



Australia's National
Science Agency



Priorities for Low Emissions Agricultural Solutions Investment

Methods, solutions and investment pathways

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Glossary of terms

Absolute reductions – The total decrease in greenhouse gas emissions across a set period (usually annually). Distinct from intensity reductions, which are per unit of output.

ACCU (Australian Carbon Credit Unit) – Tradable unit issued under the Australian Government’s ACCU scheme for verified emissions reductions or removals (e.g., soil carbon, vegetation). Used in compliance markets and can underpin revenue or claims.

ACCU Scheme – An Australian Government scheme that offers landholders, communities and businesses the opportunity to run projects in Australia that avoid the release of greenhouse gas emissions or remove and sequester carbon from the atmosphere. It is enacted through the Carbon Credits (Carbon Farming Initiative) Act 2011 and the Carbon Credits (Carbon Farming Initiative) Rule 2015

Carbon credit – A tradeable unit that represents 1 tonne of carbon dioxide equivalent (t CO₂-e) stored or avoided by a project

Emissions intensity – Total GHGs per unit of output (e.g., tCO₂-e per tonne of grain or litre of milk), typically including relevant Scope 3 emissions essential to producing the product.

Carbon markets – Systems to certify and trade emissions reductions/removals. Carbon markets can be government-administered (e.g., the Australian Carbon Credit Unit Scheme (ACCU), linked to regulation (such as the Safeguard Mechanism), which can create demand. Non-government markets are registry-based (e.g., Verra, Gold Standard, Athian).

Carbon sequestration (soil/vegetation) – Capturing atmospheric CO₂ and storing it in soils or biomass through practices like tree planting, pasture improvements, or soil management, subject to measurement, permanence, and method rules.

Co-benefits (financial/environmental/social) – Positive non greenhouse gas effects of mitigation activities, such as shade/shelter, biodiversity, pest control services, resilience, and productivity gains, often considered alongside carbon outcomes and risks.

Compliance (regulated) carbon market – Government-run market operating under legislation and approved methodologies with credits tracked in official registries (e.g., ACCU scheme, Safeguard Mechanism Credit Units).

Emissions scopes (Scope 1, 2, 3) – Scope 1: Direct, on-farm emissions. Scope 2: Indirect emissions from purchased energy. Scope 3: Other upstream/downstream value-chain emissions (e.g. inputs, transport, processing, end-of-life).

Enhanced-Efficiency Fertilisers (EEF) – Coated or inhibitor-treated fertilisers that slow N release or inhibit nitrification, lowering N₂O emissions. Evidence shows substantial N₂O abatement; yield responses vary and may not offset price premiums consistently.

Enteric methane (CH₄) mitigation – Strategies to directly or indirectly lower rumen methane (feed additives like 3-NOP/Bovaer® or *Asparagopsis*; pasture quality and species; genetics; earlier turn-off; management) with near-term climate benefits.

FLAG (Forest, Land and Agriculture Guidance) targets – SBTi guidance and targets addressing land-sector emissions and removals, often including zero-deforestation commitments and specific absolute reduction goals for supply-chain companies.

GHG (greenhouse gas) – Heat-trapping gases including CO₂, CH₄, N₂O. Agriculture contributes via enteric fermentation, manure, fertiliser use, energy use, and land management. Mitigation requires reductions and durable removals.

Insetting – Mitigation projects within a company's value chain (business, supply chain, or supply shed) that create GHG reductions/removals and broader social/environmental benefits; enables co-investment and co-claiming of Scope 3 reductions.

Intensity reductions – Lower emissions per unit of output (e.g., g CH₄/kg liveweight or L milk).

ISO 14040 / 14067 / 14021 standards – International standards for life-cycle assessment (LCA), product carbon footprint quantification, and self-declared environmental claims—used to ensure consistent, credible farm/product accounting.

Leakage – Changes in anthropogenic emissions and/or removals of GHGs that occur outside the activity boundary and that are attributable to the activity, including those resulting from changes in market demand or supply for associated outputs.

Leucaena / Desmanthus / tannin-rich forages – Pasture/forage species and plant secondary compounds that improve productivity and can reduce methane intensity or total emissions; effects depend on species, diet, and system specifics.

Life Cycle Assessment (LCA) – Method to quantify environmental impacts across a product/system boundary from pre-farm to farm gate (or further), supporting comparable emissions accounting and allocation between co-products.

Manure management (anaerobic digestion, covers, separation, composting) – Practices that avoid methane formation/release by controlling anaerobic conditions, capturing biogas, or altering handling to cut CH₄ and N₂O emissions.

Mandatory climate disclosures (Australia) – Sustainability reporting obligations (including Scope 3) for many large businesses from 2025 under Treasury Laws Amendment (Financial Market Infrastructure and Other Measures) Act 2024.

Monitoring, reporting and verification (MRV) – Monitoring, reporting, and verification requirements to evidence reductions/removals, prevent double counting, and satisfy registry or disclosure expectations for claims/credits.

Proportional MRV aligns the level of measurement precision, reporting burden and verification intensity with the values at stake and the risks being managed, rather than seeking maximum accuracy in all cases.

Methodology / protocol (crediting) – Approved rulesets that define boundaries, baselines, measurement, monitoring, and verification to quantify emissions that have been avoided, reduced or removed. Can be used to support issuance of carbon credits or to support credible claims. Availability varies by sector/activity

National Greenhouse Gas Inventory (NGGI) – Australia’s official inventory underpinning GHG factors and farm calculators; alignment with NGGI and IPCC methods is expected for credible farm/audit calculations.

Net-zero emissions – A state where all anthropogenic GHG emissions are balanced by verified removals, generally achieved by measuring existing emissions and removals, reducing emissions / maximising removals where possible and ‘offsetting’ the remainder; common in corporate claims / product labels, but application of the terminology can vary based on scale, emissions boundaries and included greenhouse gases.

Offsetting – Purchasing credits generated outside the buyer’s value chain to compensate for emissions.

Protein-based / mass-based allocation – Approach to apportion emissions between co-products (e.g., livestock protein vs co-products; lint vs seed in cotton) to avoid mis-attribution and ensure consistent product footprints.

Safeguard Mechanism – Regulatory mechanism requiring Australia’s highest greenhouse gas emitting facilities to reduce their emissions in line with Australia’s emission reduction targets.

Science Based Targets initiative (SBTi) – Global framework for corporate GHG targets aligned with climate science (1.5°C), including FLAG guidance; increasingly required by investors and drives supplier alignment and Scope 3 collaboration.

Supply shed – Defined group of equivalent suppliers within a company’s supply chain (national/sub-national) enabling co-investment and co-claiming of Scope 3 reductions across a broader geography.

Weaning rate / earlier turn-off (livestock) – Productivity improvements that reduce methane intensity by diluting emissions over more output or shorter grow-out times; often economically attractive.

Acronyms and abbreviations

ACCU – Australian Carbon Credit Unit (Australia’s compliance carbon credit)

AI – Artificial Intelligence

APL – Australian Pork Limited

ARR – Afforestation, Reforestation, and Revegetation (method category)

Bt – *Bacillus thuringiensis* (genetically engineered trait for pest resistance)

CEFC – Clean Energy Finance Corporation (Australian Government green finance institution)

CFOP -- Carbon Farming Outreach Program

CH₄ – Methane (greenhouse gas)

CO₂ – Carbon dioxide (greenhouse gas)

CO₂-e – Carbon dioxide equivalent (common unit across gases)

CRC – Cooperative Research Centre (see also ZNE-Ag CRC)

CRL – Commercial Readiness Level (used to describe maturity of solutions)

DCCEEW – Commonwealth Department of Climate Change, Energy, the Environment and Water

EEF – Enhanced-Efficiency Fertiliser (includes coated slow or controlled release fertilisers and nitrification and urease inhibitors)

EF – Emissions factor

ESG – Environmental, Social, and Governance (investor screening)

EV – Electric Vehicle

FCR – Feed Conversion Ratios

FLAG – Forest, Land and Agriculture Guidance (SBTi)

FullCAM – Full Carbon Accounting Model (Australian vegetation/soil modelling)

GAF / C-GAF – Greenhouse Accounting Framework (farm calculators aligned to NGGI)

GHG – Greenhouse Gas (CO₂, CH₄, N₂O, etc.)

GRDC – Grains Research & Development Corporation (cropping guidance/research)

IPCC – Intergovernmental Panel on Climate Change (methods, science)

IPM – Integrated Pest Management (system approach combining biological, cultural and chemical controls)

ISO 14040/14067/14021 – LCA / product carbon footprint / environmental claims standards

kt – Kilotonnes (thousand tonnes)

LCA – Life Cycle Assessment (farm/product boundary accounting)

LULUCF – Land Use, Land-Use Change and Forestry

MLA – Meat & Livestock Australia

MRV – Measurement, Reporting, Verification (for claims/credits)

Mt – Megatonnes (million tonnes)

N₂O – Nitrous oxide (greenhouse gas)

NDC – Nationally Determined Contributions (Paris Agreement commitments)

NGGI – National Greenhouse Gas Inventory (Australia)

NI – Nitrification inhibitor

NOP / 3-NOP (Bovaer®) – 3-nitrooxypropanol, a feed additive reducing enteric methane

OPEX – Operational Expenditure

PMR – Partial Mixed Ration

PV – Photovoltaic (solar electricity generation)

QA – Quality Assurance (standards and processes ensuring product quality and compliance)

R&D – Research and Development

RD&E – Research, Development and Extension

RDC – Rural Research and Development Corporation

ROI – Return on Investment (financial return relative to cost of investment)

SCaRP – Soil Carbon Research Program (sampling methodology basis)

SBTi – Science Based Targets initiative (corporate target setting framework)

SMC – Safeguard Mechanism Credit Unit (compliance credits under Safeguard)

STA – Sector / industry technology assessment

TA – Technology assessment

TMR – Total Mixed Ration

TRL – Technology Readiness Level (development stage indicator)

UI – Urease inhibitor

UNFCCC / COP21 – UN climate body / 2015 Paris conference adopting the Agreement

VEERG -Voluntary Emissions Estimation and Reporting Guidelines (DCCEEW, 2026)

ZNE-Ag CRC – Zero Net Emissions Agriculture Cooperative Research Centre (publisher)

6Rs – Fertiliser and soil management considerations, often defined as right source, right rate, right time, right place, right production/formulation, right practice.

