**	**22.6**	**8.3**	**11.4**	**85.3**

Table 3. Life cycle assessment results for sheep at port in destination countries with results for carbon footprint, freshwater consumption and energy use

	Fremantle to Israel - Feeder sheep (Sea)	Fremantle to Kuwait - Feeder sheep (Sea)	Sydney to Malaysia – feeder sheep (Air)
Carbon footprint (kg CO_2-e kg LW^{-1})	**10.6**	**10.5**	**13.1**
Freshwater consumption (L kg LW^{-1})	**181.5**	**178.8**	**186.7**
Energy (MJ LHV kg LW^{-1})	**42.6**	**44.2**	**83.1**

The breakdown of how each stage in the supply chain contributed to the GHG emissions for cattle and sheep is shown in *Table 4* and *Table 5*, with primary production being the largest contributor for cattle (averaging 96%) and sheep (averaging 75%). There was a substantial degree of variation in impacts across the cattle routes that used shipping, largely in response to differences in the length of the journey, with the Portland to China route having the longest distance and highest impacts, and Darwin to Indonesia having the shortest route and lowest impacts. Impacts were far higher from air freight resulting in a higher proportion of GHG emissions in the livestock export process, although air freight contributes a small portion of total livestock export volume.

Table 4. Relative contribution from each stage of the cattle supply chain for the carbon footprint

	Portland to China - Breeder cattle (Sea)	Fremantle to Israel - Feeder cattle (Sea)	Darwin to Indonesia - Feeder cattle (Sea)	Townsville to Vietnam (Sea)	Sydney to Malaysia - Breeder cattle (Air)	Average weight
Primary production	87%	90%	97 %	96 %	73 %	96%
Quarantine yard/shipping/ air	13%	10 %	3%	4%	27%	4%

Table 5. Relative contribution from each stage of the sheep supply chain for the carbon footprint

	Fremantle to Israel - Feeder sheep (Sea)	Fremantle to Kuwait - Feeder sheep (Sea)	Sydney to Malaysia - (Air)	Average weight
Primary production	75%	75%	63%	75%
Quarantine yard/shipping/ air	25%	25%	37%	25%

The livestock export stage on average contributed 25% (sheep) and 4% (cattle) of emissions to the final carbon footprint at the destination port but much higher fractions of fossil energy use, particularly for air freight. Air freight, while niche, was shown to be a very high impact transport system. When downstream finishing of cattle in an Indonesian feedlot was included in the system boundary, the overall impacts were reasonably similar to the average of Australian slaughter cattle, indicating that this can be an environmentally efficient supply chain considering the lower input primary production system in northern Australia and the necessity to transport cattle long distances to market either in Australia or overseas.

In the present study, sheep impacts were higher in the farming stage when compared to the previous study partly due to differences in flock performance and partly because of revisions to the methods used. When method differences were removed, impacts remained some 5% higher at farm stage. Impacts also increased in shipping, largely because of new requirements for lower stocking rates compared to the previous study. The outcome was 10% higher emissions for sheep at destination port than the previous study. This result highlighted the important interplay between requirements for animal welfare and the impact of these on environmental performance and demonstrated that trade-offs exist between stocking rate and shipping efficiency.

Results for cattle decreased and showed a larger contrast to sheep, with impacts in the present study of 17.1 kg CO_2-e kg LW^{-1} for cattle shipped to Indonesia, being 25% lower than the previous study. The principal differences related to improved breeding herd performance (scope 3). Scope 1 and 2 emissions were also lower, but this was a smaller fraction of the supply chain, leading to a lower impact on the final result. The improvements related to productivity and efficiency were substantial and resulted in a more rapid rate of reduction than what was achieved from 2010 to 2020 for the herd destined for slaughter in Australia in the Wiedemann et al. (2023) study. Noting this finding, further primary data to qualify and confirm the scope 3 model for the northern live export cattle production system would be warranted.

The previous study did not assess impacts from air freight and therefore could not be compared. No other studies were found in the literature assessing the impact of air freight. Comparing air freight and sea freight revealed large increases in impacts for both carbon footprint and fossil energy demand because of fuel requirements for planes and a smaller number of animals on a plane compared to a ship. In contrast, the short flight journey required minimal feed and freshwater inputs and generated low levels of animal emissions compared to sea consignments.

The carbon footprint for cattle exiting the Indonesian feedlot (14.3 kg CO_2-e kg LW^{-1}) decreased substantially compared to the footprint calculated by Eady (2011) (19.6 kg CO_2-e kg LW^{-1}, with GWP values and methods revised). In addition to the differences related to feeder cattle, feedlot performance was better in the present study and manure management impacts were lower than the case study completed previously.

Because there are no processing facilities consistently operating in northern Australia and the young cattle produced are not slaughter ready, all cattle must be transported from these regions for finishing, either via sea freight, or via long-distance road transport. To compare impacts, we examined transporting a feeder steer from Katherine, NT, to Indonesia via sea freight, or to Dalby, QLD which is a major feedlot finishing region in Australia.

The impact of transporting to an overseas market contributed 4% to total impacts. By comparison, transporting the same animal by truck to southern Queensland for finishing increased emissions by slightly over 2% resulting in 6% of total impacts. Transporting via live export had higher impacts, but this was not substantial over the life cycle. True comparison would need to extend to production of boxed product via both supply chains in the Indonesian market to take into account subsequent transport. It would be beneficial in the future to assess full supply chain impacts for boxed product in major markets to provide a more complete evaluation of the efficiency of the production system.

The overall improvement in both primary production and live export sectors in cattle was a positive outcome, showing a faster rate of change than the herd supporting slaughter ready cattle in Australia over a similar time period, and supporting the overall contribution of the livestock export sector to societal goals for decarbonisation. The results for the sheep sector were more circumspect and warrant further consideration by the sheep industry to address the constraints to improvement in that sector. This study supports the overall preparedness of the sector and major companies in providing environmental credentials to meet societal goals in the near future.

Benefits to industry

The benefits of conducting this study include:

- This study provided a comparable update to the previous study, where improved methods are now available to quantify impacts. The expanded datasets in this project provide more robust and recent information for benchmarking performance. This demonstrated that the industry is taking steps to address rapidly growing community expectations around environmental sustainability and the impact of climate change.
- The findings from this study provide an updated estimate of performance for the sector, which provide an industry benchmark and a platform for communicating environmental improvement credentials to banks, other institutions, and government.
- The study provided insights into the effect of animal welfare requirements and the interrelationship between these requirements and environmental impacts. In the case of sheep, impacts increased largely because of changes to stocking density requirements which reduced the efficiency of transport. This highlighted the important trade-offs that exist in supply chains between different objectives.
- This study supports the overall preparedness of the sector and major companies in providing environmental credentials to meet societal goals in the near future.

Future research and recommendations

The comprehensive benchmark provided by this study enables industry to explore options for improving its environmental impact, including the mitigation of GHG emissions. It is recommended that the product LCA is updated on a two or five yearly timeline to continue to provide accurate benchmarks, which will be essential in tracking industry progress against Australia's ambitions for emission reduction and for production systems to uphold their social licence to operate.

The promising finding from the primary production (scope 3) assessment of exported cattle and the significant improvements over time warrant further study to support these findings with primary data collection for key inputs. Specifically, further information regarding the weight and age of cattle at induction into pre-export yards is needed to improve estimates, as is confirmation of breeding herd inventories. Further, information is needed regarding sex at the point of induction to improve the herd model.

While this study improved the benchmark using a broader dataset from shipping than the previous study, it would be further strengthened with a larger dataset. This would be improved by also creating a data standard for the sector to make data collection and sectoral reporting a smooth and potentially automated approach.

Introducing livestock export indicators into the Australian Beef Sustainability Framework would be an excellent option to showcase the progress of the sector and to continue reporting progress. Considering the increased reporting frequencies and expectations of Government, society and other stakeholders, using a two-year reporting cycle would be warranted.

Table of Contents

List of Figures

List of Tables

List of Abbreviations

ABARES	Australian Bureau of Agricultural and Resource Economics and Sciences
ABS	Australian Bureau of Statistics
ADG	average daily gain
AR2	Second Assessment Report
AR6	Sixth Assessment Report
CF	carbon footprint
CH_4	methane
CO_2-e	carbon dioxide equivalent
CP	crude protein
CY	calendar year
dLUC	direct land use change
DMI	dry matter intake
DOF	days on feed
FCR	feed conversion ratio
FY	financial year
GHG	greenhouse gas
GWP	global warming potential
hdd^{-1}	$head^{-1}$ day^{-1}
LCA	life cycle assessment
LU	land use
LW	liveweight
ME	Middle East
MJ	megajoule
N_2O	nitrous oxide
NGGI	National Greenhouse Gas Inventory

NIR	National Inventory Report
NT	Northern Territory
QLD	Queensland
WA	Western Australia

1. Introduction

1.1. Background

Over the past century, the rise of globalisation, population expansion and associated economic growth has increased food demand and shifted dietary patterns, where increased urbanisation in developing nations has driven the increased consumption of animal derived food (Duver et al., 2022). To meet this demand, food production must increase by 70% by 2050, compared to 2009 (FAO, 2009). Increased consumer and market expectations regarding transparent environmental impacts associated with food production have also given rise to the expectation that supply chains disclose this information.

Livestock products are important for global food security because they provide 17% of global kilocalorie consumption and 33% of global protein consumption (Rosegrant et al., 2009). The livestock sector supports one billion of the poorest population in the world (Hurst et al., 2005), and rapid growth of the livestock industry in developing countries has been deemed the livestock revolution (Delgado et al., 2001), which is expected to continue as the revolution did not occur uniformly across the developing world (Latino et al., 2020). With sustainable development objectives and careful management, the livestock industry can continue to be a pillar in the world's food system contributing to poverty reduction, food security and agricultural development (Kennady et al., 2023).

Climate change constitutes a risk to the livestock industry due to its impact on the feed quality of crops and forages, animal performance, milk production, freshwater availability, animal reproduction, livestock diseases and biodiversity (Rojas-Downing et al., 2017). Livestock also contribute to climate change through GHG emission production, arising from livestock digestion and manure, and fossil energy use. Reducing GHG emissions, including from livestock, is a global priority for mitigating climate change (IPCC, 2021).

Australia has committed to reduce its GHG emissions by 43% on 2005 levels by 2030 as a part of the Australian Government's Net Zero Plan and under Australia's Nationally Determined Contribution as a signatory to the Paris Agreement (Albanese & Bowen, 2022; DCCEEW, 2025). In 2025, the Australian red meat industry committed to contributing to Australia's net zero ambitions (MLA, 2020, 2025; RMAC, 2019) aiming to achieve a condition where anthropogenic GHG emissions associated with all stages of Australian cattle, sheep and goat supply chains are balanced by removals.

A previous LCA for livestock export found that shipping, feeding and handling at destination can significantly affect the final environmental impact of a food product (Eady, 2011) and that the CF of products may be relatively high. However, this study was conducted over a decade ago, and changes in industry practices and research methods have resulted in the need for an update for the livestock export sector.

1.2. Project objectives and goal

This study had the following objectives:

1. Review the findings from the previous assessment (Eady, 2011) focusing on GHG emissions. (noting this study was based on data from 2010 and was published in 2011).

2. Recalculate baseline data to allow like for like comparisons between the 2010 and 2023 benchmarking results.

3. Provide baseline data for self-assessment and performance benchmarking against other industries.

4. Quantify the industry's CF. Incorporate sensitivity and uncertainty analysis from farm to in-market.
5. Develop an updated LCA focusing on carbon, targeting the livestock export industry.
6. Understand and assess the scope 1 & 2 emissions for the livestock export supply chain.
7. Assess scope 3 emissions including the primary production phase upstream scope 3 emission sources from cradle to destination port. Include a case study analysis of downstream scope 3 emissions with specific focus on feedlot 'finishing' in market.

These objectives are addressed in this final report.

1.3. Literature review

1.3.1. Review of 2011 livestock export industry life cycle assessment

The 2011 LCA of Australia's livestock export supply chain focused on case studies of sheep exported from Fremantle to the ME and cattle exported from Darwin to Indonesia. The study measured GHG emissions, energy and freshwater consumption, and nutrient discharges for a single calendar year, covering every major aspect of the supply chain from on-farm production through to delivery of the live animal at the abattoir at the destination country (Eady, 2011). The cattle export supply chain considered in the study included primary production from the Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES) survey region 713 (Victoria River District/Stuart Plateau/Katherine) and 714 (Top End and Gulf) in the NT to determine mean on-farm annual GHG emissions. Primary production enterprises generated interrelated beef products (steers, heifers, cull cows and bulls), where economic allocation was used to partition inputs between the representative outputs generated.

The study was undertaken using methods in the AusLCI Data Guidelines for Agricultural LCI (2008) framework developed by the RIRDC Project – Methodology for Agricultural LCA in Australia, LCA standards ISO14040:2006 and ISO14044:2006, and used then current National Greenhouse Gas Inventory (NGGI) emission factors (Eady, 2011). The functional unit was one beast/wether, delivered to the abattoir in the destination country (reported as kilograms [kg] of carbon dioxide equivalent [CO_2-e] per kg liveweight [LW]). Specifically, it was reported as one Australian Merino sheep shipped at 46 kg LW delivered to the ME abattoir at 48 kg LW and one Australian *Bos indicus* steer delivered to the Indonesian abattoir after feedlot finishing at 470 kg LW.