Executive summary

Purpose

This report and the accompanying Summary Report provide a national, technology-centred assessment of priorities for reducing on-farm (scope 1) greenhouse gas (GHG) emissions from Australian agriculture. It focuses on investment, intervention and sequencing of actions. It is intended to support senior decision-makers across government, industry and the research system in making coordinated, evidence-based choices about where to focus effort and investment over the next decade and beyond to drive the scaling of technologies that will enable emissions reduction in the sector.

The report supports the Agriculture and Land Sector Plan, in particular, the plan's foundational action 2: “Support innovation to deliver commercially viable abatement options”. It complements ZNE-Ag CRC Stocktake and State-level low-emissions options assessments. The report places particular weight on sector-specific feasibility, delivery constraints, technology stacking, and the sequencing of action over time. Differences between this report and those assessments reflect analytical purpose and resolution, rather than disagreement on direction. This report places greater emphasis on sector-specific technology assessment, feasibility constraints, and the sequencing of investment and intervention over time, and at a national scale. Because it focuses solely on reducing on-farm emissions, this report's findings should be considered alongside other assessments of mitigation, adaptation and other sustainability and productivity-oriented work.

The challenge

Australian agriculture faces a persistent, long-term emissions reduction challenge. Scope 1 emissions are dominated by biological sources—enteric methane and nitrous oxide—that are inherently difficult to abate and highly heterogeneous across regions and farming systems. While land-based sequestration has played, and will continue to play, an important role, these opportunities are finite and will saturate. Over time, achieving national emissions goals will increasingly depend on direct emissions reduction within production systems. Technologies, in some cases, may be deployed to provide improvement in emissions intensity rather than to create absolute emissions reduction. Such practices and technologies may create options for absolute emissions reduction at some future point. While these applications of technologies are included in the report where they create entry points, capability building, or testing of technologies for later scaling into absolute emissions reduction applications, the overall focus is on the potential for technologies to provide absolute emissions reductions.

At the same time, pressures on agriculture are intensifying. As the rest of the economy reduces emissions, agriculture's relative share of national emissions will rise. Markets, financiers and supply chains are moving faster than on-farm capability, driven by Scope 3 reporting, climate disclosure and procurement requirements. This creates a risk of fragmented, poorly aligned demand and opportunity if adoption pathways are not credibly supported.

Critically, technological availability has not translated into widespread adoption. Many emissions-reduction options offer weak private returns, impose management complexity, or depend on immature delivery, regulatory or measurement systems to verify their efficacy. Experience to date shows that technology readiness alone is a poor predictor of adoption, scaling and impact.

What this report adds

This report examines not only *what technologies could reduce emissions*, but what can plausibly be delivered, scaled and sustained, and under what conditions.

The report is underpinned by a set of Sector Technology Assessments (Appendix C). These assessments examined 84 emissions-reduction technologies across six agricultural subsectors—red meat and sheep, dairy, cropping, horticulture, pigs, and poultry—and use a consistent analytical framework and repeatable method.

Technologies were evaluated against multiple criteria, including feasible abatement potential, breadth of application, co-benefits, barriers and knowledge gaps, stacking potential, technology and commercial readiness, and system fit.

This analysis provides an understanding of technologies within systems, explicitly considering the enabling environment required for uptake, including monitoring, reporting and verification (MRV), advisory capability, regulation, finance, markets, supply-chain engagement, and interactions with energy and digital infrastructure. Investment patterns were reviewed to identify misalignment between effort and likely abatement impact.

Actions are organised across three time horizons, recognising that progress depends on deliberate sequencing: building capability and confidence first, enabling scale second, and embedding outcomes in normal market function over the long-term.

A distinctive feature of this work is its intention to form the basis of a living, updateable evidence base—not a static set of actions. As technologies, markets and policy settings evolve, so too must investment priorities.

Strategic insights

Several cross-cutting insights emerge:

1. **Early abatement will be modest, but enabling value is high**

In the near-term, the greatest returns come from deploying existing “win-win” technologies, building system capacity (see 3 and 4, below) and maturing next generation technologies, rather than maximising immediate abatement.

2. **Stacking matters**

Meaningful on-farm reductions will rarely come from a single intervention. Instead, there is a need for **integrated technology stacks**, tailored to enterprise and regional characteristics. Stacking in this report refers to combined technologies and practices. These may work synergistically or through distinct abatement pathways. They may be accounted for by different MRV approaches in terms of their abatement effects.

3. **Proportional MRV is enabling infrastructure.**

Adoption and market mechanisms stall unless MRV is low-cost, stack-aware, and proportional to claims, risk and payments, rather than always needing research-grade precision. As such, MRV is considered important enabling infrastructure. Early, coordinated, system-level investment is required to handle the complex delivery and practice mix that will underpin abatement on farms.

4. **Demand-side signals are as important as supply-side R&D**

Without procurement, contracting, or finance structures that reward performance of low-emissions agriculture, many technologies will remain stuck despite technical readiness due to low on-farm return on investment or high risk in investing initial capital.

5. **Sequencing reduces risk**

Mis-timed incentives or premature mandates can crowd out investment and learning and erode trust. Deliberate, staged and coordinated interventions and investments can effectively build adoption and scaling pathways, and critical infrastructure to underpin integrity and trust. For example, too-early promotion of technologies that are not proven or have a limited value proposition can undermine not only technology scaling but organisations, programs and individuals that promote it.

6. **Coordination is critical to progress**

Emissions reduction will be accelerated by aligning action across research, policy, markets, advisory services and supply chains. Strengthening direction-setting, coordination, learning and legitimacy across the innovation system is essential to convert technological potential into durable, sector-wide outcomes.

Best-bet actions and investment across three horizons

Specific actions for sectors and technology scaling are in the body of the report and outlined in the Summary Report. For brevity, actions here are high-level and span across industries. Many are already being progressed. Recognising that, beyond Horizon 2, desirable actions become hard to predict, we highlight a desirable future state for Horizon 3.

Horizon 1 (2025–2030): Build capability, confidence and investable pathways

Core objective: Position the sector to scale emissions reduction.

Expected outcome: Limited national abatement, but substantial system readiness and risk reduction.

Priority actions

- Invest in robust farm-level emissions accounting platforms and proportional MRV to support market-based mechanisms and accounting, and thereby incentives for adoption and scaling.
- Test and develop demand-side mechanisms (e.g. procurement, contracting, inseting and finance) in targeted contexts where delivery and MRV are credible, to reduce risk and create viable scaling pathways for mature technologies with low/negative return on investment.

- Build shared digital, data and AI-enabled infrastructure to support emissions measurement, decision-making and technology deployment.
- Establish baseline emissions data and digital platforms to support learning and continuous improvement beyond pilots
- Upskill advisors and farming system groups through well-targeted processes and programs, especially via long-term investment in a hub-and-spoke model centring on state-owned research farms, data and knowledge sharing, and as critical, long-term infrastructure supporting development of regionally focused technology stacks and solutions and extension.
- Use grants, concessional finance and risk-sharing mechanisms to crowd in private investment and support early adoption.
- Streamline regulatory approvals (across all areas that pertain to emissions reduction, including national grid regulations) and harmonise standards to fast-track pilots.
- Leverage agriculture–energy integration opportunities, including renewable fuels, electrification, biogas, distributed energy and resilient regional infrastructure.

Horizon 2 (2030–2035): Selectively scale those next-generation technologies that have achieved delivery feasibility, credible MRV and investable economics

Core objective: Translate readiness into repeatable, enterprise- and regional-scale abatement.

Expected outcome: scaling reductions in scope 1 emissions and/or emissions intensity consistent with national ambitions.

Priority actions

- Deploy enterprise- and region-specific technology stacks at scale across agricultural industries.
- Embed MRV, data and digital systems as routine agricultural infrastructure, reducing transaction costs and supporting trusted claims.
- Establish effective cost- and benefit-sharing mechanisms that make emissions reduction profitable for producers.
- Expand market-based incentives, procurement programs and concessional finance mechanisms built on Horizon 1 pilots.
- Align policy, finance and supply-chain markets so emissions performance is consistently recognised and rewarded.
- Catalyse “spill-in” benefits from advances in energy, transport, digital technologies and other agricultural sectors.
- Strengthen connected policy–industry–research capability to identify, coordinate and solve emerging system-level challenges.

Horizon 3 (post 2035): Embed emissions performance into normal business

Core objective: Consolidate low-emissions agriculture.

Expected outcome: World-leading agricultural emissions intensity embedded in markets, maintained through ongoing shared infrastructure (MRV, standards, coordination), rather than stand-alone programs.

Future state being advanced:

- Emissions performance is routinely embedded in commodity markets, contracts, procurement systems and investment decisions.
- MRV operates as trusted, low-friction shared infrastructure underpinning markets, finance, reporting and product claims.
- Advisory and supply-chain systems continuously support optimisation and adoption of integrated low-emissions technology stacks.
- Private capital drives commercialisation and rapid scaling within a stable and supportive policy and market environment.
- High-risk, high-reward technologies matured earlier are deployed where viable, within a system that supports rapid scaling.
- Australian agriculture maintains world-leading emissions intensity, reinforcing competitiveness, market access and climate leadership.

Caveats and next steps

Estimates of feasible abatement and other drivers of adoption remain imperfect, particularly for emerging technologies and variable systems, and national-level analysis cannot capture regional dynamics. For many technologies, little data is available about aspects of efficacy, adoptability, or financial and other costs, risks and benefits. The report does not attempt to predict future policy or market settings.

The analysis allows the report to go beyond prioritising technological winners. It suggests pathways that can lead to portfolios of viable technologies supported by actions that expand the options space, that reveal the uncertainties, synergies and trade-offs with different technology choices (such as highly effective but low application extent compared with general application but highly speculative), and coordinate policy and industry actions to support the building of an enabling environment for technology scaling and adoption.

Part of the analysis of these pathways was the identification of current investment patterns. This investment analysis draws on indicative RDC data covering emissions-reduction projects from 2022/23 to 2024/25, supplemented by publicly available ZNE-Ag CRC investment information. These data provide a snapshot of investment direction and relative emphasis, rather than a comprehensive account of all low-emissions agricultural RD&E activities. They do not allow detailed assessment of the current investment focus across the agrifood innovation system, but rather whether and where it is broadly aligned with the pathways proposed in the report.

Used as a living resource, this report and the analysis it rests on provide a credible, system-aware foundation to support deliberation and prioritisation for reducing agricultural scope 1 emissions and emissions intensity of agricultural products. It clarifies, at a national level, where investment can unlock progress, where key constraints lie, and how action can be sequenced to minimise risk while maximising long-term impact.

Part I Scene setting



1 Introduction and Scope of Work

1.1 Purpose of this Report

This report develops and implements a methodology for assessing investment options to advance farm-level emissions reduction technologies and practices (hereafter simplified as ‘technologies’) for Australian agriculture. The report identifies and enables prioritisation of investments targeted at reducing farm emissions. Focus on reducing farm emissions, in conjunction with other priorities, will help ensure the sector is well-placed for a low emissions future and can contribute effectively to Australia’s emissions targets as set out in the Agriculture & Land Sector Plan (DAFF, 2025).

The focus of the report is the technologies that can advance *scope 1 emissions* reduction across six agricultural sub-sectors (we also refer to these as industries): Dairy; Red Meat and Sheep; Cropping, Horticulture; Poultry; and Piggeries. *The report explores technologies for emissions reduction, not sequestration or carbon removals, which have recently been reviewed* (Fitch et al., 2025). For Australia to achieve and sustain net-zero, it is likely that agricultural emissions (not just net emissions) will need to be reduced. This report examines emerging emissions reduction technologies that provide options for Australia now and into the future.

As a hard-to-abate sector of the economy, agriculture’s overall contribution to GHG emissions is expected to decline slowly, and its relative contribution is projected to rise as Australia pursues an ambitious economy-wide target. This position of agricultural emissions presents technical, practical, policy, and political challenges. However, opportunities are emerging through technological change.

As this report details, such technological change can be enabled or constrained by a variety of financial, social, institutional and other factors and drivers that need to be considered, both for individual technology development and scaling, as well as within and across industries and within the broader economy.

The combination of focus on technologies, enablers and managing system interactions covered in this report will help ensure that agriculture can make an appropriate contribution to reducing Australia’s overall emissions in a way that supports farmers, regional and rural communities and the various benefits that the food system provides for Australia.

1.2 Scope of Work

The project was commissioned by, and produced with the assistance of, DAFF. The CSIRO team developed the methods and undertook the independent analyses, and the preparation of the report and sector technology assessments. The DAFF team managed the stakeholder engagement processes, access to data (where relevant), and advised on strategic science-policy alignments. Both parties maintained a dialogue to ensure rigour, legitimacy and relevance. The project set out to:

1. Identify priority greenhouse gas emissions reduction solutions and enabling factors to progress and/or deploy for major agricultural industry sectors and establish the methodology to do this subsequently for the forestry and fisheries sectors.
2. Undertake a preliminary assessment of the current scale of investment in each priority solution and the enabling factors required for these priority solutions to be adopted.
3. Assess this investment profile in relation to the scale of the abatement opportunity and identify investment/action gaps, using a representative window of time.
4. Identify a comprehensive set of explicit, tangible, prioritised actions and investments to accelerate the emergence and scaling of the identified priority solutions and enabling factors.
5. Establish a foundational framework for periodic, repeatable analyses in the future

Beyond sets of phased actions, the report identifies cross-cutting and supporting functions and mechanisms that could accelerate the scaling of solutions, including data infrastructure, innovation architecture, and system-wide capacities. Scaling here refers to the process through which a technology, practice, or set of interventions achieves sustained and widespread impact within an industry or sector. Scaling is not treated as a discrete phase, but as an outcome that emerges when enabling conditions—such as capability, evidence, infrastructure, market demand, coordination, and policy alignment—are sufficiently developed (Conti et al., 2026).

These mechanisms go well beyond the role of government, in recognition that the decisions, processes and arrangements that affect emissions reduction in Australian agriculture span supply chains, research and development, as well as other sectors of the economy.

1.3 Approach

The approach used for the analysis of technologies and their associated enablers and investment is detailed in Chapter 3 of the report. Analysis for each industry is in Chapter 4, and across industries and beyond agriculture in Chapter 5. The detailed technology assessments are in Appendix C. The overarching process included engagement with a project Reference Group and a wider group of industry and technical experts (see Acknowledgements) who respectively guided on strategic and analytical matters, as well as a group of peer reviewers who provided critical expert feedback on the final report. Participants in each of these groups were invited to participate based on their expertise and experience with respect to systems and technologies being examined, and (in the case of reviewers) their ability to contribute to specific reviews in a timely and effective manner. Analyses drew on international and Australian scientific, industry and government publications, and focused on five key areas:

1. **Technology assessment:** what characteristics of available and emerging technologies make them more or less likely to advance low-emissions agriculture?
2. **Portfolio analysis:** across the portfolio of technologies, what enablers, constraints, and risks need to be addressed to enable adoption and/or scaling?

3. **Systems interactions analysis:** what systems interactions and risks could affect the development and scaling of technologies, and effectiveness, efficiency, desirability of intended and unintended outcomes?
4. **Investment analysis:** What is the current direction of investment? What levels and types of investment are directed to technologies, and innovation functions and mechanisms that enable scaling?
5. **Prioritisation analysis:** What are the priority areas of investment and action across agriculture and the wider policy and industry environment that can most efficiently, effectively and equitably drive scope 1 emissions reduction?

1.4 How this report builds on other related work

As the main focus of this report is the assessment of existing technologies to inform prioritisation of investment, it is important to recognise the breadth of existing work that contributes to the scaling of technologies. Significant activity and investment have contributed to strong foundations for future success, including investment from federal and State governments, Research and Development Corporations, and the development of a Net Zero Emissions Agriculture Cooperative Research Centre (NZE Ag CRC). Some other notable programs include the federally funded Carbon Farming Outreach Program (CFOP) and Methane Emissions Reduction in Livestock (MERiL) program, and the NSW Decarbonisation Hub.

Forward delivery from these needs to be considered when defining investment prioritisation. Within the scope of this report, we could only canvass these briefly in each of the industry analyses in Chapter 4 via investment assessments, and in Chapter 5 in relation to specific priority action areas identified across industries and beyond through the analysis. That is, we started with an analysis of need and then undertook a preliminary assessment of how and where this need was currently being addressed.

Beyond these initiatives, *how* technologies will scale needs to be considered. We explore key aspects of this in preliminary terms in Chapter 2. Central to these, is the understanding that scaling pathways will be driven by the relative advantage of new options at an enterprise level. For some technologies explored in this report, relative advantage is already apparent through positive financial return on investment (ROI), or social, environmental and other long-term benefits, such as soil health, water retention, drought resilience and more – these are referred to in the report as co-benefits. For other technologies, the relative advantage of these technologies can only be bestowed by additional incentives, often delivered through market mechanisms, which in turn require forms of assurance. Box 1.1 outlines how proportional monitoring, reporting and verification (MRV) relates to such incentives. These are important background concepts for this report.

Box 1.1 Proportional MRV and incentives: aligning assurance with market function

This report uses monitoring, reporting and verification (MRV) in a broad sense, recognising that MRV is required for a wide set of learning, decision, market and regulatory purposes. These include corporate reporting, supply-chain participation, financial decisions and participation in carbon markets. Each application requires credible data, but these may differ in precision, cost and verification approach (CCA, 2023). The credibility of MRV depends on auditing, compliance processes and enforcement powers to maintain confidence in both markets and policy mechanisms (ANAO, 2024).

Within these constraints, MRV can be understood as proportional to the function it serves, within an overarching framework that maintains consistency, transparency and integrity across the national system. Systems already incorporate differentiated approaches. These can be illustrated via a simple MRV–assurance ladder:

	Low - moderate assurance	Moderate assurance	High assurance
Focus	Management, learning and finance access	Supply chain differentiation and reporting	Crediting, compliance and regulated markets
Purpose	Inform decisions; enable participation; reduce uncertainty; support early action	Support product claims; benchmarking; transparent reporting across value chains	Support tradable units; enforce compliance obligations; ensure environmental integrity
Mechanisms	Advisory tools; benchmarking; concessional finance; internal decision support	Supply chain programs; procurement policies; corporate reporting (including Scope 3); climate disclosures	ACCU scheme (carbon markets); Safeguard Mechanism; regulated disclosures
MRV features	Modelled estimates; proxy data (e.g. inputs, productivity); simplified methods	Standardised methods; auditable datasets; increasing use of facility-level data; alignment with life cycle assessment frameworks	Method-based accounting; strict baselines; additionality requirements; independent auditing and verification
Illustration	Lenders or corporates using emissions intensity metrics derived from standard methods to inform risk and investment decisions	Facility-level emissions data informing corporate disclosures or supply chain reporting	ACCU projects requiring approved methods, audit schedules and regulatory oversight

Proportional MRV should be designed to:

- Maintain integrity across all levels (recognising that credibility is foundational to both reporting systems and markets) and harmonise core methods which are prerequisites for effective proportional MRV.
- Align assurance with risk and use, with higher-stakes applications requiring more rigorous measurement, verification and audit
- Enable participation across diverse producers and systems by allowing lower-cost approaches where appropriate, recognising that parallel MRV systems can impose multiple
- Facilitate interoperability and data reuse across assurance levels, recognising that multiple accounting ledgers (national inventories, Scope 3 reporting, product footprints and project-level accounting) increasingly rely on shared farm-level data foundations.
- Support consistency and comparability, particularly where data contributes to, or is derived, from national reporting frameworks and international obligations.

MRV is foundational enabling infrastructure that supports learning and enables incentives, procurement, finance and claims systems to operate. It does not itself generate demand or drive adoption and scaling.

1.5 How to use this report

As the report is large and detailed, this section provides a guided pathway through the report, depending on your role, time constraints, and decision context. This report is designed to support strategic investment and policy decisions on reducing scope 1 greenhouse gas emissions in Australian agriculture. It brings together technical assessments, system analysis, and prioritised actions across sectors and time horizons. Because it serves multiple audiences and purposes, not all readers will need to engage with every chapter in detail.