The 2011 study included the transit time for the vessel to return to Australia due to repeated return voyages to Australia to collect more livestock made by some vessels, while others were deployed to alternate routes for part of the year. Transporting one consignment of sheep to the ME took two days loading at the Fremantle port, 12 days in transit, five days unloading at the ME port and 11 days to return to Fremantle. Transporting one consignment of cattle to Indonesia was five days loaded and five days for return to port. It was assumed that there was no external supplied power to the vessel while in port. GHG emissions (excl. land use [LU] and direct land use change [dLUC] emission sources) from Australian cattle are dominated by enteric CH_4 and manure emissions, with smaller contributions from fossil fuel energy use (Eady et al., 2011; Peters et al., 2010; Wiedemann et al., 2017; Wiedemann, McGahan, et al., 2015). Results from the 2011 study are provided in *Table 6* along with recalculations of the results using AR6 values. The majority of emissions for exported sheep occurred at the 'production to farm-gate' level followed by the 'shipping to foreign port' stage. For export cattle, the majority of emissions occurred at 'production to farm gate' followed by 'finishing to feedlot gate' in the destination country *(Table 6)*. A similar trend in this study was expected. Results at mid-points in the supply chain were also calculated for comparison to the current study. This was done including updates to the GWP_{100} factors. Results were also recalculated using changed assumptions, and these are discussed in section 2.8.

Table 6. Summary of carbon footprint results from Eady 2011 with recalculated AR6 values

Emission source	GHG emissions (kg CO_2-e) AR2 GWP_{100}	Recalculated using AR6 GWP_{100}
Livestock exports of sheep from WA to ME		
Production to farm gate (kg CO_2-e)	5.3	6.2
Preparation to quarantine yard gate (kg CO_2-e)	0.1	0.2
Shipping to foreign port (kg CO_2-e)	1.7	1.7
Finishing to feedlot gate (kg CO_2-e)	0.2	0.2
Total for 1 kg LW (48 kg) (kg CO_2-e LW^{-1})	7.3	8.3
Livestock export of cattle from the NT to Indonesia		
Production to farm gate (kg CO_2-e)	22.3	26.8
Preparation to quarantine yard gate (kg CO_2-e)	0.1	0.1
Shipping to foreign port (kg CO_2-e)	0.3	0.3
Finishing to feedlot gate (kg CO_2-e)	3.4	3.9
Delivered to abattoir (kg CO_2-e)	0.01	0.01
Total for 1 kg LW (470 kg) (kg CO_2-e LW^{-1})	26.1	31.1

Table 7. Summary of cattle carbon footprint results from Eady 2011 with recalculated AR6 values

	Original study reported value	Updated GWP
Feeder cattle – farm gate – kg CO_2-e kg LW	31.5	38.4
Feeder cattle – destination port – kg CO_2-e kg LW	32.1	39.0

Finished cattle – ex feedlot – kg CO_2-e kg LW	26	31.5

Table 8. Summary of sheep carbon footprint results from Eady 2011 with recalculated AR6 values

	Original study reported value	Updated GWP
Sheep – farm gate – kg CO_2-e kg LW	5.5	6.4
Sheep – destination port – kg CO_2-e kg LW	7.4	8.4

A review of the 2011 study (Eady, 2011) and understandings of current available data identified several gaps. Assumptions or estimation calculations were also used that are no longer best practice. These gaps and out-dated assumptions include:

Data and representativeness:

> Limitations to primary data from shipping and small sample sizes for shipping and quarantine yards may have limited the representativeness of the results.

> Only one destination was studied for cattle (Indonesia) and air freight was not assessed.

Methods:

> The prediction equation for enteric methane from cattle was updated in 2016 and resulted in approx. 30% lower estimated enteric methane from northern cattle herds.

> The study used AR2 GWP_{100} methods which have subsequently been updated by the IPCC.

> The study included emissions from savanna burning as an attributable source to cattle in northern Australia.

> The study used the blue water use indicator and included desalinised water as a blue water source attributed to livestock. As blue water is commonly defined as freshwater abstraction, this overestimated water consumption.

1.3.2. Other recent benchmarking studies

To track performance towards reducing emissions in the beef industry, impacts from Australian beef, including the CF of the slaughter herd, are reported in the Australian Beef Sustainability Framework (ABSF) for cattle processed in Australia (excl. exported cattle), based on the research of Wiedemann et al. (2019; 2015; 2023). The 2020 update to the beef trends analysis (Wiedemann et al., 2023) found a 22% reduction in CF and 73% reduction in freshwater consumption over 40 years due to several factors including increased production efficiency, bore capping and reduced use of irrigation water for pastures. In contrast, fossil energy use increased as industry relied more on intensive production systems (Wiedemann et al., 2023). CF reductions were supported by revisions to the enteric CH_4 calculation method for feedlot cattle, which were later included in the 2023 Australian National Inventory Report (NIR) (Commonwealth of Australia, 2025), resulting in lower emissions while cattle were finished on grain (Wiedemann et al., 2023).

CF and net emissions for the Western Australian (WA) beef industry for financial years (FY)18 and FY19 were determined in a cradle-to-gate LCA (Wiedemann et al., 2023). The WA study reported a mean CF of 15.3 kg CO_2-e kg LW^{-1}. There was a significant difference between the southern (agricultural) region (11.7 kg CO_2-e kg LW^{-1}), northern tropical region (19.2 kg CO_2-e kg LW^{-1}) and the central arid region (18.2 kg CO_2-e kg LW^{-1}) (Wiedemann et al., 2023). Cattle in the southern (agricultural) region had heavier slaughter and export weights, faster growth rates and younger turn off age compared to the other two regions, resulting in lower CFs. Live export cattle were older than domestic slaughter cattle, resulting in higher emissions (Wiedemann et al., 2023). The northern tropical CF was significantly lower than the CF reported in the 2011 LCA at the farm gate for an average 333 kg NT live export feeder steer as reported by Eady (2011). Since 2011, improvements have been made to reduce cattle CFs, including productivity enhancements such as higher quality feedbase with irrigated pastures, increased LW gain and beef production per cow joined, and increased growth rates in younger cattle.

Recent LCA research of the WA sheep industry found a 9% increase in the CF of sheep production from 7.4 to 8.2 kg CO_2-e kg LW^{-1} from FY05 to FY20, respectively (Wiedemann et al., 2022). This trend was related to intensification of the production system without significant enough increases in productivity to offset the higher purchased inputs. Reported impacts were higher than Eady (2011) and this was also partly influenced by method choices; Eady used an economic allocation method between wool and meat which resulted in relatively low reportable impacts for meat compared to Wiedemann et al. (2022).

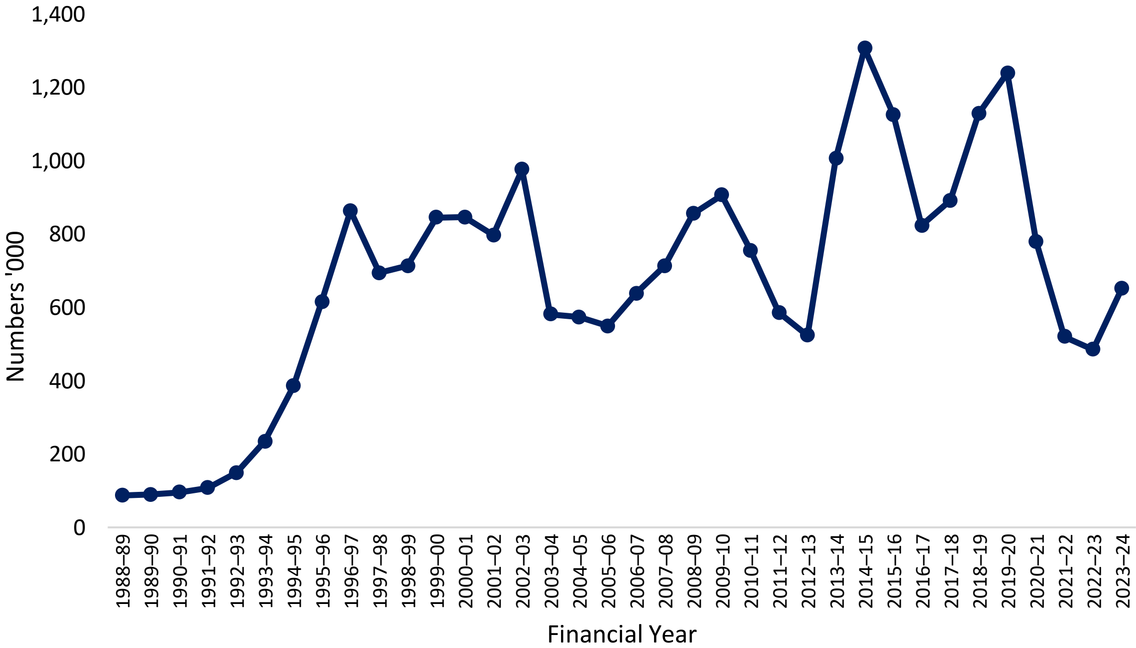
The implications of the aforementioned studies suggested that the CF of feeder cattle would likely be lower than the results reported in the 2011 LCA while sheep may be higher. Differences that related to methods were revised where possible and methods to achieve this are described in section 2.8.

1.4. Live export industry supply volumes and supply chain

Publicly available livestock export statistics were obtained and analysed to gather information on Australia's livestock export market. Livestock export data were available at a consignment level and were compiled from information included on the export permit and health certificate issued by the department to exporters at departure, where this study presented the 2022 live export data as of August 2023 (DAFF, 2023). General livestock export numbers were obtained from the Agricultural commodities June quarter 2024 data (ABARES, 2024a). Other data were obtained through industry resources (e.g., MLA, Dairy Australia and LiveCorp databases).

1.4.1. Australia's live export industry overview

A review of total recorded livestock export numbers for all markets (ABARES, 2024a) showed a material decrease in total sheep (*Figure 1*) and feeder and slaughter cattle



(

Figure 2) exports; however, live export of breeder cattle has steadily increased since 2000 (Figure 3).