The report is structured to move from context, to method, to sector analysis, to cross-sector/systems synthesis, to action priorities:

- Part I explains *why* emissions reduction remains hard, and *how* the assessment framework was designed.
- Part II applies that framework consistently within industries in Chapter 4, and in Chapter 5 pulls findings across and beyond these industries together to identify system-level priorities. Horizon-based pathways translate analysis into sequenced investment logic in both these chapters.

1.5.1 For decision-makers (government, boards, executives)

If you have limited time and are setting direction or priorities, focus on the following sections:

A. Executive Summary

Read in full. This sets out:

- the problem framing (why emissions reduction—not just sequestration—must now be prioritised),
- the central insights (delivery, MRV, stacking, sequencing),
- the three time-horizons and associated investment logic.

B. Chapter 5: Cross-sector priorities and system enablers. This chapter distils the analysis across all sectors and identifies:

- system-level constraints that repeatedly limit adoption (MRV, weak demand, coordination failures),
- enabling investments that lift multiple technologies at once,
- actions best addressed at a national or cross-industry level
- how these actions intersect with and extend existing initiatives and work led by state governments, national programs and industry investment.

C. Sector pathways and best-bet actions (Chapter 4, sector subsections)

For any sector of direct responsibility (e.g. dairy, red meat, cropping):

- read the “Pathways”, “Key barriers/enablers”, and “Best-bet actions” tables,
- skim tables in the Technology assessment sections of Chapter 4 to understand *relative maturity and scale* of technologies.

You do *not* need to read the full technology assessment tables or methods chapters to engage meaningfully with the recommended actions.

1.5.2 For technical experts and analysts

If you are interrogating the evidence base or testing assumptions, or considering targeting of investment, your primary sections are:

1. Chapter 3: Methods
Provides full detail on criteria, archetypes, confidence scoring, and limitations.
2. Chapter 4: Sectoral technology assessments
Use these sections to:
 - examine the technology-by-technology assessments,
 - understand how feasibility and confidence vary by system and region,
 - test the robustness of classifications and abatement estimates.
3. Appendices C.1 to C.6
Refer here for:
 - detailed technology assessments,
 - workshop inputs and expert validation processes,
 - underlying assumptions and definitions.

Note that the sector technology assessments are descriptive and comparative, rather than predictive or prescriptive.

1.5.3 For industry leaders, RDCs, and practitioners

If your interest is “what this means for my sector or supply chain”, focus on:

1. Your sector chapter in Chapter 4
Read:
 - the sector background (to confirm framing),
 - the portfolio analysis (to understand why adoption has stalled),
 - the pathways and best-bet actions (to see where effort is most likely to pay off).
2. Chapter 5 sections on enabling mechanisms
These sections clarify:
 - which barriers are not solvable by producers and industries acting alone,
 - where collective action, co-investment, or coordination is required,
 - why some technologies will not scale without demand-side signals.

2 Historic analysis of GHG abatement, ambitions and mitigation technology adoption in the Australian agricultural sector

This chapter presents two important analyses as context for the report. The first briefly focuses on the reasons that emissions reduction has received little traction in agricultural abatement and what this implies about how scaling of emissions reduction technologies in Australian agriculture might be usefully treated. This analysis highlights why the focus of this report on low-emissions agricultural technologies is important, even though the major actions that drive a net reduction in emissions from the sector may come in the short-term from sequestration on lands managed by agriculture. The second section explores, through two cases, some of the core challenges of scaling technologies in agriculture, especially where public benefits (such as GHG abatement) are not matched by clear and compelling private benefits.

2.1 Moving beyond sequestration: a brief history of Australian agricultural abatement

Historical abatement estimates in Australia have consistently assigned very different roles to sequestration activities (primarily land-use change and carbon storage) and agricultural emissions reduction technologies (methane, nitrous oxide and efficiency interventions). These differences reflect underlying policy expectations, economic incentives and structural barriers—not simply the biophysical potential of the sector. A short review is provided here to explain the focus on emissions reduction technologies rather than the combined effect of sequestration activities in combination with emissions reduction technologies.

2.1.1 Approach and analysis

A sample of 24 documents produced between 2006 and 2024 was selected based on their relevance to national ambitions to mitigate Australia's GHG emissions to combat climate change (see Appendix A). Fifteen of the reports provide mitigation claims that can be quantified in terms of carbon dioxide equivalents in millions of tonnes per year (MtCO₂-e/yr) (see Figure 2.1.1).

The estimates of agricultural mitigation generally apply to a target year, such as 2050, or an average year within a range of years. Projection periods generally ranged from 20 to 30 years into the future, often focusing on years denoting a new decade, such as 2030 or 2050, although shorter and longer projections were present in the sample.

Classification of agricultural mitigation options was inconsistent across the 24 studies and has evolved over the period covered by Figure 2.1.1. To the extent possible, mitigation claims were categorised as those mostly arising from changes in agricultural management practices within an

existing land use (blue in Figure 2.1.1), versus those mostly arising from a change in land use (orange). Ambiguity between these categories does not affect the trends revealed by the analysis.

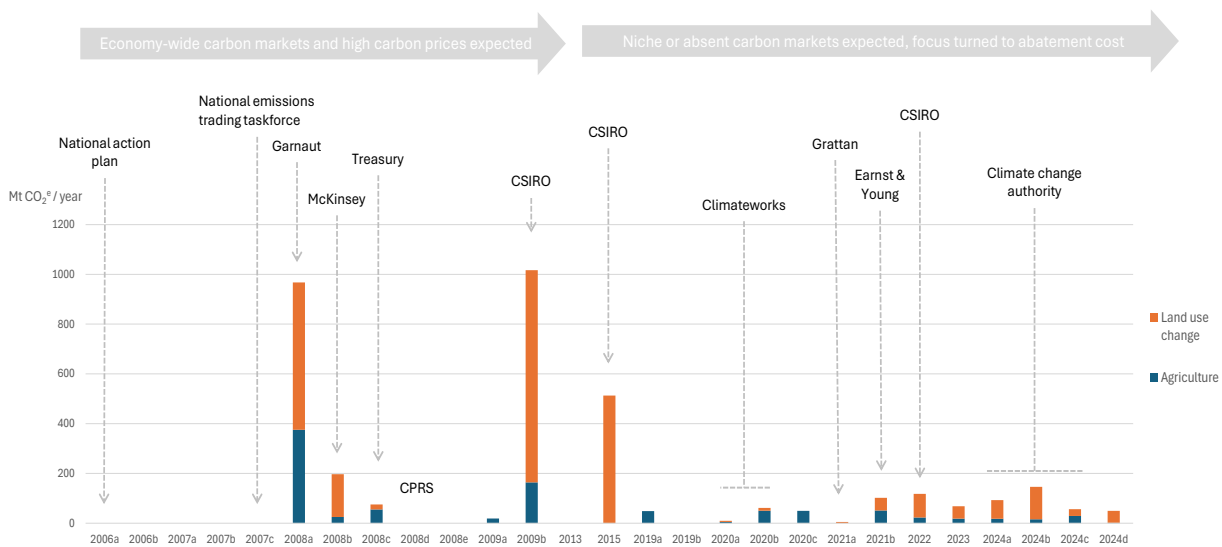


Figure 2.1-1. Selected estimates of potential GHG mitigation from agriculture and land use change for Australia.

Figure 2.1.1 shows that estimates assigned very large abatement roles to sequestration to drive down net emissions for the sector, especially through afforestation and reforestation. These projections assumed high carbon prices would make major land-use change financially attractive, with the potential to offset a significant share of national emissions.

After 2013, weakening carbon price policy settings forced downward revisions: opportunity costs of land, landholder preferences, and the finite nature of carbon sinks became more visible. Sequestration remained a significant contributor to planned emissions goals, but long-term soil carbon values were predicted to reach a plateau at a new steady state, and competition with agricultural production, and regional social licence constraints seen to impose limits to uptake.

The contribution of emissions reduction is low in the historical projections. Projections have long regarded agricultural emissions reduction as difficult and slow to scale, due to the biological nature of emissions, the diversity of farming systems and the absence of near-term technological substitutes. Moreover, the agricultural sector is highly fragmented, with adoption decisions made by thousands of producers whose incentives are shaped by cost, risk, labour and system compatibility (see Section 2.2). Policy uncertainty also contributed to a lack of industry confidence that early adoption would be rewarded.

This analysis suggests that sequestration has been seen as offering a large, near-term offset mechanism in sector pathway analyses. It was therefore prioritised over emissions reduction, which, by contrast, has a long-term, gradual technological transition, requiring sustained investment, capability development and consistent enabling policy. Treating these aspects of abatement as interchangeable (or taking sector capacity as the aggregate of short- to medium-term trajectories) can distract from longer-term goals and has masked the structural and policy barriers that limit emissions reduction uptake on farms.

Sequestration plays an important role in achieving national emissions reduction targets and reducing the net emissions from agriculture (DAFF, 2025). However, if agriculture is to reduce

emissions, or improve emissions intensity of production, and sustain these trends over the long-term, sequestration cannot substitute indefinitely for emissions reduction. This is primarily because sinks are subject to diminishing returns. For agriculture to contribute appropriately to national emissions reduction, relying only on sequestration has a relatively short lifespan. Meanwhile, as is noted throughout this report, scaling emissions reduction technologies will have long lead times and require sustained effort. This reasoning underpins this report's focus on emissions-reduction technologies and the capabilities needed to develop and scale them. It aims to identify ways to create the long-term opportunities for agriculture to sustain emissions reduction, not least via industry and enterprise-level improvements in emissions intensity of products.

2.2 Drivers of scaling and adoption of emissions-reducing technologies

The relative advantage of new practices over existing ones is a well-recognised driver of adoption (Kuehne et al., 2017). However, adoptability is rarely straightforward. It reflects interactions beyond return on investment (ROI) and economics, including producer characteristics, advisory systems, and technology attributes—many of which are difficult to assess early in the development of technologies.

A determining factor is whether or not a technology will 'fit' within the existing farm system. This often depends on farmers' willingness and capacity—individually or through groups—to trial and adapt technologies. The complexity of technologies, processes, and logistics of trialling costs lead to higher transaction costs and slow adaptation and adoption. However, adoptability is also affected by the population of farmers, their values and beliefs, and the networks of advisors, and researchers who co-produce knowledge and influence goals within a region or locality (Allan et al., 2022).

Exemplar cases help illustrate how the interaction between farming system, environments, institutions and culture play out in practice.

Key Messages from exemplar cases

- Adoptability is shaped by complex interactions among farmers, advisors, technologies, and institutions—not just relative advantage.
- Technologies rarely move from lab or demonstration farm to widespread adoption without iterative adaptation and investment.
- Regional systems need flexibility to embed technologies locally while aligning with national priorities.
- Place-based knowledge (producers, advisors) is critical for tailoring technologies.
- Scaling of technologies will often require co-innovation of broader system capacities that, refine implementation and enabling infrastructure, improve MRV, and address regulatory and compliance barriers.
- Multiple levels of intervention—technical, institutional, and policy—are usually necessary for successful adoption and scaling. Information alone doesn't solve adoption; coordinated technical, institutional, and policy interventions are usually necessary.

2.2.1 Case #1: Beyond RD&E – why investment alone is insufficient for scaling solutions to decarbonise the agriculture sector

Phosphorus (P) supplementation is a technically effective option to increase productivity and reduce emission intensity in the Northern Australian Beef industry, yet it faces scaling challenges.

Overview

In 2024, emissions from Australian beef cattle accounted for approximately 78% of the nation's total agricultural greenhouse emissions (National Inventory Report, 2026). Notably, Northern Australia plays a significant role in this output, holding 64% of the national beef herd, which is managed predominantly within extensive grazing systems (Bray et al., 2015). These systems are often situated on phosphorus (P)-deficient soils, making it hard for cattle to obtain adequate P from their diet. Highly weathered, low-fertility soils are a critical constraint to cattle productivity and reducing GHG emissions. P-deficiency results in poor feed conversion, growth, fertility, increased mortality, and ultimately, reduced efficiency in productivity and GHG emissions (Dixon et al., 2020; Jackson et al., 2023). There is broad agreement among researchers that addressing P deficiency in these systems has the potential to increase cattle productivity and thereby reduce emissions intensity.

Significant RD&E investment through MLA and others since the 1990s has refined actions for phosphorus (P) supplementation during the wet season into long-standing and simple guidance. The adoption rate has remained generally low (Bell et al., 2014; Bowen et al., 2019).

The promise of P supplementation

Unlike fertilisers, which generally are not cost-effective on large, extensively managed properties, P supplementation is identified as a “low-hanging fruit” strategy. It is backed by science and offers clear economic benefits in addressing P deficiency and improving cattle health, productivity, and profitability (Bell et al., 2014; Bowen et al., 2019).

In Northern Australia, low-emission farming can be achieved through management practices that increase both productivity and profitability without ‘carbon income’ (Bray et al., 2015). Among these approaches, P supplementation is one of the promising strategies. It has the potential to improve animal efficiency without leading to increased herd sizes that would offset emission reductions. Enhancing cattle growth and health through improved nutrition, such as P supplementation, can reduce methane (CH₄) emissions intensity by boosting weaning rates and reducing mortality, thereby increasing productivity per animal rather than through increases in herd size (Munidasa et al., 2024). Moreover, P supplementation can be combined with other nutrition, genetics, management, and feed-based interventions to further improve productivity and emissions outcomes.

Barriers to scaling P supplementation

Operational and logistic challenges

The large scale of Northern Australia's beef farming presents significant operational and logistical hurdles for implementing routine and technical interventions (Henry et al., 2012). For P-deficient cattle, a large and economically important increase in cattle production can be achieved by P supplementation (Bowen et al., 2019). However, key barriers to scaling P supplementation in the

region include the difficulty in identifying subclinical P deficiency, estimating optimal supplementation rates, and efficiently delivering supplements during the wet season when they are most effective (Dixon et al., 2020). Delivering supplements during the wet season requires additional investments in feeding troughs or shades, a dedicated truck and other machinery costs, and additional labour (Bowen et al., 2019), which further reduces the feasibility of implementing P supplementation at scale. Assessing phosphorus deficiency before supplementation is essential to ensure economic returns, especially on acutely deficient land types where cattle are likely to respond strongly to appropriate P inputs. In practice, however, assessing P deficiency is especially challenging due to high variability in soil types and pasture P concentrations, conditions that vary even within a single paddock. This variability is compounded by regional and seasonal variation, and a lack of sufficient P-deficient diagnosis tools to help.

Economic factors - delayed return on investment (3-5 years)

Although MLA investment in RD&E efforts has primarily focused on technical aspects—such as developing guidelines for diagnosing P deficiency and designing delivery systems—the adoption rate remains low due to delayed return on investment. The second edition of Phosphorus Management of Beef Cattle in Northern Australia (Jackson et al., 2023) provides detailed technical guidance for producers and extension officers, including how to assess need, determine dosage, and evaluate profitability. P supplementation improves long-term herd fertility and growth, but in practice, the benefits are not immediately visible or easily quantifiable, making it difficult for producers to justify the high upfront costs (Bowen et al., 2019). The extensive grazing systems pastoral business model often relies on a low-input and low-output model, and investments with delayed return in P supplementation are not aligned with this short-term cash flow business model. According to the FutureBeef website “productivity improvements take 2–3 years to achieve, as the benefits of P supplementation take time to build up in terms of improved reproduction rates.” The implications are higher costs and reduced cashflow until returns are realised. Munidasa et al. (2025) argue that adoption is constrained by the absence of region-specific, integrated strategies underpinned by long-term, whole-farm research to demonstrate cost–benefit outcomes.

Evidence, extension and lack of awareness

Analyses of the economic benefits from the 1990s onwards is consistently justified by claims that there is limited awareness of the economic benefits among producers, and that lack of awareness and the evidence underpinning it is the main reason for the low adoption rate.

Institutional and systemic barriers

The tendency to treat the problem of adoption as a knowledge or capability gap at the individual enterprise level tends to dominate over attention to systemic issues and the potential for coordinated institutional support. There has been limited research on the role of institutional, organisational, and social innovations that enable coordinated, place-based approaches and create supportive environments for producers to implement and sustain practice changes at scale. A more supportive institutional environment could include:

- Innovative financing mechanisms such as blended finance, risk-sharing models, or concessional loans tailored for the extensive grazing systems, helping producers overcome upfront capital and labour costs associated with supplementary infrastructure.

- Regional programs incentivising early adoption of new management practices or to demonstrate their on-farm productivity or emissions intensity benefits.
- Cross-sector coordination between MLA and RD&E providers, industry groups, financiers, state/federal governments, and supply-chain actors to align priorities, share data, and develop scalable, region-specific delivery models towards achieving a shared goal of addressing barriers for producers to bring about practice changes.
- Investments in long-term experimentation to address existing knowledge gaps about the relative merits of different strategies for total enterprise profitability and emissions efficiency.
- Investment in infrastructure and diagnostic tools such as regional laboratories or a real-time data platform to improve and simplify the diagnosis of P deficiency. Also, upskilling and reorienting the extension efforts, and grower networks towards a peer-learning and on-ground implementation.

Such approaches often combine institutional, social, organisational, and technological innovation, and can be supported by well-targeted monitoring and evaluation to improve systemic learning and performance that is responsive to place-based producer contexts and capable of facilitating collective actions.

Key insights from case study 1.

1. **Technical merit is not the same as adoptability:** Even proven, profitable technologies fail if delivery or adoption complexity is high. Compatibility with existing systems and ease of trialling, evaluating and implementation are critical. In this use case, diagnostic uncertainty and wet-season logistics have made P supplementation hard to operationalise.
2. **Time-to-benefit is a major barrier:** Producers discount future gains heavily; delayed returns from P supplementation (2–3 years) clashed with short-term cash-flow needs. Adoption theory highlights that observability and trialability drive uptake. When benefits are slow or intangible, adoption stalls without bridging finance or staged incentives.
3. **Context specificity matters:** Generic actions underperform in heterogeneous environments. Evidence shows that relative advantage must be demonstrated under local conditions. Region-specific trials, simple diagnostics, and peer learning reduce perceived risk and increase adoption likelihood.
4. **Knowledge or more R&D alone doesn't solve systemic constraints:** Framing adoption barriers as an “information gap” ignores institutional, logistical and structural barriers. For wide-scale adoption of technologies, we need to create enabling environments by considering factors such as finance, coordination, and risk-sharing mechanisms, rather than relying solely on information provision, extension and awareness campaigns.
5. **Integration and stacking increase perceived value:** Technologies adopted in isolation often underdeliver or have cost constraints. Combining interventions with stacked benefits can increase the value proposition and increase the ‘stickiness’ of practice adoption. Bundled solutions aligned with producer goals (profitability and emissions) improve uptake by increasing overall utility.

2.2.2 Case #2: Unpacking progress in scaling Nitrogen Use Efficiency (NUE) in the Australian Cotton Industry

Background

Since its establishment in 1990, the Cotton Research and Development Corporation (CRDC) has helped drive major gains in productivity and sustainability across the Australian cotton industry. Cotton yields have risen from 6.6 bales/ha in 1991 to over 10 bales/ha today, while producing more bales from a smaller cropped area. Environmental performance has also improved substantially, including 92% less pesticide use, 52% less water use, and 34% less land per bale produced (CRDC, 2025).

These advances reflect decades of RD&E investment in genetics, pest control, and irrigation (Macdonald et al., 2018; Wilson et al., 2018). However, despite more than 40 years of research and industry investment effort, progress on nitrogen use efficiency (NUE) remains limited and well below optimal levels (Macdonald et al., 2018; CRDC, 2025).