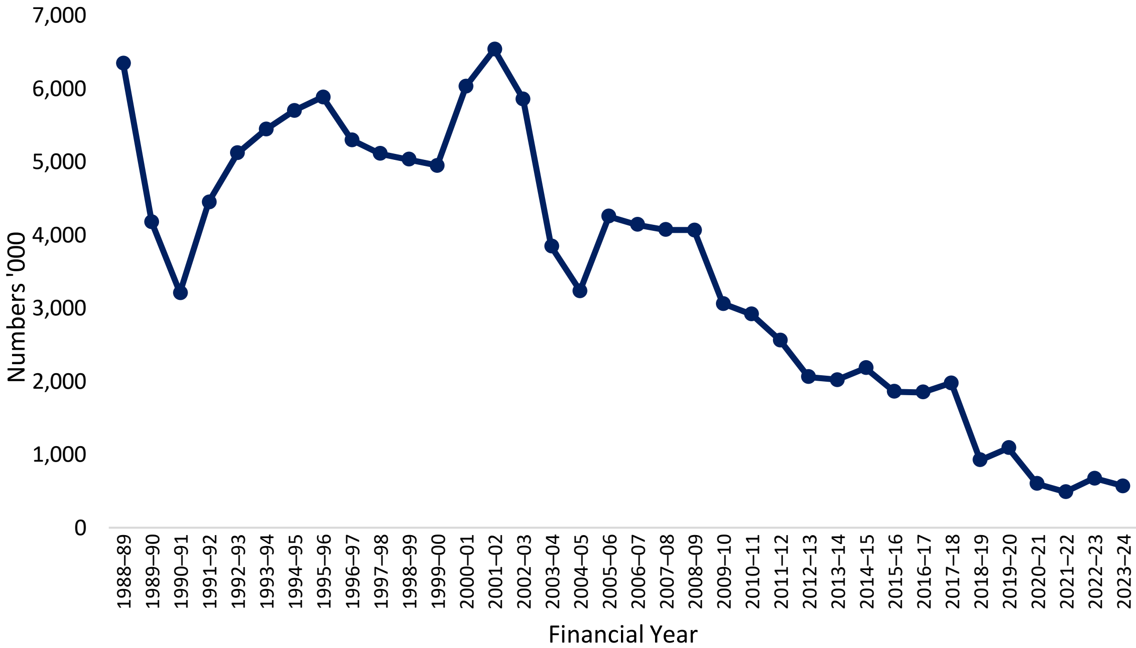


Figure 1. Trend in live sheep export numbers including breeding stock

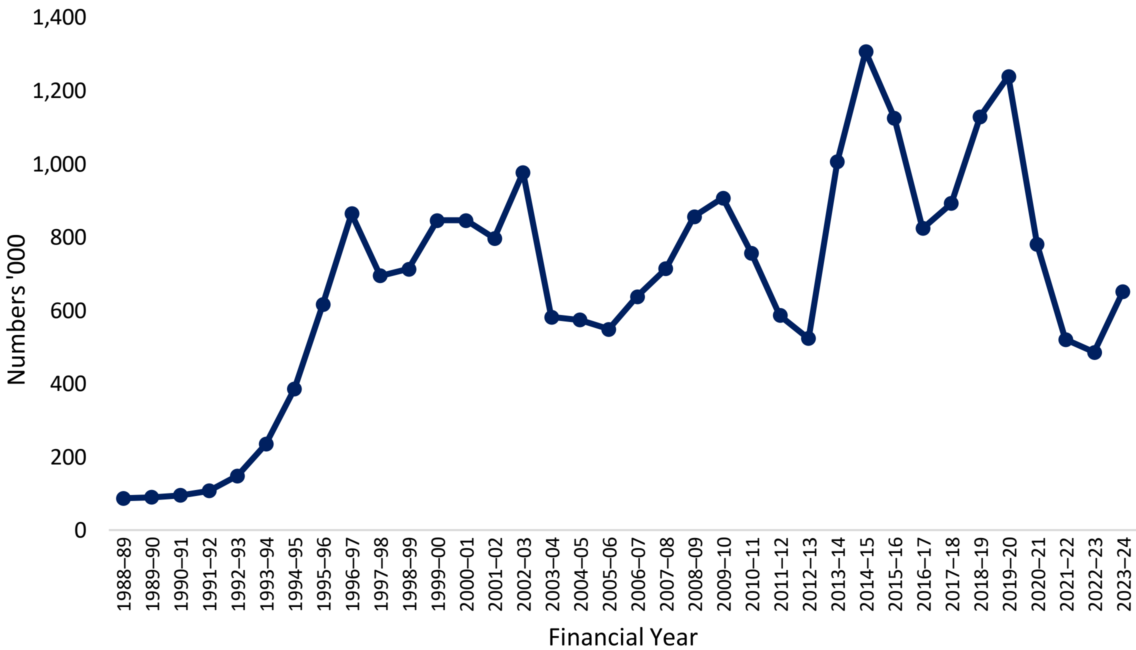
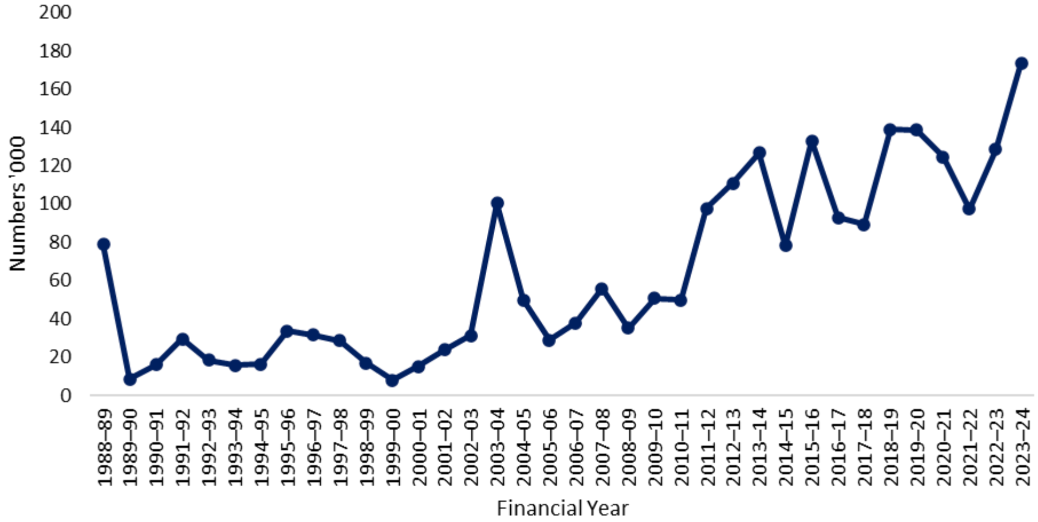


Figure 2. Trend in the number of live feeder and slaughter cattle (incl. buffalo) exported to destination markets.



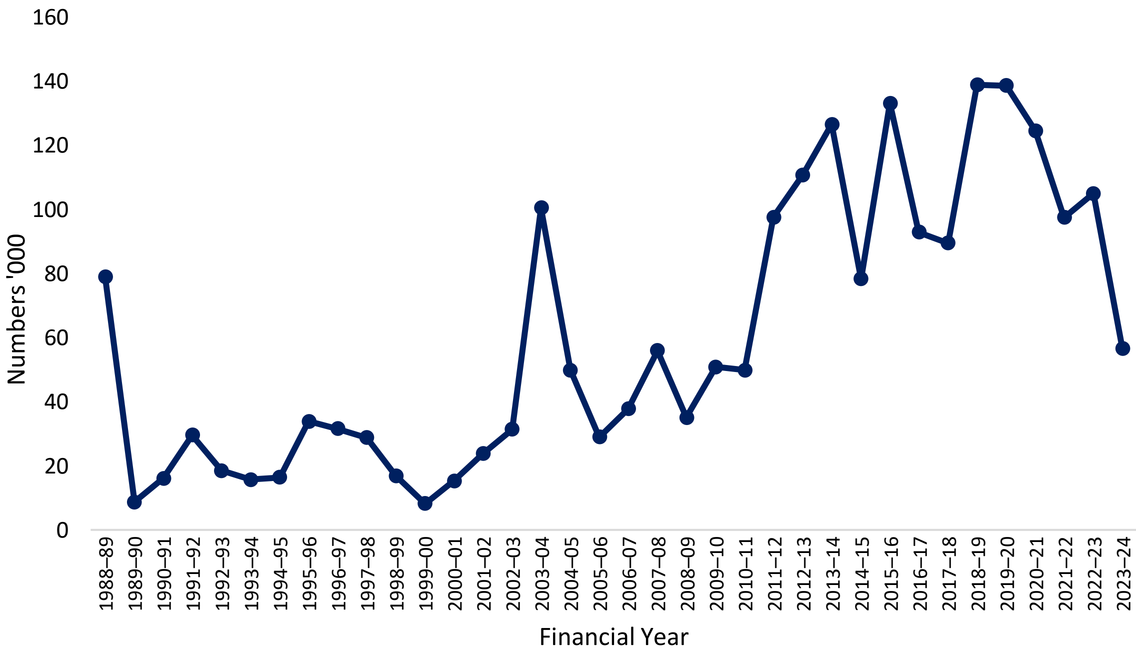


Figure 3 Trend in live breeder cattle (incl. dairy and buffalo) exports to destination markets.

1.4.2. Live cattle export markets

Main export ports for cattle are Darwin, Portland, Broome and Townsville, with Indonesia, China and Vietnam the major destinations. In 2022, exports from seaports in Australia's northern cattle regions (Darwin, Broome, Brisbane, Townsville and Wyndham Port) totalled 398,015 head (342,465 feeders, 48,434 slaughter and 7,116 breeders). Indonesia is a long-established importer of feeder cattle from northern Australia, typically departing from Darwin or Broome. Slaughter ready cattle are predominately exported to Vietnam from Townsville, while most breeder purpose cattle are exported to China from Victorian ports (*Figure 4*) (ABARES, 2024b).

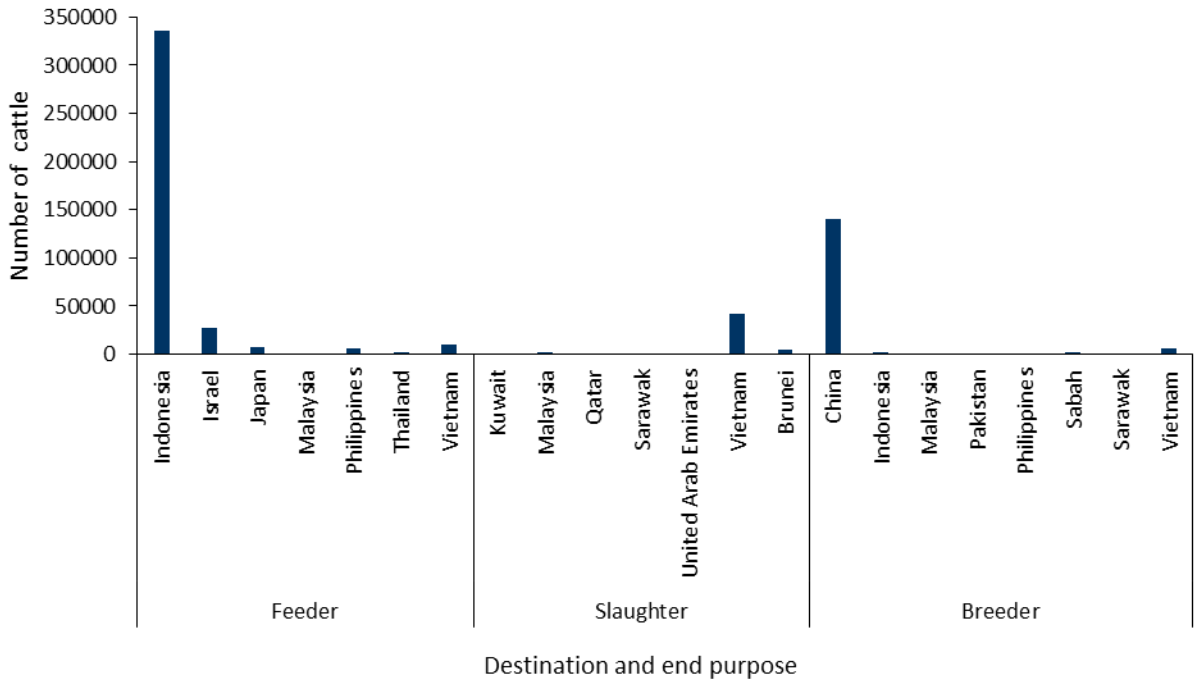


Figure 4 Showing 2022 cattle export numbers via sea freight, based on end purpose and destination

The majority of live cattle are exported via sea freight, with a small number of breeder cattle exported by air (*Table 9*).

Table 9. Key supply chains of the live cattle export industry by end purpose, mode of transport and quantity transported in 2022

Departing port	Destination	End purpose	Mode of transport	Quantity exported	Travel Distance (km)	Estimated Travel time
Darwin	Indonesia (Jakarta port)	Feeder	Sea	203,381	2,719	5 days 15 hours
Townsville	Vietnam (Haiphong port)	Slaughter	Sea	28,583	7,452	16 days 8 hours
Portland	China (Tianjin port)	Breeder	Sea	135,924	12,080	22 days 8 hours
Sydney	Malaysia	Breeder	Air	2,485	6,584	< 1 day
Fremantle	Israel (Tel-Aviv)	Feeder	Sea	27,490	14,430	29 days 3 hours

Approximately 200,000 live cattle were sent from Darwin to Indonesia, representing the main export supply chain for cattle (*Figure 5*). Destination ports in Indonesia include Muara, Panjang and Belawan.

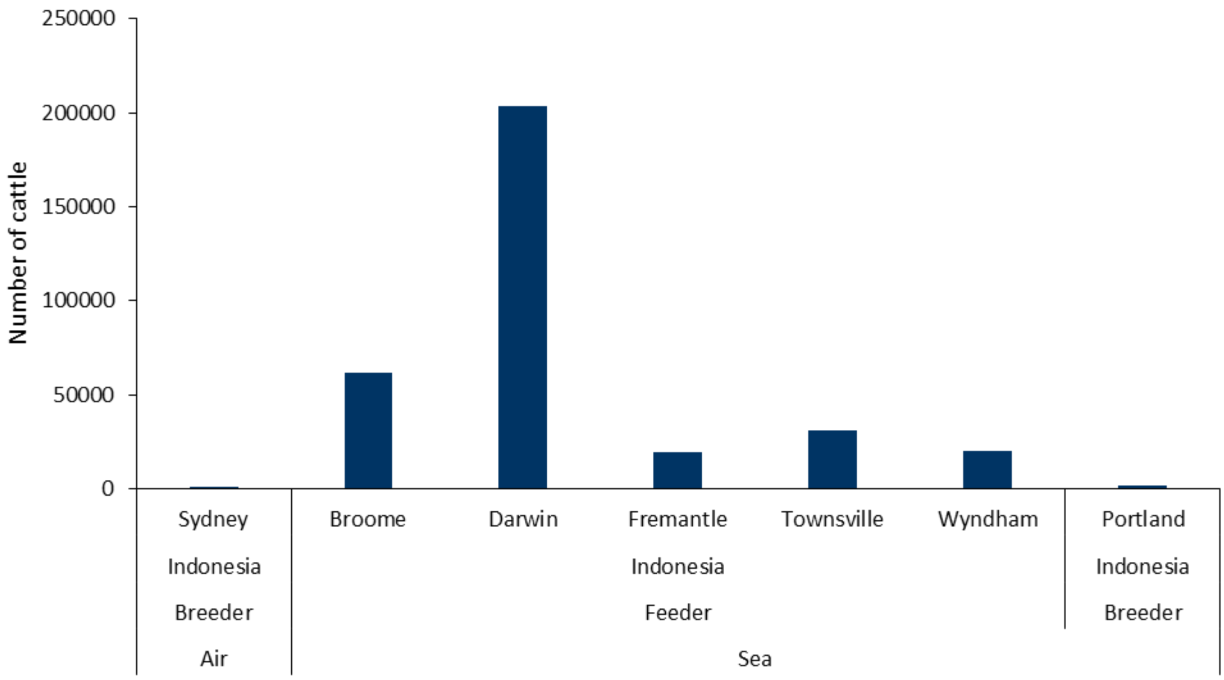


Figure 5 Number of live cattle sent from different ports in Australia to Indonesia in 2022

Another major destination was Vietnam where slaughter ready cattle were predominantly exported from the ports of Townsville, Broome and Darwin. A small number of breeder cattle (42) were sent via air freight from Melbourne (*Figure 6*).

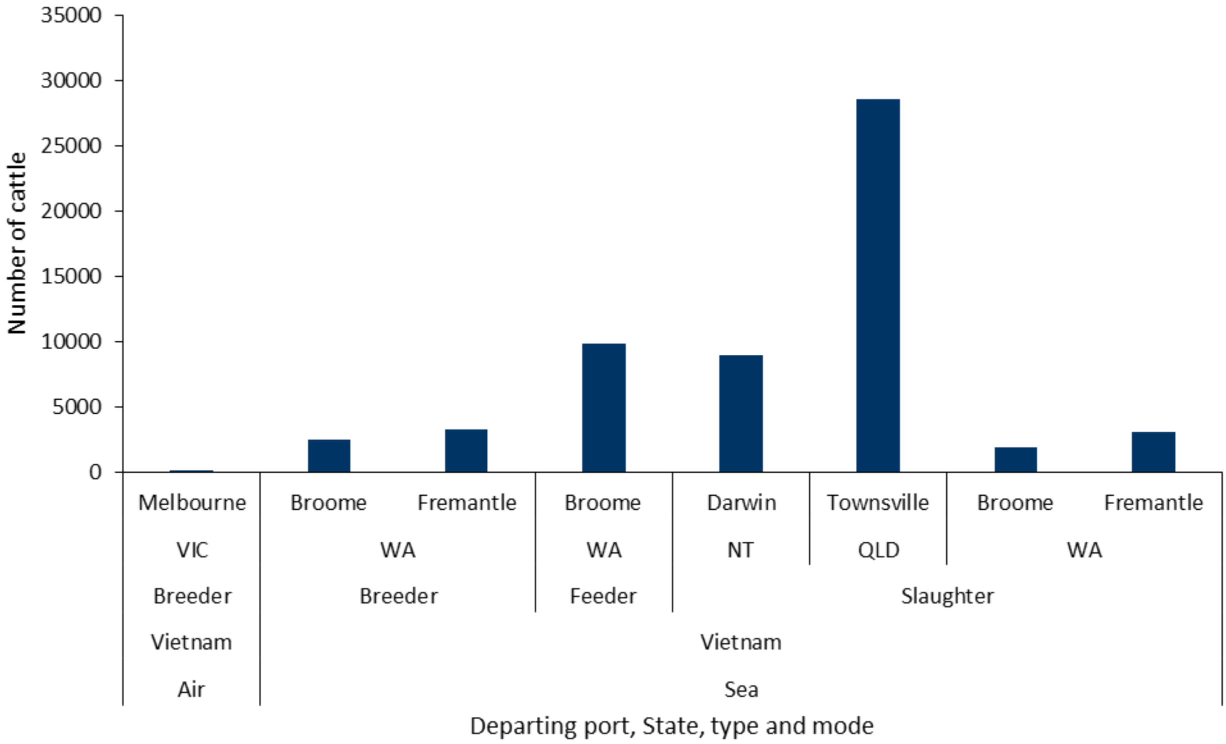


Figure 6 Number of cattle sent from different ports in Australia to Vietnam in 2022

1.4.3. Dairy cattle exports to China

Since 2018, the number of cattle sent from Portland to China (predominantly dairy cattle) has increased, with over 140,000 breeder purpose cattle sent to China in 2022 (*Figure 7*). Cattle destined for China, including the ports of Qinhuangdao, Qinzhou, Weifang, Tianjin and Yantai, must be exported from Bluetongue virus-free areas, explaining the lack of exports from other states (ABARES, 2024b).

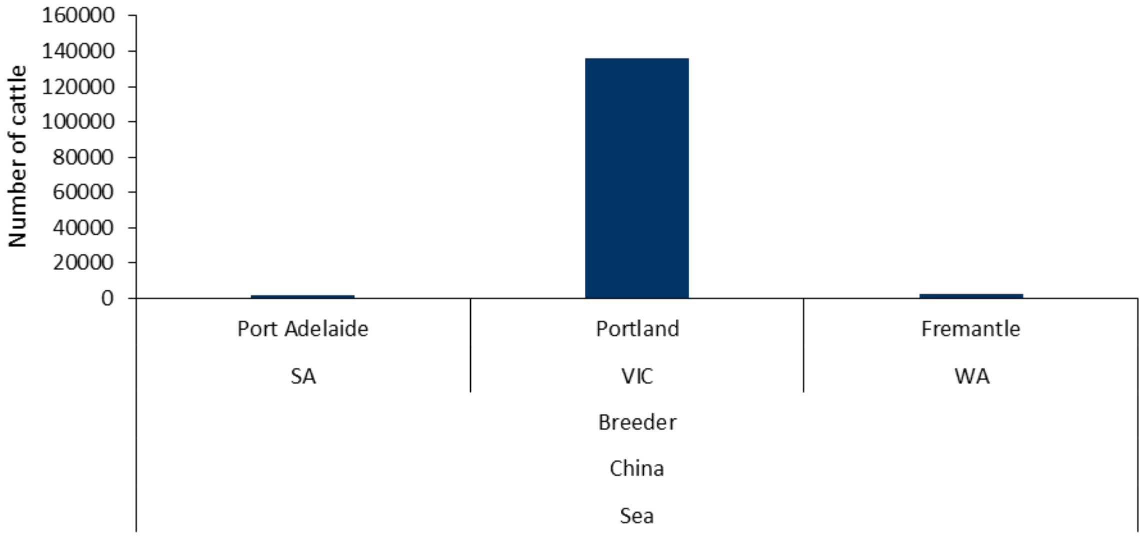


Figure 7 Breeder cattle exports to China from Portland Victoria, Port Adelaide South Australia, and Fremantle Western Australia in 2022

Export data for dairy cattle is largely unpublished, a report by BDO on the economic analysis of the live dairy cattle export trade (BDO EconSearch, 2022) reported basic export data, and showed an increase in dairy cattle exported to China FY17 to FY20 (*Figure 8*), and a decrease in all other countries combined (BDO EconSearch, 2022). Presumably, many of these are described as 'breeders' in the livestock export data and travel via sea freight, with most exported from Victoria (*Figure 8*).

Figure 8. Total dairy exports per state from FY16-20

1.4.4. Live sheep exports

In 2022, approximately 300,000 slaughter sheep (60% of market) were sent to Kuwait via sea from the Fremantle port, with Israel being the second largest importer (*Figure 9*). Perth was the main exporter of sheep by air, and Maylasia the main destination *(Figure 9*) (ABARES, 2024b).

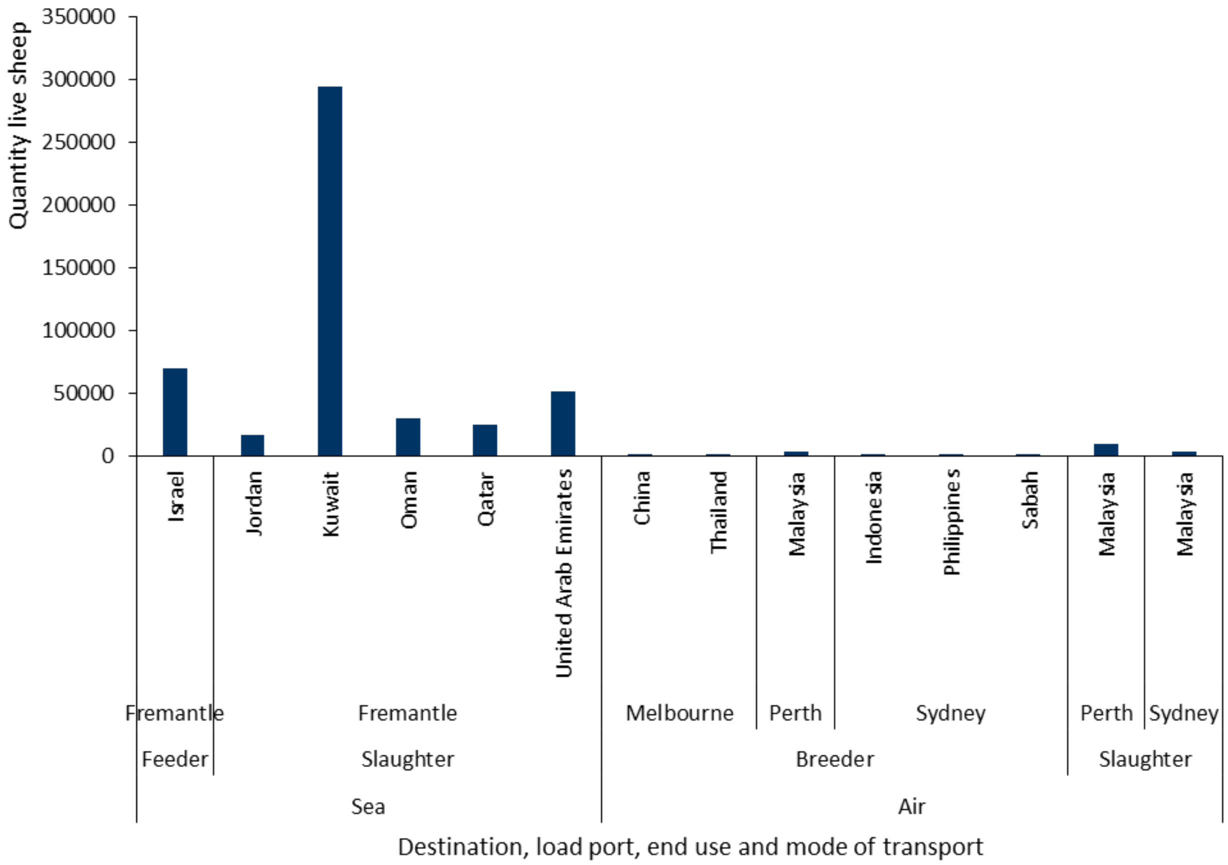


Figure 9. Live sheep exports by sea freight in 2022

The sea shipping routes for sheep export (as determined using online route planning software) are shown in *Table 10*.

Table 10. Key supply chains of the export industry for sheep by end purpose and mode of transport and quantity exported in 2022

Departing port	Destination	End purpose	Mode of transport	Quantity exported	Travel Distance (km)	Travel time (one direction)
Fremantle	Kuwait	Slaughter	Sea	294,216	12,445	18 days 18 hours
Fremantle	Israel	Feeder	Sea	69,308	14,430	29 days 3 hours
Perth	Malaysia	Slaughter	Air	9,192	4,124	< 1 day

2. Methodology

2.1. Selection of environmental indicators

This study developed a CF analysis for live cattle and sheep exports and provided emission intensities for each stage of the supply chain. These indicators align with industry standards, including the ASBF (ABSF, 2023) and the feedlot carbon-neutral manual (Wiedemann & Longworth, 2021). The study also assessed energy use and freshwater consumption

2.2. GHG calculation methods

2.2.1. Emission boundary

The CF assessed impacts from cradle-to-gate, with a focus on the export supply chain, from arrival at quarantine yards and shipping to international markets via sea or air (*Figure 10*). The product CF was determined following methods in the ISO Standard 14067: 2018 and LEAP (LEAP, 2015a, 2015b). The LCA modelling was conducted using SimaPro v9.6.0.1 (Pré-Consultants, 2021). A case study was also included which investigated an Indonesian feedlot in alignment with the Indonesian feedlot case study included in the previous study. CFs for cattle and sheep for the supply chain used a reference unit of 'one kg of LW', while scope 1 and 2 emissions were reported using a reference unit of 'head^{-1} day^{-1} (hdd^{-1}).'