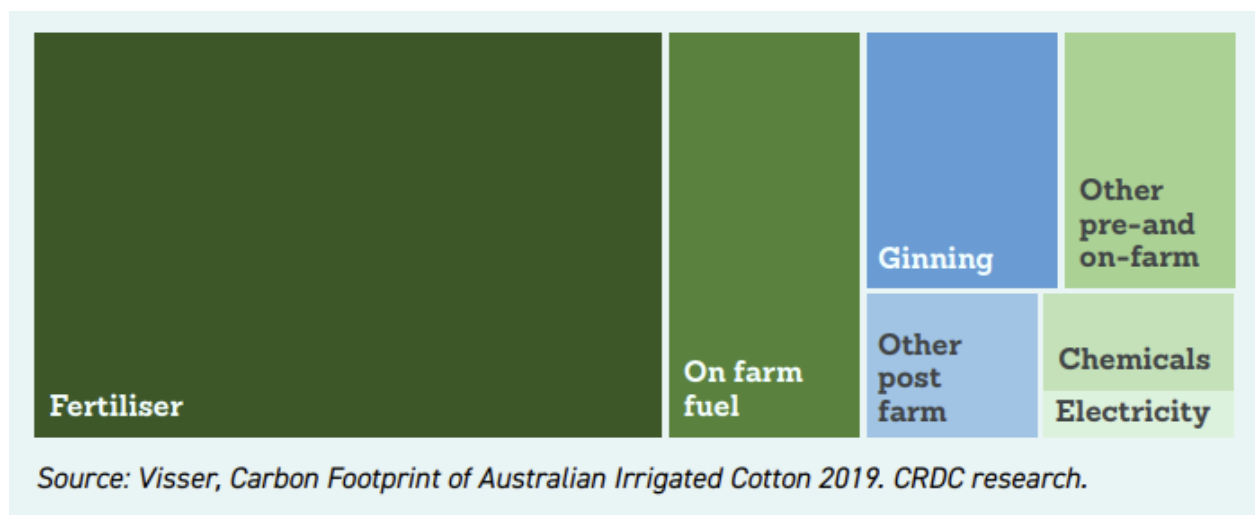


Figure 2.2-1. Sources of emissions from the production of Australian cotton

Nitrogen fertiliser is essential for cotton growth and productivity and is one of the largest contributors to the industry's GHG footprint. Life-cycle assessments indicate that nitrogen fertiliser accounts for about 60%, with emissions arising from both fertiliser manufacture and field-based nitrogen application (Sevenster et al., 2016; Hedayati et al., 2019). Overuse of synthetic nitrogen is associated with growers trying to reduce production risks. It remains a major challenge as it does not always translate into higher lint yields and can increase nitrogen losses to the environment (Macdonald et al., 2018; Scheer et al., 2023). These losses occur through denitrification, runoff, and deep drainage pathways and can contribute to GHG emissions and declining water quality in agricultural catchments (Macdonald et al., 2018; Scheer et al., 2023).

Recognising these challenges, industry programs such as *More Profit Through Nitrogen* (2016–2021) have highlighted the need to improve NUE to reduce production costs, cut emissions and support industry's sustainability goals. Industry benchmarking and grower surveys show considerable variation in NUE performance across farms, suggesting significant scope to reduce nitrogen inputs without sacrificing yield (Antille and Moody, 2021; Macdonald et al., 2018; Rochester, 2011; Scheer et al., 2014). Thus, improving NUE represents the largest on-farm

opportunities to reduce GHG emission intensity in Australian cotton production (Hedayati et al., 2019).

Barriers to scaling on-farm strategies to enhance NUE

Nitrogen fertiliser as a risk-management strategy

Recent research indicates that decisions on the rate of nitrogen application in irrigated cotton are made within a complex production system in which growers and advisers must balance yield potential, profitability, water-use efficiency and production risk under seasonal, soil, regional and other uncertain conditions. Applying nitrogen above the expected crop requirement can therefore function as a risk-management strategy against uncertainty in soil nitrogen supply, mineralisation, seasonal yield potential, irrigation conditions and potential nitrogen losses. This challenge is compounded by the difficulty of determining the most economic rate of nitrogen before planting, because the economically optimal rate can change during the season as weather conditions, crop development and yield potential become clearer (Macdonald et al. 2018).

Long-standing industry expressions such as “nitrogen shouldn’t be a limiting factor” and “Yield is King” can be understood as practical principles that guide nitrogen decisions under these uncertainties. The relatively high profit margins associated with irrigated cotton also increase the perceived economic consequences of under-application relative to the cost of applying additional nitrogen, which is the best lever for growers within their control.

Although additional nitrogen is frequently used as a risk-management strategy to protect yield, applications above crop requirements do not necessarily increase lint yield or profitability. Research across five commercial Australian cotton farms found consistently low fertiliser nitrogen-use efficiency and no significant effect of the fertiliser products and rates tested on lint yield, indicating scope to reduce nitrogen losses without compromising productivity (Scheer et al., 2023). The central scaling challenge is therefore not to discount growers’ and advisers’ focus on maintaining yield, but to provide reliable, locally relevant and timely information that enables them to identify the most economic nitrogen rate under uncertain production conditions. This requires a whole-farm systems approach, supported by economic analysis, that accounts for interactions among soil mineral nitrogen, in-season mineralisation, crop rotations, irrigation methods, seasonal nitrogen-loss risks, changing yield potential, profitability and production risk.

Limited information to make informed decisions

Despite decades of investment in RD&E, accurately predicting soil nitrogen supply, in-season mineralisation, crop nitrogen demand and nitrogen-loss risks under commercial conditions remains challenging. Recent Australian research has improved understanding of soil-derived nitrogen, regional variation in nitrogen performance and the effects of fertiliser timing on nitrogen recovery (Scheer et al. 2023; Smith, Fukai, and Bell 2023; Baird et al. 2025). However, translating these advances into a practical, timely and reliable method for determining the most economic nitrogen rate for individual paddocks remains difficult because nitrogen availability and crop demand vary with soils, rotations, irrigation practices, seasonal conditions and attainable yield.

Regional differences further limit the applicability of uniform nitrogen recommendations and industry-wide NUE benchmarks. Research conducted on commercial farms in southern Queensland and southern NSW found that existing industry nitrogen-performance indicators were

not suitable as universal targets because soil nitrogen supply, soil type and other constraints on yield varied among sites (Smith et al., 2023). Northern and southern cotton-growing regions also differ in temperature accumulation, season length, irrigation systems, rotations and attained yield or yield potential. In lower day-degree growing environments, including part of Southern NSW, overapplication of nitrogen may encourage excessive vegetative growth, delay crop maturity and complicate late-season crop management. Consequently, nitrogen recommendations and performance benchmarks developed in one region require local validation before being applied in another.

Growers, advisers and industry stakeholders increasingly recognise the potential for improved NUE to reduce input costs, nitrogen losses and reduction in GHG emissions, but the adoption and performance of NUE on-farm practice changes vary among farms and regions. The Australian Cotton Industry: Fourth Independent Environmental Assessment report (2024) commissioned by CRDC and Cotton Australia identified both substantial improvements in environmental performance and areas requiring further industry attention. It highlighted opportunities for further improvement through enhanced monitoring, reporting, decision-support tools and regionally tailored approaches to industry engagement and practice change. For example, there is uncertainty about whether the additional cost of using Enhanced Efficiency Fertilisers (EEFs) generates reliable agronomic, economic, and environmental benefits across different soils, irrigation systems, regions and seasonal conditions. Approximately 16% of surveyed cotton growers reported using EEFs during the 2024–25 season, with higher reported adoption in Central Queensland (38%) and among larger farms (24%), indicating that adoption is emerging but uneven across the industry (CRDC 2025). Current research is examining whether EEFs can support lower nitrogen application rates while maintaining cotton productivity and is addressing the limited recognition of EEF-specific emission factors within government GHG accounting frameworks.

However, further evidence is needed as to whether EEFs used at appropriately adjusted nitrogen rates as part of integrated irrigation and nitrogen management strategies can maintain lint yield, fibre quality, improve NUE, reduce GHG emissions and deliver positive net financial returns. These trials could help determine whether combined improvements in water and nitrogen management can maintain lint yield and fibre quality, improve NUE, reduce GHG emissions and deliver positive net financial returns. Research should be embedded and co-designed within regional cotton farming systems to help build confidence among growers and advisers through generating evidence on where and under what conditions EEF adoption provides sufficient value to encourage wider practice changes.

Timing and application methods

Australia's irrigated cotton industry is predominantly composed of large-scale family-operated farms. Labour efficiency, equipment access, and infrastructure limitations often influence fertiliser practices. As a result, many growers have traditionally relied on large pre-plant nitrogen applications. This approach stems from historical practices in the industry, where all seasonal nitrogen was applied upfront. However, applying a large proportion of seasonal nitrogen before crop establishment can reduce synchrony between nitrogen supply and crop uptake during peak demand periods and may contribute to lower NUE (Baird et al., 2025).

The timing of nitrogen application is determined not only by crop demand but also by practical and logistical considerations associated with in-crop application. Once the crop canopy closes, accessing fields with machinery becomes difficult and risky. Moreover, many farms lack fertigation or side-dressing capabilities for in-season nitrogen application. Pre-planting N also simplifies labour planning by reducing workloads and machinery demands during the busy mid-season. Irrigation system choice and management are also influenced by labour and water considerations, with some irrigation systems providing opportunities to apply fertiliser through irrigation (Roth et al., 2013).

To offset anticipated early nitrogen losses and uncertainty about seasonal conditions, growers may apply higher pre-plant nitrogen rates than ultimately required by the crop, which can increase total seasonal nitrogen rates and contributes to low NUE (Baird et al., 2025). This decision is also made in the context of seasonal variability and unpredictability, which strongly influence irrigation requirements and water-use efficiency. Australian cotton production is exposed to substantial variation in rainfall, including droughts and flooding rains, while water availability is a major constraint on production (Roth et al., 2013). However, recent studies highlight a shift away from large, single pre-plant nitrogen applications toward more split or in-crop applications that better align nitrogen supply with crop demand (Baird et al., 2025). In-crop nitrogen application can reduce early-season nitrogen losses (e.g. N₂O and other gaseous losses) by better matching fertiliser supply with crop demand and avoiding high-loss periods after initial irrigation, without compromising yield (Baird et al., 2025).