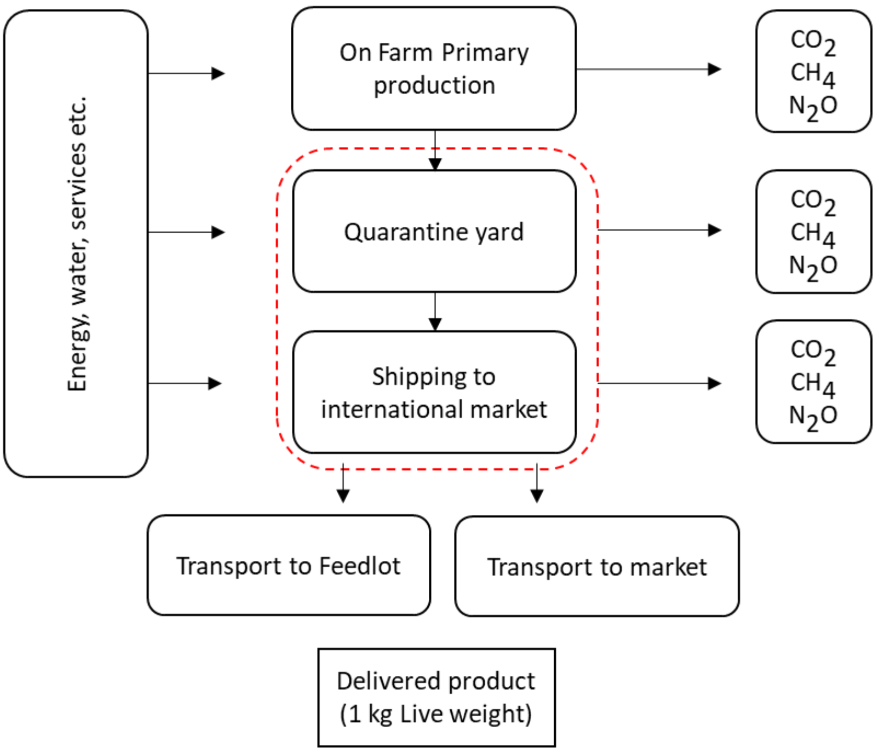


Figure 10 Live export supply chain system boundary. Dotted line indicates the boundary of the foreground system and study focus

For the purpose of the carbon account, emissions were disaggregated into scope 1, 2 and 3 (*Table 11*) sources according to the GHG Protocol (Ranganathan et al., 2004). These emission sources are described as follows:

- Scope 1: "Direct GHG emissions occur from sources owned or controlled by the company".
- Scope 2: "Accounts for GHG emissions from the generation of purchased electricity consumed by the company."
- Scope 3: "Are a consequence of the activities of the company but occur from sources not owned or controlled by the company. Some examples of Scope 3 activities are extraction and production of purchased materials; transportation of purchased fuels; and use of sold products and services." These can be further broken down into two sources:
  - > Upstream emissions: from pre-farm sources such as the production of purchased grain, manufacturing of chemicals, purchased livestock emissions and the burning of fossil fuels, including the extraction, production and transport of fuel and electricity. These sources were included in the present analysis.
  - > Downstream emissions: are post-farm emissions associated with retail of boxed beef products, including emissions from transportation and distribution. These sources were included in the present analysis.

Table 11. Summary of data sources for the stages of the supply chain

Stage of the primary production supply chain	Data source
Quarantine yard operation (sheep or cattle) (Scope 1 & 2)	Data obtained from industry survey
Feed for quarantine yards and shipping voyage (Scope 3)	Data obtained from industry survey
Transport from quarantine yards to port (Scope 3)	Data obtained from industry survey
Shipping from port to destination country (sea and air) including return voyage (Scope 1 & 2)	Data obtained from industry survey
Indonesian feedlot finishing (cattle) (Scope 3 downstream)	Data obtained from industry specialists

2.3. Inventory data

Detailed production data, livestock inventories and input data were collected and modelled from surveys, industry reports and publicly available export data (ABARES, 2024a) using the Integrity Ag iVCF model. Breeder cattle were modelled as beef breeders. No data were available to quantify the impacts of dairy breeders.

Major energy inputs at the quarantine yards were mainly related to diesel for vehicle operation, including pen cleaning and feed delivery. Data from quarantine yards, including energy use, were determined through industry surveys and targeted site visits. Inventory data for the Indonesian feedlots was sourced from an industry expert. .

Livestock inventory data for cattle at backgrounding, quarantine yards, shipping journey, and the Indonesian feedlot are provided in *Table 12, Table 13*, *Table 14* and *Table 15*, and sheep inventory data for GHG emissions at quarantine yards and shipping are provided in *Table 16* and *Table 17*.

Table 12. Key parameters for the cattle inventory for on-farm production (breeding/backgrounding) up to the point of cattle arriving at quarantine yards for CY23

Site identification	Portland to China - Breeder cattle by sea	Fremantle to Israel - Feeder cattle by sea	Darwin to Indonesia - Feeder cattle by sea	Townsville to Vietnam – Slaughter cattle by sea	Sydney to Malaysia - Breeder cattle by air	Average
Livestock data						
Livestock number (head)	50,000	27,490	388,544	60,397	5,000	531,431
Average daily gain (ADG) (kg day^{-1})	0.73	0.42	0.42	0.50	0.38	0.46
Closing LW (kg)	280	350	345	556	409	378
Weaning rate (%)	85%	84%	65%	65%	65%	67%
Cow weight (kg)	482	462	421	490	490	440

[1]Total livestock head number across all sites (not average).

Table 13. CY 23 cattle inventory data for quarantine yard

Site identification	Portland to China - Breeder cattle by sea	Fremantle to Israel - Feeder cattle by sea	Darwin to Indonesia - Feeder cattle by sea	Townsville to Vietnam – Slaughter cattle by sea	Sydney to Malaysia - Breeder cattle by air	Average
Livestock data						
Livestock number (head)	50,000	27,490	388,544	60,397	5,000	531,4311
Days on feed (DOF) (days)	35	5	5	5	11	7
Entry weight (kg)	280	350	345	556	409	377
Exit weight (kg)	298	353	347	558	415	381
Total LW gain in quarantine yard (kg)	875,000	68,725	935,281	140,926	28,000	2,047,9323
Feed data						
Feed intake (dry matter intake [DMI] kg head^{-1} day^{-1})	6.7	7.8	7.7	11.0	8.7	8.2
Feed conversion ratio (FCR)	13.3	15.6	15.4	21.9	17.5	16.4
Crude protein (CP) (% of DM)	10%	10%	10%	10%	10%	10%

[1]Total livestock head number across all sites (not average).
[2]Total LW sold across all sites (not average).
[3]Total LW gain in quarantine yard across all sites (not average).

Weight gain, based on survey data, was 0.5 kg LW day^{-1} in the quarantine yards, and weight gain was zero during transport.

Table 14. CY 23 cattle inventory data for sea/air freight

Site identification	Portland to China - Breeder cattle by sea	Fremantle to Israel - Feeder cattle by sea	Darwin to Indonesia - Feeder cattle by sea	Townsville to Vietnam - by sea	Sydney to Malaysia - Breeder cattle by air	Average
Livestock data						
Livestock number (head)	50,000	27,490	388,544	60,397	5,000	531,431[1]
DOF (days)	11	15	6	11	1	8
Entry weight (kg)	300	365	356	566	420	389
Exit weight (kg)	300	365	356	566	420	389
Feed data						
Feed intake (DMI kg head^{-1} day^{-1})	6.8	7.9	7.8	11.0	NA	8.2
CP (% of DM)	10%	10%	10%	10%	NA	10%

[1]Total livestock head number across all sites (not average).

Table 15. CY 23 cattle inventory data for Indonesian feedlot

Activity data	Average
Livestock data	
DOF (days)	100
Entry weight (kg)	354
Exit weight (kg)	504
ADG (kg day^{-1})	1.5
Feed data	
Feed intake (DMI kg head^{-1} day^{-1})	8.9
FCR	6.0
CP (% of DM)	14%

Table 16. CY 23 sheep inventory data for quarantine yard

Site identification	Fremantle to Israel - Feeder sheep by sea	Fremantle to Kuwait - Feeder sheep by sea	Sydney to Malaysia – Feeder sheep by air	Average
Livestock data				
Livestock number (head)	16,000	271,152	15,000	302,152[1]
DOF (days)	12	12	2	12
Entry weight (kg)	50	53	35	52
Exit weight (kg)	51	54	35.1	53
ADG (kg day^{-1})	0.08	0.08	0.05	0.08
Total LW sold (kg)	816,000	14,642,208	526,500	15,984,708[2]
Total LW gain in quarantine yard (kg)	16,000	271,152	1,500	288,652[3]
Feed data				
Feed intake (DMI kg $head^{-1}$ day^{-1})	1.3	1.3	1.3	1.3
FCR	15.1	15.1	25.2	15.5
CP (% of DM)	11%	11%	11%	11%

Table 17. CY 23 sheep inventory data for sea/air freight

Site identification	Fremantle to Israel - Feeder sheep by sea	Fremantle to Kuwait - Feeder sheep by sea	Sydney to Malaysia – Feeder sheep by air	Average
Livestock data				
Livestock number (head)	16,000	271,152	15,000	302,152[1]
DOF (days)	22	17	1	17
Entry weight (kg)	51.0	54.0	35.1	53.2
Exit weight (kg)	52.1	56.0	35.1	55.1
ADG (kg day^{-1})	0.05	0.12	0.01	0.11
Feed data				
Feed intake (DMI kg $head^{-1}$ day^{-1})	1.3	1.3	0.4	1.2
CP (% of DM)	11%	11%	11%	11%

[1]Total livestock head number across all sites (not average).

2.4. Scope 1 & 2 emissions estimation

GHG emissions were modelled by region for livestock emissions (enteric CH_4 and manure) and purchased inputs (fuel, electricity, feed, cattle, etc.) throughout the supply chain. Manure emissions were determined using methods outlined in the NIR (Commonwealth of Australia, 2024).

The study determined feed intake from the grazing herd using the method of Minson & McDonald (1987) while quarantine yard and Indonesian feedlot feed intakes were determined from surveys.

Enteric methane, manure methane and manure nitrous oxide in the Indonesian feedlot were determined based on cattle kept under cover with bedding that was removed frequently. Emissions were determined using methods from the IPCC (2019); enteric methane was 21 g CH_4 kg DMI (based on a ration with >15% roughage), manure methane MCF was 18% and nitrous oxide was 0.01. Manure emission factors reflected conditions where cattle were kept under cover with bedding, where bedding was removed at frequencies <1 month and bedding was not actively mixed.

2.5. Handling co-production

Farm services and purchased inputs associated with multiple enterprise systems (cattle, sheep and cropping) were subdivided, and inputs associated with crop production and sheep were excluded following recommendations from ISO 14044 (ISO, 2006) and as applied in previous studies (Wiedemann et al., 2019; Wiedemann, McGahan, et al., 2015). Allocation in the sheep breeding flock between live weight and wool, prior to live export, was handled using biophysical allocation based on protein mass (Wiedemann et al. 2015). The functional unit of the study did not differentiate between cattle from different animal classes. Consequently, allocation was not required within the cattle herd. Manure nutrients from the grazing herd were assumed to return directly to pasture and were considered as a biological feedback loop without the need for allocation. Manure nutrients from quarantine and feedlot manure were treated as residuals, following guidance from LEAP (FAO, 2016).

2.6. Scope 3 emissions estimation

Scope 3 fuel and electricity emissions were determined using the National Greenhouse Accounts (Commonwealth of Australia, 2021). Other factors associated with inputs utilised life cycle inventory (LCI) data from the Australian LCI database (Life Cycle Strategies, 2015), published literature and the Integrity Ag database. The LCA modelling was conducted using SimaPro v9.4 (PréConsultants, 2021). Specific details for major scope 3 emission sources are detailed below.

2.6.1. Scope 3 livestock emissions

Upstream scope 3 sheep emissions were modelled using the methods outlined in section 2.4, using data from WA sheep and cattle studies (Wiedemann et al., 2022). Scope 3 emissions associated with feeder cattle were assessed using the Integrity Ag Verified Carbon Footprint model (iVCF), which applied methods published in Wiedemann et al. (2015) which were consistent with the methods of the ABSF benchmark.

Downstream emissions from the transport of purchased inputs and livestock were included using known or estimated transport distances. Relevant steps in the supply chain relating to downstream scope 3 emissions of the feedlot 'finishing' market in Indonesia were also assessed. This included data related to operations, transport from port to feedlot, feed type and energy use. The building of infrastructure, veterinary medicines and pesticides were excluded.

2.7. Freshwater consumption

Water was assessed using the Freshwater Consumption indicator, which considered water from fresh sources that was consumed through use, either via evaporation, incorporated into a product or removal from the catchment where it was extracted (ISO 14046). Freshwater consumption methods were applied following previous red meat studies (Wiedemann, Henry, et al., 2015) and are briefly described here.

Drinking water for grazing cattle was estimated using the prediction equation derived from CSIRO (CSIRO, 2007) as applied by (Ridoutt et al., 2011) which is based on LW, feed intake, moisture content of feed and ambient temperature. Drinking water requirements for feedlot cattle were determined from feed intake and ambient temperature using Winchester & Morris (1956). Drinking water supply loss rates were determined for different sources and evaporation losses from farm dams were estimated using the methods of Wiedemann et al. (2015). Sheep drinking water and supply losses were estimated using the methods in Wiedemann et al. (2016). Irrigation water use and supply losses were minimal and were determined for cattle using methods previously applied (Wiedemann, Henry, et al., 2015), with data updated to the most recent release. No irrigation was used in the WA sheep supply chain.

2.8. Baseline recalculation

The results presented by S. J. Eady (2011) were recalculated using AR6 GWP_{100} values (27 for biogenic CH_4 and 273 for N_2O), as per the GWP values at the time of this study. Recalculations were made of cattle enteric methane, which was subsequently updated, and impacts from savanna burning were removed as this was methodologically different to the current study. Sheep results were more difficult to re-analyse because of the different allocation method for farm gate production. A revised value was calculated using Wiedemann et al. (2022b) which reported 2005 and 2020 results for the total WA industry. The 2005 and 2020 values were averaged to provide an indicative 2010 value, which was methodologically consistent with the current study.

Table 18. Revised cattle carbon footprint results from Eady 2011 with recalculated AR6 values and revised methods for enteric methane

	Original study reported value	Updated GWP, revised enteric methane formula, excl. savanna burning
Feeder cattle – farm gate – kg CO_2-e kg LW	31.5	22.2
Feeder cattle – destination port – kg CO_2-e kg LW	32.1	22.8
Finished cattle – ex feedlot – kg CO_2-e kg LW	26	19.6

Table 19. Revised sheep carbon footprint results with farm-gate results from Wiedemann et al. (2022b)

	Original study reported value	Updated GWP, updated farm gate result derived from Wiedemann et al. (2022b)
Sheep – farm gate – kg CO_2-e kg LW	5.5	7.6
Sheep – destination port – kg CO_2-e kg LW	7.4	9.5

3. Results

3.1. GHG emissions

3.1.1. Primary production – scope 3

The CF for cattle to the point of leaving the grazing property (excl. LU and dLUC) varied between the different supply chains based on the source regions and specifications of the cattle required in these markets. Impacts tended to be higher in the northern export regions though the overall range was not large (*Table 20*). Sheep impacts prior to live export were 8.2 kg CO_2-e kg LW^{-1} and this value was used for all sheep exported from WA.

Table 20. Carbon footprint for cattle closed out from backgrounding (to the point of leaving the grazing property)

Gas	Portland to China - Breeder cattle by sea	Fremantle to Israel - Feeder cattle by sea	Darwin to Indonesia - Feeder cattle by sea	Townsville to Vietnam – Slaughter cattle by sea	Sydney to Malaysia - Breeder cattle by air	Average
Carbon dioxide	3%	2%	2%	2%	5%	2%
Nitrous oxide	10%	9%	6%	6%	10%	6%
Methane	85%	89%	93%	93%	83%	92%
Remaining substances	1%	0%	0%	0%	2%	0%
Carbon footprint (kg CO_2-e kg LW^{-1})	**14.4**	**15.4**	**17.0**	**15.6**	**16.5**	**16.5**

3.1.2. Quarantine yard – scope 1 and 2

The emissions from cattle in the quarantine yard (*Table 21*) were reported per hdd^{-1}, as a means of describing impacts on a normalised basis between different quarantine yards. Emissions were primarily explained by feed consumption (DMI) and ADG. Animal performance was lower than typical confinement feeding (feedlots) because quarantine yards were not production feeding the cattle, and the duration in the yard was short.

Table 21. Scope 1 & 2 emission intensity and emissions per hdd^{-1} for cattle at quarantine yard in CY 23

Gas	Portland to China - Breeder cattle by sea	Fremantle to Israel - Feeder cattle by sea	Darwin to Indonesia - Feeder cattle by sea	Townsville to Vietnam – Slaughter cattle by sea	Sydney to Malaysia - Breeder cattle by air	Average
Carbon dioxide	11%	10%	10%	9%	9%	10%
Nitrous oxide	9%	8%	8%	8%	9%	8%
Methane	80%	82%	81%	83%	82%	82%
Remaining substances	0%	0%	0%	0%	0%	0%
Emissions (kg CO_2-e hdd^{-1})	**4.8**	**5.5**	**5.5**	**7.6**	**6.2**	**5.8**

3.1.3. Shipping & transport – scope 1 and 2

The emissions per hdd^{-1} from cattle during the shipping journey were high due to significant shipping fuel inputs (*Table 22*). Emission intensities were not calculated because there was no live weight gain. Fremantle to Israel had the highest emissions due to having the longest journey compared to the other consignments.

Table 22. Scope 1 & 2 emissions per hdd^{-1} for cattle during shipping journey in CY 23

Gas	Portland to China - Breeder cattle by sea	Fremantle to Israel - Feeder cattle by sea	Darwin to Indonesia - Feeder cattle by sea	Townsville to Vietnam – Slaughter cattle by sea	Sydney to Malaysia - Breeder cattle by air	Average (sea-only)
Carbon dioxide	83%	82%	71%	75%	99%	73%
Nitrous oxide	3%	3%	5%	5%	0%	5%
Methane	13%	14%	24%	21%	1%	22%
Emissions (kg CO_2-e hdd^{-1})	**34.9**	**37.7**	**21.2**	**34.9**	**2,424.9**	**25.4**

Most emissions during the shipping journey for sheep arose from fuel, with smaller contributions from livestock emissions. Air freighted sheep had much higher emissions than sheep on ships due to the very large amounts of fuel used for air transport and the relatively smaller number of sheep on a plane compared to a ship.

Table 23. Scope 1 & 2 emissions for sheep during the shipping journey in CY 23

Gas	Fremantle to Israel – Feeder sheep by seat	Fremantle to Kuwait - Feeder sheep by sea	Sydney to Malaysia – Slaughter sheep by air
Carbon dioxide	84%	88%	99%
Nitrous oxide	2%	1%	0%
Methane	14%	10%	1%
Emissions (kg CO_2-e hdd^{-1})	**5.9**	**8.3**	**202.8**

3.1.4. Quarantine yard & shipping journey – scope 1 and 2

The emissions for cattle at both the quarantine yard and during the shipping journey are provided in *Table 24*, where results are proportional to ADG and shipping input impacts. The emission intensity for cattle during the quarantine yard and shipping journey (LWG) was high and varied significantly depending on the length of the journey. Because LWG was relatively low through export (quarantine yard to destination port), the longer duration journeys resulted in high emission intensities. These were not highly material once calculated on a CF basis because of the relatively small portion of the animal's life spent in transit.

Variation in impacts was also reasonably high on a per hdd^{-1} basis, and this arose from differences in fuel use efficiency between ships used on the different routes, and to a lesser extent from variation in the amount of feed fed per day. Cattle on the Vietnam route, for example, were heavier than other cattle and required more feed per day and more pen area per animal, resulting in higher emissions on a per hdd^{-1} basis. Impacts on the Israel route were influenced by higher fuel use.

Table 24. Scope 1 & 2 emissions for cattle at the quarantine yard and during the shipping journey in CY 23

Gas	Portland to China - Breeder cattle by sea	Fremantle to Israel - Feeder cattle by sea	Darwin to Indonesia - Feeder cattle by sea	Townsville to Vietnam – Slaughter cattle by sea	Sydney to Malaysia - Breeder cattle by air
Carbon dioxide	61%	79%	61%	69%	98%
Nitrous oxide	5%	4%	6%	5%	0%
Methane	34%	17%	33%	26%	1%
Emissions (kg CO_2-e hdd^{-1})	**12.0**	**29.7**	**14.4**	**26.7**	**7,820.6**

The emissions for sheep in the quarantine yard and during the shipping journey combined are provided in *Table 25*.

Table 25. Scope 1 & 2 emission intensity and emissions per hdd^{-1} and LWG for sheep at quarantine yard and during shipping journey in CY 23

Gas	Fremantle to Israel - Feeder sheep by sea	Fremantle to Kuwait - Feeder sheep by sea	Sydney to Malaysia – Slaughter sheep by air
Carbon dioxide	80%	80%	98%
Nitrous oxide	2%	2%	0%
Methane	17%	17%	1%
Emissions (kg CO_2-e hdd^{-1})	**5.0**	**4.7**	**228.6**

3.1.5. Supply chain to destination port - carbon footprint (scope 1, 2, 3)

The CFs for cattle and sheep at arrival to export destination are provided in *Table 26* and *Table 27* respectively, where both cattle and sheep transported by air have the highest CFs due to significant fuel inputs. Variation in other markets was most strongly influenced by source livestock region and stage in the production cycle; lighter feeder cattle had higher impacts than cattle that were closer to slaughter weight, for example in the Vietnam market.

There was a substantial degree of variation between the cattle routes that used shipping with respect to the contribution of emissions to the life cycle, from 3-13% for ship routes and 27% for air freight routes. This was largely in response to differences in the length of the journey, with the Portland to China route having the longest distance and highest impacts, and Darwin to Indonesia having the shortest route and lowest impacts. Impacts were far higher from air freight resulting in a higher proportion of GHG emissions in the livestock export process.

Table 26. Carbon footprint for cattle at arrival to export destination in CY 23

Gas	Portland to China - Breeder cattle by sea	Fremantle to Israel - Feeder cattle by sea	Darwin to Indonesia - Feeder cattle by sea	Townsville to Vietnam – Slaughter cattle by sea	Sydney to Malaysia - Breeder cattle by air	Average
Primary production	87%	90%	97%	96%	73%	96%
Quarantine yard/ shipping/air	13%	10%	3%	4%	27%	4%
Carbon footprint (kg CO_2-e kg LW^{-1})	**15.3**	**16.4**	**17.1**	**16.1**	**21.1**	**16.8**

Impacts in sheep were similar for the sea routes and significantly higher for air freight (*Table 27*). The large contribution from the primary production stage decreased the scale of impacts in shipping and quarantine handling.

Table 27. Carbon footprint for sheep at arrival to export destination in CY 23

Process	Fremantle to Israel - Feeder sheep by sea	Fremantle to Kuwait - Feeder sheep by sea	Sydney to Malaysia – Slaughter sheep by air	Average
Primary production	75%	75%	63%	75%
Quarantine yard / shipping/ air	25%	25%	37%	25%
Carbon footprint (kg CO_2-e kg LW^{-1})	**10.6**	**10.5**	**13.1**	**10.6**

3.1.6. Case study – feedlot finishing of cattle in Indonesia

To provide further insight into the full supply chain, a case study was included of feedlot finishing in the Indonesian market, which is a key market for northern cattle. Impacts during feeding and for finished cattle are shown in the next two tables.

Table 28. Scope 1 & 2 emission intensity for cattle at Indonesian feedlot in CY 23

Gas	Indonesian feedlot cattle
Carbon dioxide	26%
Nitrous oxide	18%
Methane	56%
Emission intensity (kg CO_2-e kg LWG^{-1})	**7.8**

Impacts for cattle finished from the feedlot are shown in

Table 29. This showed a significant reduction in CF after feedlot finishing, resulting in impacts that were more similar to cattle finished in Australia. The carbon footprint for cattle exiting the Indonesian feedlot was 14.3 kg CO_2-e/kg LW (Table 29). For comparison, the Australian average for slaughter cattle is ~12.8 kg CO_2-e/kg LW (Wiedemann et al. 2023), meaning the Indonesian result was approximately 12% higher. This is not a direct like-for-like comparison, as the Indonesian figure incorporates the export leg while the Australian slaughter average does not.

Table 29. Carbon footprint for cattle exiting Indonesian feedlot in CY 23

Stage	Indonesian feedlot cattle (Finished)
Primary production	82%
Quarantine yard and shipping	2%
Indonesian feedlot	15%
Residual	1%
Carbon footprint (kg CO_2-e kg LW^{-1})	**14.3**

3.2. Freshwater consumption

3.2.1. Quarantine yard and shipping journey

Freshwater consumption results for cattle during quarantine yard and shipping are provided in *Table 30*. Air freight results are not included due to the short flight journey and subsequent negligible freshwater consumption. Freshwater consumption was negligible on the ship, because all water was supplied via desalination and saltwater was not included in the freshwater consumption indicator.

Table 30. Freshwater consumption for cattle during quarantine yard & shipping in CY 23 (hdd^{-1})

	Portland to China - Breeder cattle by sea	Fremantle to Israel - Feeder cattle by sea	Darwin to Indonesia - Feeder cattle by sea	Townsville to Vietnam – Slaughter cattle by sea
Drinking water	98.9%	99.5%	99.6%	99.6%
Other	1.1%	0.5%	0.4%	0.4%
Freshwater consumption (L hdd^{-1})	**15.2**	**36.5**	**34.3**	**35.7**

Freshwater consumption results for sheep during quarantine yard and shipping are provided in *Table 31*.

Table 31. Water consumption for sheep during quarantine yard & shipping in CY 23 (hdd^{-1})

Process	Fremantle to Israel - Feeder sheep by sea	Fremantle to Kuwait - Feeder sheep by sea
Drinking water	99.6%	99.4%
Other	0.4%	0.6%
Freshwater consumption (L hdd^{-1})	**7.2**	**8.4**

3.2.2. Supply chain to destination port – life cycle impacts

Freshwater consumption results for cattle and sheep at arrival to export destination are provided in *Table 32* and Table 33.