Limitations of soil testing devices and limited use of other decision support tools:

Research indicates that a significant amount of nitrogen used by cotton can come from pre-existing soil pools, including mineralisation of soil organic nitrogen, residual fertiliser and nitrogen returned through crop residues. Across five commercial Australian cotton farms, Scheer et al. (2023) found that, on average, only 17% of the nitrogen taken up by the crop was derived from fertiliser applied during the study. Similarly, Baird et al. (2025) found that soil-derived nitrogen supplied 60–75% of plant nitrogen in the field experiments examined. Interviews conducted by CSIRO also indicated that some growers assess nitrogen use across the crop rotation, considering nitrogen not taken up by the current cotton crop as potentially available to subsequent crops rather than necessarily lost from the farming system (CSIRO, unpublished data). Together, these findings highlight the importance of considering soil-derived and residual nitrogen in nitrogen management, including its potential contribution to subsequent crops (Schwenke et al., 2021). However, the availability of residual nitrogen to subsequent crops can vary with soil and seasonal conditions (Bell et al., 2025)().

Soil testing is often treated as a foundational decision-support tool for nitrogen management; however, its effectiveness is constrained by paddock-level soil variability, logistical and methodological limitations rather than by grower uptake. Indeed, CRDC survey evidence indicates that soil testing is already widely used, with 77% of surveyed cotton growers reporting that they conducted soil testing for mineral nitrogen before cotton planting in 2024-25 (CRDC, 2025). Soil testing utility for farmers is also constrained by the time it takes to collect samples and send them to the lab, particularly samples from remote areas, where results may not arrive for two weeks

(CSIRO, unpublished data). This may not be in line with farmers' logistical requirements to apply nitrogen before rain events; they are often carrying out operations within limited weather windows. This turnaround constraint may be less material for water-run nitrogen in irrigated systems, where application can occur through irrigation, but may still be relevant where decisions depend on narrow operational or weather windows. Additionally, in large and spatially variable paddocks, limited sampling density can reduce the representativeness of soil test results for whole-field applications. Researchers in the More Profit from Nitrogen program ensured the method provided comprehensive coverage, but also observed that the number of soil cores collected was often inadequate to capture paddock variability, which they considered a likely contributor to growers' lack of trust in soil testing (Schwenke et al., 2021). Under these conditions, soil testing is more suited to periodic validation and longer-term planning than to time-critical fertiliser decisions.

Scaling pathway – coordinated and integrated approach to enhance NUE and realise low-carbon cotton for Australia

Until now¹, there have been limited external imperatives, legal requirements, or incentives for Australian cotton growers and industry stakeholders to accelerate on-farm practices that would improve NUE. This low rate of NUE uptake contrasts with the success of cotton's area-wide integrated pest management (IPM), where there are strong motivating factors. The IPM initiative has achieved an impressive 92% reduction in pesticide use in cotton farming and earned global recognition for producing low-pesticide cotton (refer to the success story of the industry's integrated pest management in the box below).

¹ Current drivers, as at early 2026, include price shocks and volatility in fuel and fertiliser costs associated with war and supply chain risks.

A survey of 28 growers and consultants (CSIRO, unpublished data) indicates that the cotton industry may be at a turning point in its efforts to adopt low-carbon practices. This shift is driven by the success and existing cultural and social opportunities the cotton industry is uniquely known for, being a proactive knowledge sharing and collaborative community; Australia's national commitment to achieving net-zero emissions; an emerging narrative about the urgency to reduce GHG emissions in the agricultural sector; the demands of global markets for product sustainability evidence; and the need to improve soil health as a means of sustaining longer-term farm productivity. These drivers also underpin emerging whole-of-system approaches, such as the cotton LEIFS program in NSW and Queensland, which recognise that improving environmental

Box 2.1 - Scaling Success Story of Integrated Pest Management (IPM) that led to Australia's Low-Insecticide Cotton: Integrated, Collaborative, Area-Wide Approaches

Australian cotton growers reduced insecticide usage by 96% per hectare between 1998 and 2023 (five-year average) as GM cotton and IPM were introduced. The industry's dramatic reduction in pesticide use was triggered by a crisis of escalating pest resistance and rising control costs, reaching a tipping point that forced growers to seek sustainable alternatives. According to Wilson et al. (2018) this led to the accelerated adoption of a holistic, year-round IPM framework integrating pest ecology, resistance management, and strategic decision-making. The introduction of GM *Bt cotton* played a pivotal role by providing effective, built-in control of key lepidopteran pests, significantly reducing the need for chemical sprays. Co-developed by growers, researchers, and extension staff, the IPM system ensured strong industry ownership and practical fit. The availability of selective insecticides and clear economic benefits supported uptake, while an area-wide management approach coordinated pest control across regions to reduce reinfestation and delay resistance development. Extensive extension and education campaigns further embedded these practices, driving one of the world's most successful low-pesticide cotton industries.

outcomes may require consideration of broader system constraints and interactions rather than focusing on individual practices in isolation.

Changing the success metrics to a holistic systems approach—highlighting nitrogen efficiency, cost-effectiveness, risk management, and emissions intensity together with mechanisms that incentivise water and NUE practices—will be vital for the implementation of integrated measures to support the scaling of practices to increase NUE, maintain profitability, and help the shift to a low-carbon cotton production system.

Key insights from Case study 2

- **Technical success does not guarantee adoption:** Despite evidence that reducing nitrogen inputs can maintain yields and cut emissions, adoption remains low. This shows that technical feasibility and profitability are necessary but not sufficient to motivate practice change.
- **Risk management and whole-of-business priorities shape nitrogen decisions:** Growers may overapply nitrogen as this is the only decision they control against uncertainty and the risk of yield limitation, particularly where water availability and seasonal conditions create uncertainty about crop yield potential. From a whole-of-business perspective, maintaining

sufficient nitrogen to avoid yield limitation can therefore be economically rational, given that nitrogen is a relatively low-cost and comparatively easy-to-manage input relative to other yield-limiting factors such as seed, water and disease. These considerations suggest that strategies to improve NUE need to address the broader risk, water and profitability context in which nitrogen decisions are made.

- **Information gaps and complexity slow uptake:** Regional variability, uncertainty about alternative fertilisers, and limitations in diagnostic tools make decisions complex. Adoption depends on locally validated evidence and simple, trusted decision-support systems.
- **External drivers accelerate change:** The success of integrated pest management was linked to strong incentives and coordinated industry action. At an industry level, NUE currently lacks similar widespread imperatives, although some cotton businesses have already developed markets and sustainability credentials around improved environmental performance. Emerging pressures such as net-zero targets, global market demands, and soil health concerns could create a tipping point across a broader part of the industry if paired with systemic enablers.
- **Integrated nutrient and water management is important for scaling NUE:** Large-scale operations and the timing of in-crop operations create practical considerations for nitrogen management, including labour, equipment, and application timing and irrigation management. While split and water-run nitrogen applications are already established practices in Australian irrigated cotton, their contribution to NUE depends on how application timing and rates are integrated with crop demand, irrigation management and seasonal conditions (Macdonald et al., 2018; Baird et al., 2025). This suggests that improving NUE may require system-level changes in how nitrogen and water are managed, rather than scaling individual NUE practices in isolation.

3 Methods

3.1 Overview

This Chapter provides an overview of the methods used to prioritise investment options to advance low-emissions technologies for Australian agriculture.

The method uses 12 criteria to assess each prospective technology. For each industry, this Sector Technology Assessment is detailed in Appendices C.1-C.6. The technology assessment allows classification of each technology into one of seven technology archetypes (Section 3.3), each of which is aligned with a transition phase (Section 3.2, see Figure 3.1.1). This reflects recognition that technologies at different stages of development tend to share similar enablers and constraints to scaling (Murphy et al., 2025). While every technology has unique attributes, a similar (and limited) set of actions can significantly progress technologies and their scaling based on common constraints and enablers (Rotmans and Loorbach, 2009). While this assumption will not necessarily apply consistently for each technology, it will be robust across a portfolio where there is a concentration of technologies within a specific archetype. This central assumption of the report is detailed in this section, and a method is set out to test its validity.

This method involves a series of analyses based on the technology assessment, including analysis of enablers (Section 3.4) and system interactions (Section 3.5). These respectively focus attention on the mechanisms and innovation system functions that are likely to enable scaling, and the wider set of cross-sectoral, technological, and socio-cultural considerations that need to be considered at a technology and portfolio level. For each technology and the wider portfolio, these analyses provide a foundation for identifying investment priorities. In this report, these analyses are supplemented with a preliminary analysis of the current directions and priorities for investment, based on data from investment information from relevant RDCs and the NZE-Ag CRC (Section 3.6). Taken together, these analyses provide a foundation for prioritisation and scaling pathways analysis (Section 3.7). The approach, and the data it relies on, have key limitations and caveats, discussed in Section 3.8.

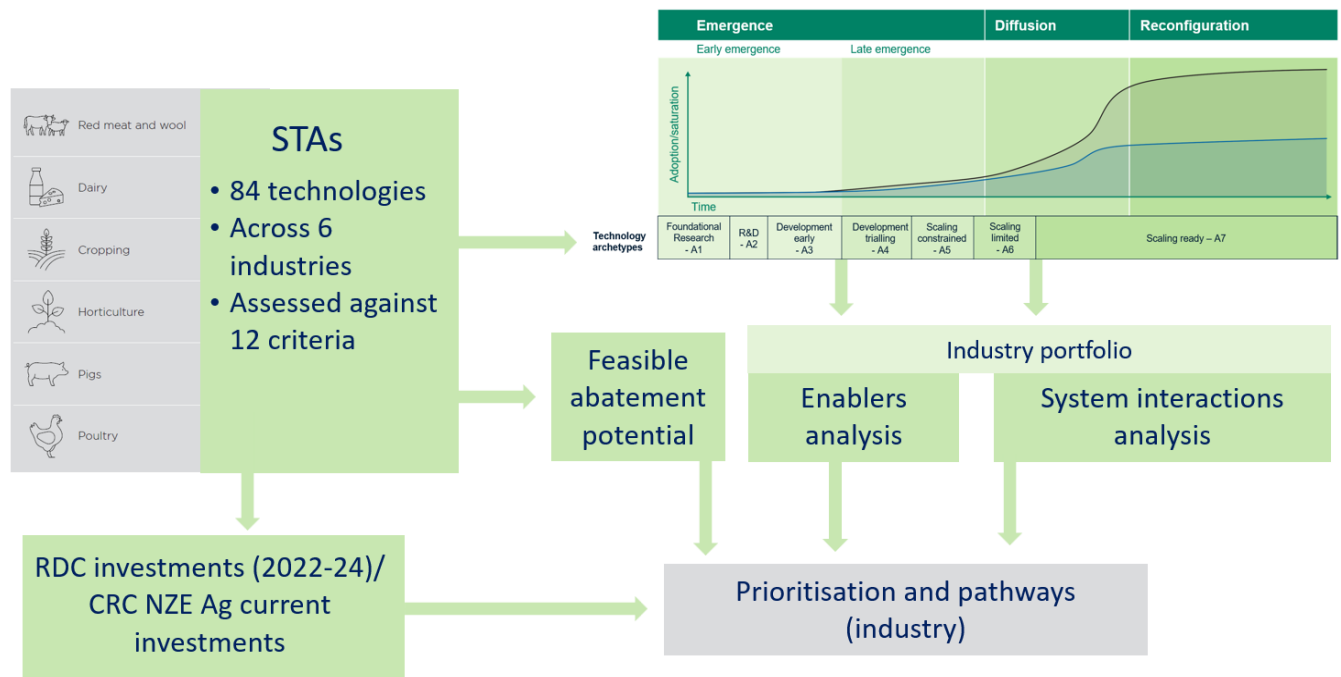


Figure 3.1.1. Overview of the process and analyses used in this report, detailed in this chapter.