Table 32. Freshwater consumption for cattle at arrival to export destination in CY 23

	Portland to China - Breeder cattle by sea	Fremantle to Israel - Feeder cattle by sea	Darwin to Indonesia - Feeder cattle by sea	Townsville to Vietnam – Slaughter cattle by sea	Sydney to Malaysia - Breeder cattle by air
Drinking water - primary production	57%	60%	60%	60%	55%
Drinking supply losses -primary production	38%	40%	40%	40%	36%
Freshwater use - Quarantine/shipping/air	4%	1%	0%	0%	9%
Freshwater consumption (L kg LW^{-1})	**144**	**160**	**186**	**170**	**176**

Table 33. Freshwater consumption for sheep at arrival to export destination in CY 23

Process	Fremantle to Israel - Feeder sheep by sea transport	Fremantle to Kuwait - Feeder sheep by sea transport	Sydney to Malaysia – Slaughter sheep by air
Freshwater use – primary production	98.4%	98.7%	99.4%
Freshwater use – quarantine/shipping/air	1.6%	1.3%	0.6%
Freshwater consumption (L kg LW^{-1})	**182**	**179**	**187**

3.3. Fossil fuel energy

3.3.1. Quarantine yard and shipping journey

Energy results for cattle and sheep during quarantine yard and shipping are provided in *Table 34* and

Table 35. For both cattle and sheep, most energy was associated with transport fuel during shipping.

Table 34. Energy breakdown for cattle during quarantine yard & shipping in CY 23 (hdd^{-1})

	Portland to China - Breeder cattle by sea	Fremantle to Israel - Feeder cattle by sea	Darwin to Indonesia - Feeder cattle by sea	Townsville to Vietnam – Slaughter cattle by sea	Sydney to Malaysia - Breeder cattle by air
Fossil energy demand (MJ LHV kg hdd^{-1})	**102.2**	**330.7**	**116.7**	**250.0**	**2,496.3**

Table 35. Energy breakdown for sheep during quarantine yard & shipping in CY 23 (hdd^{-1})

Process	Fremantle to Israel - Feeder sheep by sea	Fremantle to Kuwait - Feeder sheep by sea	Sydney to Malaysia – Slaughter sheep by air
Fossil energy demand (MJ LHV kg hdd^{-1})	**59.2**	**56.1**	**3,385.8**

3.3.2. Supply chain to destination port – life cycle impacts

Energy results for cattle and sheep for the whole supply chain to arrival at export destination are provided in *Table 36* and *Table 37*, respectively. Energy results for cattle and sheep for the whole supply chain are the highest for Sydney to Malaysia due to the substantial energy demand required in air freight.

Table 36. Energy breakdown for cattle at arrival to export destination in CY 23

	Portland to China - Breeder cattle by sea	Fremantle to Israel - Feeder cattle by sea	Darwin to Indonesia - Feeder cattle by sea	Townsville to Vietnam – Slaughter cattle by sea	Sydney to Malaysia - Breeder cattle by air
Primary production	41%	30%	59%	45%	15%
Quarantine yard/shipping/air	59%	70%	41%	55%	85%
Fossil energy demand (MJ LHV kg LW^{-1})	**23.5**	**22.6**	**8.3**	**11.4**	**85.3**

Table 37. Energy breakdown for sheep at arrival to export destination in CY 23

Process	Fremantle to Israel - Feeder sheep by sea	Fremantle to Kuwait - Feeder sheep by sea	Sydney to Malaysia – Slaughter sheep by air
Primary production	30%	29%	13.9%
Quarantine yard/shipping/air	69%	71%	86%
Fossil energy demand (MJ LHV kg LW^{-1})	**42.6**	**44.2**	**83.1**

4. Discussion

The livestock export industry represents a small but vital segment of the supply chain including quarantine facilities and shipping. Carbon impacts during these stages were dominated by livestock emissions, which was similar to other stages of the supply chain such as production feedlots (Wiedemann et al. 2017). Shipping contributed substantial energy related impacts, but for sea freight these remained lower than livestock related emissions. In contrast, air freight used very large amounts of fossil fuel energy and had high GHG emissions from these sources due to the very large fuel requirements for planes for the relatively small number of livestock compared to ships.

Live export is an important market particularly for sheep in WA and cattle across northern Australia. The system extends primary production beyond Australia's shores and enables finishing and processing to occur close to market, in much the same way as the domestic beef feedlot and processing sector operates in Australia. In the cattle export market to Indonesia, this represents an environmentally efficient production system, and in the present case study of feedlot finished cattle in Indonesia, resulted in impacts that were not substantially higher than the average of slaughter ready cattle in Australia.

4.1. Comparison to the baseline study

In the present study, sheep impacts ranged from 10.5 – 10.6 kg CO_2-e kg LW^{-1} for sheep transported to the ME. After adjusting the previous study results to account for different GWP values and different farm-gate methods, the estimated increase in impacts was 10%. Impacts were higher than the previous study, partly because of reported increases in farm-gate impacts and partly because of increased impacts from shipping.

With respect to the farm-gate stage, the LCA for sheep production in WA(Wiedemann et al., 2022) found that CF to farm gate increased from 2005 to 2020 (Wiedemann et al., 2022). This was associated with reported intensification of the production system through the use of more supplementary feed, but without corresponding increases in livestock performance. This resulted in an estimated 5% increase in farm-gate impacts between the two reporting time periods.

Differences in impacts during the livestock export phase were principally driven by changes to regulations which resulted in reduced stocking density on ships compared to the 2011 study and correspondingly increased energy and GHG for transport. This result highlighted the important interplay between requirements for animal welfare and the impact of these on environmental performance and demonstrated that trade-offs exist between stocking rate and shipping efficiency.

Results for cattle showed a larger contrast. At the destination port, feeder steers into the Indonesian market had an estimated 17.1 kg CO_2-e kg LW^{-1} in the present study compared to 22.8 kg CO_2-e kg LW^{-1} in the previous study, when updated with revised GWP_{100} values and revised calculation methods. This 25% reduction in impacts arose because of improved performance in the grazing herds supplying feeder cattle and decreases in emission intensity during live export.

There have been substantial productivity improvements in northern herds in the past decade as a result of investment in property infrastructure, management, and genetics, resulting in substantial estimated improvements in performance. This noted, the present study relied on estimated animal age at induction into quarantine yards and uncertainty remains around the cattle performance assumptions. Herd performance in the present analysis, which included all northern live export regions, was 10% better than results for the Kimberley region of WA published by Wiedemann et al. (2023). Considering the current study had a larger draw region, the difference may be related to better performance across the whole live export region. However, there was insufficient primary data in the present study to be confident of this.

Nonetheless, the improvements related to productivity and efficiency for feeder cattle were substantial and resulted in a more rapid rate of reduction than the herd destined for slaughter in Australia achieved over the decade from 2010 to 2020 (see Wiedemann et al. 2023). Further primary data collection is warranted to improve this estimate and confirm the rapid rate of reduction in impacts in this sector of the industry.

Impacts during live export were lower than previously estimated, largely because of more efficient production. Based on survey responses, cattle were estimated to gain weight at 0.5 kg day^{-1} in quarantine yards in the present study but were assumed to have no weight gain in the previous study. This resulted in higher turnoff weight in the present study for a similar level of inputs, reducing emission intensity. Energy related inputs were also lower in shipping, which contributed to the lower impacts. On a per head day basis, these reductions were estimated to be 30% compared to the previous study.

No other studies were found in the literature assessing the impact of air freight. Comparing air freight and sea freight revealed very large increases in impacts for both CF and fossil energy demand for air freight, because of the very large fuel requirements for planes for the relatively small number of livestock compared to ships. In contrast, the short flight journey required minimal feed and freshwater inputs and generated low levels of animal emissions compared to sea consignments. Nonetheless, overall impacts were much higher on a per head day basis and contributed to about 26% higher carbon footprints for cattle at the destination port, compared to sea freight.

The CF for cattle exiting the Indonesian feedlot ready for slaughter (14.3 kg CO_2-e kg LW^{-1}) was substantially lower than the CF calculated by S. J. Eady (2011) (19.6 kg CO_2-e kg LW^{-1} with revised GWP_{100} values and revised calculation methods). In addition to the lower impacts for feeder cattle, already described, the feedlot had lower methane and manure related emissions, and slightly better ADG and feed conversation, resulting in lower emissions. In the present study manure was managed with bedding which was cleaned out about every 15 days. The estimated methane emissions were high by comparison to Australian feedlots but still substantially lower than the previous study where a large proportion (32%) of manure was assumed to be treated in an effluent pond. Some differences in performance and manure management may be site-specific, reflecting different feedlots being assessed in each case study and for this reason the feedlot results should not be considered representative. The significance of manure emissions to total emissions, and the variation that could exist under different treatment systems, was notable and should be carefully evaluated if future studies aim to determine representative impacts for all of Indonesia.

4.2. Comparison to Australian slaughter cattle

Few studies have examined the primary production systems supporting live export in Australia. The previous study by S. J. Eady (2011) analysed feeder cattle supplied to Indonesia, and Wiedemann et al. (2023) analysed feeder cattle from the Kimberley. The present study assessed cattle across northern Australia from multiple regions. Generally, impacts from these production regions are higher than southern Australia. However, as noted by Wiedemann et al. (2023), the comparison has not been made on like terms. Feeder cattle are traded at a lower turnoff weight than slaughter cattle, and this results in higher carbon footprints per kilogram of live weight. For this reason, impacts decrease between feeder weight and finished weight in the current study, the previous study and the scenarios analysed by Wiedemann et al. (2023). Because there are no processing facilities consistently operating in northern Australia and the young cattle produced are not slaughter ready, all cattle must be transported from these regions for finishing, either via sea freight, or via long-distance road transport. To compare impacts, this study examined transporting a feeder steer from Katherine, NT, to Indonesia via sea freight, or to Dalby, QLD which is a major feedlot finishing region in Australia.

The impact of transporting to an overseas market contributed 4% to total impacts for a feeder steer. By comparison, transporting the same animal by truck to southern Queensland for finishing increased emissions by slightly over 2%. Transporting via live export had higher impacts but this was not substantial over the life cycle.

True comparison of the supply chains would need to consider cattle at point of exit from the feedlot, or more correctly, boxed product in the destination market.

Results at exit from the feedlot in the present study were slightly better than Wiedemann et al. (2023) who assessed the impact of transporting steers to feedlots from the Kimberley to southern WA and found impacts of 15.5 kg CO_2-e kg LW^{-1} (adjusted to AR6 GWPs).

To create a truly comparative supply chain, this would need to extend to production of boxed product via both supply chains, with transport of the product from Australia as boxed meat into the Indonesian market, to take into account subsequent transport to the same location. It would be beneficial in the future to assess full supply chain impacts for boxed product in major markets to provide a more complete evaluation of the efficiency of the production system.

4.3. Improvement options

Within the livestock export sector, opportunities exist to reduce GHG emissions through improved feeding and potentially via emission reducing supplements. Research in the Australian feedlot sector has shown reductions in scope 1 and 2 emissions by more than 50% (Lawrence et al., 2024) were achieved through feeding Bovaer. Reductions could also be achieved by feeding higher oil content rations (Almedia et al., 2025). These options are able to be readily adopted in the livestock export sector because livestock are fed a mixed ration while in the quarantine yards and on the ship. It is reasonable to expect emissions could be reduced by a maximum of 40% through these strategies. However, these options are not currently cost-effective and are not likely to be implemented without a shift in market expectations and demand for lower emissions livestock.

The projected improvement in the northern breeding herd for the present study was significant. While scope 3 emissions assessment was not a major focus in the study, the results suggested an important trend towards improved performance. Herd improvement has been a trend in the sector caused by multiple drivers, including the Beef Herd Management (BHM) ERF method, which has been adopted by some major live export herds such as those of Consolidated Pastoral Company and AA Co. This method encourages participants to lower herd emission intensity through improved infrastructure, genetics, nutrition and management. The present study was modelled from best-available data sources, but more primary data relating to the weight, age and sex of cattle sold for export is needed to establish a firm benchmark and determine variability across major draw regions.

5. Conclusions

5.1. Key findings

This study presented updated insights into the environmental performance of the livestock export sector in Australia. The carbon footprint for cattle were found to have decreased since the baseline study of Eady (2011) was conducted, both because of improved scientific knowledge regarding the enteric CH_4 production from northern cattle herds, and because of the better performance of northern cattle herds. In contrast, sheep impacts increased since the previous study, partly because of method differences, but also because of changed stocking rate requirements during live export by sea. This result highlighted the important interplay between requirements for animal welfare and the impact of these on environmental performance, and demonstrated that trade-offs exist between stocking rate and shipping efficiency.

Cattle results were most strongly influenced by herd efficiency in feeder cattle herds. When the results from this study are compared to the recent work in the Kimberley, WA by Wiedemann et al. (2023), impacts were estimated to be 10% lower across the northern live export herd than in the Kimberley, but caution should be used in interpreting the result. The present study was modelled from best-available data sources, but more primary data relating to the weight, age and sex of cattle sold for export is needed to establish a firm benchmark and determine variability across major draw regions.

Results from the case study of cattle fed in an Indonesian feedlot showed impacts were 12% higher than the average of slaughter ready cattle in Australia (when compared to the 2020 study used for the ABSF benchmark) which indicated northern herds utilising feedlot finishing in Asian countries can produce cattle with sound environmental performance, close to consumer markets that don't have reliable supply chains for chilled, boxed product. This supports the ongoing use of the supply chain.

Results from air freight livestock export showed that these impacts were much higher than sea freight, and environmental impacts would therefore be lower if sea freight was used.

If future market pressures promote lower emissions from the sector, technical options are available to reduce emissions through low CH_4 supplements that could be fed to sheep or cattle during live export. This could reduce emissions, though current costs will generally prohibit use until market demand and price expectations change to enable supplement use.

5.2. Benefits to industry

The benefits of conducting this study and achieving success against the strategic priority and objectives include:

- This study provided a comparable update to the previous study, where improved methods are now available to quantify impacts. The expanded datasets in this project provide more robust and recent information for benchmarking performance. This demonstrated that the industry is taking steps to address rapidly growing community expectations around environmental sustainability and the impact of climate change.
- The findings from this study provide an updated estimate of performance for the sector, which provide an industry benchmark and a platform for communicating environmental improvement credentials to banks, other institutions, and government.
- The study provided insights into the effect of animal welfare requirements and the interrelationship between these requirements and environmental impacts. In the case of sheep, impacts increased largely because of changes to stocking density requirements which reduced the efficiency of transport. This highlighted the important trade-offs that exist in supply chains between different objectives.
- This study supports the overall preparedness of the sector and major companies in providing environmental credentials to meet societal goals in the near future.

6. Future Research and Recommendations

The comprehensive benchmark provided by this study enables industry to explore options for improving its environmental impact, including the mitigation of GHG emissions. It is recommended that the product LCA is updated on a two or five yearly timeline to continue to provide accurate benchmarks to industry, which will be essential in tracking industry progress against Australia's ambitions for emission reduction and for production systems to uphold their social licence to operate.

The promising finding from the primary production (scope 3) assessment of live export cattle and the significant improvements over time warrant further study to support these findings with primary data collection for key inputs. Specifically, further information regarding the weight and age of cattle at induction into pre-export yards is needed to improve estimates, as is confirmation of breeding herd inventories. Further, information is needed regarding sex at point of induction to improve the herd model.

While this study improved the benchmark using a broader dataset from shipping than the previous study, it would be further strengthened with a larger dataset. This would also be improved by creating a data standard for the sector to make data collection and sectoral reporting a smooth and potentially automated approach.

Introducing livestock export indicators into the Australian Beef Sustainability Framework would be an excellent option to showcase the progress of the sector and to continue reporting progress. Considering the increased reporting frequencies and expectations of Government, society and other stakeholders, using a two-year reporting cycle would be warranted.

7. References

ABARES. (2024a, June). *Agricultural commodities: June quarter 2024*. Australian Bureau of Agricultural and Resource Economics and Sciences. https://doi.org/10.25814/g0cz-s307

ABARES. (2024b, July 5). *ABARES Trade dashboard*. Department of Agriculture, Fisheries and Forestry, Australian Bureau of Agricultural and Resource Economics and Sciences. https://www.agriculture.gov.au/abares/research-topics/trade/dashboard

ABSF. (2023). *Australian Beef Sustainability Annual Update*. https://www.sustainableaustralianbeef.com.au/globalassets/beef-sustainability/documents/absf-annual-update-2023-web.pdf

Albanese, A., & Bowen, C. (2022). Australia National Determined Contribution (NDC) Letter to UNFCCC. In *Official letter*. https://unfccc.int/sites/default/files/NDC/2022-06/NDC 2022 Update Letter to UNFCCC.pdf

Almedia, A. K., McMeniman, J. P., Van der Saag, M. R., & Cowley, F. C. (2025). Evaluation of methane prediction equations for Australian feedlot cattle fed barley and wheat-based diets . *Animal Production Science*, *65*. https://doi.org/10.1071/AN24212

BDO EconSearch. (2022). *Live dairy cattle export industry economic assessment A Report for the Livestock Export Program and Dairy Australia* (Vol. 61, Issue August).

Commonwealth of Australia. (2021). *Australia's National Greenhouse Accounts*. https://www.greenhouseaccounts.climatechange.gov.au/

Commonwealth of Australia. (2024). *National Inventory Report 2022 - Volume 1*. https://www.dcceew.gov.au/climate-change/publications/national-inventory-report-2022

Commonwealth of Australia. (2025). *National Inventory Report 2023 - Volume 1*. https://www.dcceew.gov.au/sites/default/files/documents/national-inventory-report-2023-volume-1.pdf

CSIRO. (2007). *Nutrient Requirements of Domesticated Ruminants* (M. Freer, Ed.). CSIRO publishing.

DAFF. (2023). *All livestock exports 2018-2023*. All Livestock Exports. https://www.agriculture.gov.au/biosecurity-trade/export/controlled-goods/live-animals/live-animal-export-statistics/livestock-exports-by-market

DCCEEW. (2025). *Net Zero*. https://www.dcceew.gov.au/climate-change/emissions-reduction/net-zero

Delgado, C., Rosegrant, M., Steinfeld, H., Ehui, S., & Courbois, C. (2001). Livestock to 2020: The Next Food Revolution. *Outlook on Agriculture*, *30*(1), 27–29. https://doi.org/10.5367/000000001101293427

Duver, A., Hogan, L., Gunning-trant, C., & Dahl, E. (2022). *Australia's biosecurity market access and agricultural exports Case study of cattle exports to ASEAN countries*. *April*. https://daff.ent.sirsidynix.net.au/client/en_AU/search/asset/1033443/0

Eady, S. J. (2011). Undertaking a life cycle assessment for the livestock export trade. In *Meat & Livestock Australia Limited: North Sydney, Australia*. Meat & Livestock Australia Limited (MLA).

Eady, S., Viner, J., & McDonnell, J. (2011). On-Farm Greenhouse Gas Emissions and Water Use: Case Studies in the Queensland Beef Industry. *Animal Production Science*, *51*(8), 667–681. https://doi.org/10.1071/AN11030

FAO. (2009). *How to Feed the World in 2050*. Food and Agriculture Organisation of the United Nations (FAO).

FAO. (2016). *Environmental performance of large ruminant supply chains: Guidelines for assessment*. Food and Agriculture Organization (FAO).

Hurst, P., Termine, P., & Karl, M. (2005). *Agricultural workers and their contribution to sustainable agriculture and rural development. FAO, Rome*.

IPCC. (2021). Climate Change 2021 – The Physical Science Basis. In *Climate Change 2021 – The Physical Science Basis* (p. 1017). Cambridge University Press. https://doi.org/10.1017/9781009157896

ISO. (2006). *ISO 14040: 2006 - Environmental management - Life cycle assessment - Principles and framework*. International Organisation for Standardisation (ISO).

Kennady, V., Chakraborty, S., Biswal, J., & Rahman, H. (2023). Sustainable Livestock Production: A Systematic Review of Different Constraints Associated with Sustainable Livestock Production. *European Journal of Agriculture and Food Sciences*, *5*(2), 1–11. https://doi.org/10.24018/ejfood.2023.5.2.663

Latino, L. R., Pica-Ciamarra, U., & Wisser, D. (2020). Africa: The livestock revolution urbanizes. *Global Food Security*, *26*, 100399. https://doi.org/10.1016/j.gfs.2020.100399

Lawrence, R., Loxton, I., Lisle, A., Shirley, D., & Doyle, J. (2024). *Effect of Bovaer®10 on performance, health, carcase characteristics and carbon footprint of Australian feedlot cattle*.

LEAP. (2015a). *Environmental Performance of Large Ruminant Supply Chains: Guidelines for Assessment*. Food and Agriculture Organization of the United Nations (FAO), Livestock Environmental Assessment Program (LEAP).

LEAP. (2015b). *Greenhouse Gas Emissions and Fossil Energy Use from Small Ruminant Supply Chains: Guidelines for Assessment*. Food and Agriculture Organization of the United Nations (FAO), Livestock Environmental Assessment Program (LEAP).

Life Cycle Strategies. (2015). *Australasian LCI database 2015*. Life Cycle Strategies Pty Ltd.

Minson, D., & McDonald, C. (1987). Estimating forage intake from the growth of beef cattle. *Tropical Grasslands*, *21*(3), 116–122.

MLA. (2020). *CN30 overview*. https://www.mla.com.au/research-and-development/Environment-sustainability/carbon-neutral-2030-rd/cn30/

MLA. (2025). *Strategic Plan 2030*.

Peters, G., Rowley, H., Wiedemann, S., Tucker, R., Short, M., & Schulz, M. (2010). Red Meat Production in Australia: Life Cycle Assessment and Comparison with Overseas Studies. *Environmental Science Technology*, *44*(4), 1327–1332. https://doi.org/10.1021/es901131e

Pré-Consultants. (2021). *SimaPro 9.3 Software*. Pré-Consultants.

Ranganathan, J., Corbier, L., Bhatia, P., Schmitz, S., Oren, K., Dawson, B., Spannagle, M., McMahon, M., Boileau, P., Frederick, R., Vanderborght, B., Thomson, F., Kitamura, K., Woo, C., Phankida, N., Miner, R., Segalen, L., Koch, J., Bhattacharjee, S., … Cook, E. (2004). *The greenhouse gas protocol: A corporate accounting and reporting standard*. World Business Council for Sustainable Development & World Resources Institute, Geneva.

Ridoutt, B. G., Sanguansri, P., Freer, M., & Harper, G. S. (2011). Water footprint of livestock: comparison of six geographically defined beef production systems. *The International Journal of Life Cycle Assessment*, *17*(2), 165–175.

RMAC. (2019). *Red Meat 2030*. Reat Meat Advisory Council (RMAC). https://www.flipsnack.com/BBB766ED75E/red-meat-2030-vt5ofslpma/full-view.html

Rojas-Downing, M. M., Nejadhashemi, A. P., Harrigan, T., & Woznicki, S. A. (2017). Climate change and livestock: Impacts, adaptation, and mitigation. In *Climate Risk Management* (Vol. 16, pp. 145–163). Elsevier B.V. https://doi.org/10.1016/j.crm.2017.02.001

Rosegrant, M. W., Fernández, M., Sinha, A., Alder, J., Ahammad, H., Fraiture, C. de, Eickhout, B., Fonseca, J., Huang, J., & Koyama, O. (2009). Looking into the future for agriculture and AKST. In R. T. McIntyre, B. D.; Herren, H. R.; Wakhungu, J.; Watson (Ed.), *International Assessment of Agricultural Knowledge, Science and Technology for Development (IAASTD): Agriculture at a Crossroads, global report.* (pp. 307–376). Island Press.

Wiedemann, S., Biggs, L., Watson, K., Gould, N., & McGahan, E. (2019). *Beef industry 35 year trends analysis*. Meat & Livestock Australia (MLA).

Wiedemann, S., Davis, R., McGahan, E., Murphy, C., & Redding, M. (2017). Resource use and greenhouse gas emissions from grain-finishing beef cattle in seven Australian feedlots: a life cycle assessment. *Animal Production Science*, *57*(6), 1149. https://doi.org/10.1071/AN15454

Wiedemann, S., Henry, B., McGahan, E., Grant, T., Murphy, C., & Niethe, G. (2015). Resource use and greenhouse gas intensity of Australian beef production: 1981-2010. *Agricultural Systems*, *133*, 109–118. https://doi.org/10.1016/j.agsy.2014.11.002

Wiedemann, S., & Longworth, E. (2021). *Pathways to carbon neutrality for Australian feedlots*. Meat & Livestock Australia (MLA).

Wiedemann, S., Longworth, E., & O'Shannessy, R. (2023). Net greenhouse-gas emissions and reduction opportunities in the Western Australian beef industry. *Animal Production Science*. https://doi.org/10.1071/AN23111

Wiedemann, S., McGahan, E., Murphy, C., & Yan, M.-J. (2015). Resource use and environmental impacts from beef production in eastern Australia investigated using life cycle assessment. *Animal Production Science*, *56*(5), 882–894. https://doi.org/10.1071/AN14687

Wiedemann, S., McRae, D., & Longworth, E. (2022). *An Industry Life Cycle Assessment for Sheep Production in Western Australia*. https://www.agric.wa.gov.au/

Wiedemann, S., Neale, L., & O'Shannessy, R. (2023). *Beef industry trends analysis - 2020*. https://www.mla.com.au/research-and-development/reports/2023/e.sub.0010---trends-analysis-of-the-australian-beef-industry-2020/

Wiedemann, S., Yan, M.-J., Henry, B., & Murphy, C. (2016). Resource use and greenhouse gas emissions from three wool production regions in Australia. *Journal of Cleaner Production*, *122*, 121–132. https://doi.org/10.1016/j.jclepro.2016.02.025

Winchester, C. F., & Morris, M. J. (1956). Water intake rates of cattle. *Journal of Animal Science*, *15*(3), 722–740.