The results of the approach, across the six agricultural industries, are presented in Chapter 4, and a synthesis and cross-industry analysis based on the approach here is presented in Chapter 5, with a brief review of the utility and weaknesses of this approach in Chapter 6.

3.2 Introducing the concept of transition phases

A transition to low-emissions agriculture requires shifts in practices and technologies, and significant work in the invention and scaling of new emissions reduction solutions. Widespread and far-reaching transitions of this kind are increasingly understood as the emergence, diffusion and reconfiguration of socio-technical systems. Each of these transition phases requires distinctly different forms of intervention and investment (Jewell et al., 2026; Murphy et al., 2025). Intentional transitions often require clear direction-setting and coordinated intervention across the public and private sectors to achieve goals (Rotmans and Loorbach, 2009), rather than pre-existing directions to be determined based on financial imperatives and inertia (Beck et al., 2021; Jewell et al., 2026; Mazzucato, 2016).

In this analysis, we draw on the concepts and language of the four transition phases that Murphy et al. (2025) use to convey key and common characteristics and needs across diverse sustainability transitions. This is a recent, rigorous and clear synthesis of a large body of research over many decades. Figure 3.2.1 provides a framework (adapted from Murphy et al., 2025) that outlines these phases and describes some example actions and investments typically deployed in each phase to assist in scaling. Scaling of technologies and practices here is considered integral to transitions. While it occurs largely through the diffusion phase, other phases can enable or constrain scaling.

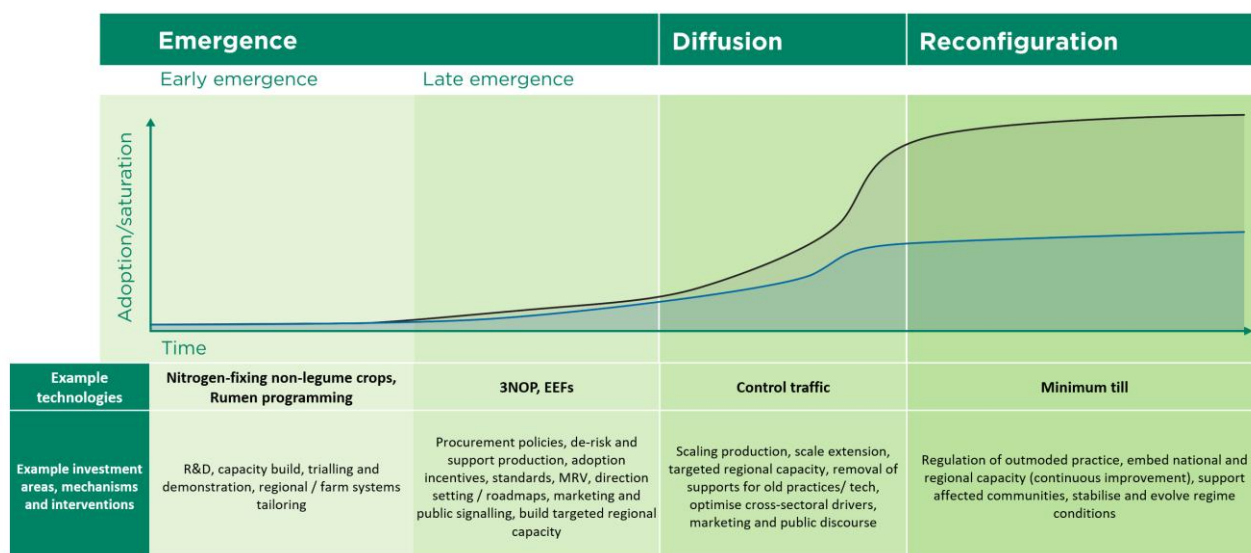


Figure 3.2.1. Overarching framework identifying different transition phases and mechanisms to advance development or scaling with different phases (adapted from Murphy et al. 2025)

3.3 Assessment of Technologies

The Technology Assessment framework used by this project was developed through a review of relevant literature, stocktake of lessons from related analysis, and engagement with other analysts doing comparable work in New Zealand and Australia. The results of this analysis are summarised in Chapter 4 and detailed in Appendix C. Further details of the method can be found in Appendix B.

Our approach considers the drivers of scaling across transition phases and types of technologies (Table 3.1). For example, the relative advantage of technologies (see Chapter 3) is a key focus for relatively mature, standalone, often replacement technologies. Thus, it is central to considering scaling in terms of the private benefits of producers. Productivity-enhancing technologies in the diffusion phase tend to score highly, whereas technologies in the early emergence phase score lower unless bold assumptions are made (Fig.3.2.1).

Our approach aimed to accommodate technologies in all transition phases. This means it needed to encompass diverse indicators. For mature technologies, indicators align with Rogers' 'triggers to diffusion' (Rogers, 2003) and reflect aspects of adoptability such as those used in CSIRO's ADOPT model (Kuehne et al., 2017). Such models are especially useful for standalone or replacement technologies because they rely on the assessment of relative advantage, which implies an understanding of the relative goals of a target population. Early-stage technologies (i.e. lower TRL, or experimental methods) require indicators and approaches to assessing them that estimate their potential value. Where details of the population for whom the technology is relevant are not known or vary widely, a generic description of value is required.

Technology Readiness Level and Commercial Readiness Level are explicitly assessed in this report. However, successful deployment and scaling are also affected by regulatory readiness and market readiness factors, including approvals, standards, MRV systems, financing mechanisms, procurement pathways and demand-side incentives. These dimensions are considered qualitatively throughout the report but are not independently scored.

The framework ultimately used 11 criteria to create brief descriptive accounts of each technology, and a comparable rating system across them (Table 3.3.1).

Table 3.3.1. Assessment criteria used in this report to evaluate technologies on their ability to advance low-emissions agriculture. Included are their definitions, rationale and measures applied. A detailed method to assess these criteria is in Appendix B.

Criteria name	Definition	Rationale	Measure
Abatement Potential (Technical)	Proportion of the GHG from the targeted emissions source that could be theoretically abated by the technology in a given year.	Helps prioritise high-impact technologies, though it lacks insight into feasibility.	% of targeted emissions
Abatement Potential (Feasible)	The estimated total feasible abatement per annum if the technology were widely adopted across a realistic range over a ten-year window. Low and high estimates are given in STAs, with the high value used in Chapter 4, as an estimate of maximum feasible potential.	Reflects the practical level of abatement possible across real-world settings. This is expressed as a range given uncertainties in adoptability, system fit, and other variables over a ten-year timeframe, contingent on incentives, capability, etc.	Mt CO ₂ -e /yr
Breadth of Application	The extent to which the technology can be applied across Australian farm enterprises.	Helps define the potential scale of applications.	high, medium, low
Co-Benefit Potential	The potential for the technology to deliver additional benefits at a business level (economic, social, environmental, cultural).	Defines key actual or potential co-benefits that may encourage adoption or enhance adoptability.	high, medium, low
Barriers and Knowledge Gaps	Evaluation of obstacles facing the technology across financial, scientific, policy, regulatory, supply chain, and market dimensions.	Identifies why technologies may fail to scale and where interventions are needed. This informs policy, investment, and research focus, and helps determine the role of government and other stakeholders in bridging the “valley of death”.	high, medium, low
Stacking Potential	The ability of the technology to combine synergistically with others for enhanced outcomes.	Supports bundling of technologies to maximise emissions reductions and cost-effectiveness.	high, medium, low
Technology Readiness Level (TRL)	A scale (1–9) assessing the maturity of the technology.	Helps gauge development risk, time to deployment, and suitable investor types. Informs how technologies can be sequenced within an investment portfolio.	1–9
Commercial Readiness Level (CRL)	A scale (1–6) assessing commercial viability and scalability of the technology.	Highlights the readiness of a technology for market uptake and identifies gaps where public investment might be warranted.	1–6

Enabling Potential	The capacity of the technology to facilitate or accelerate other abatement solutions at a system level .	Recognises system-level innovations (e.g., accounting frameworks, advisory systems) that support the scaling of other technologies; recognises that sometimes it is technology suites rather than individual technologies alone that create adoption potential and value creation.	high, medium, low
Estimated cost range	The current cost (and variability in this) of application of the technology on-farm. This will usually be in dollars per unit of production, which varies across industries.	Provides insight into the financial viability of a technology for on-farm adoption.	\$/ha/year or similar
Estimate benefits	The current financial return of application of the technology on-farm, in the same units as above, based on available valorisation.	Provides insight into the financial viability of a technology for on-farm adoption.	\$/ha/year or similar
Minimum RoI	Based on the above, minimum RoI is estimated.	Synthesise the worst case of costs and returns, to provide an indication of whether costs/benefits are likely to limit scaling.	\$/ha/year or similar

The technology assessment criteria were applied to each of the 84 technologies across the six sub-sectors according to the following broad steps:

1. Identification and validation of solutions through preliminary desktop research and early consultation.
2. Collation of sectoral and technology-specific resources: relevant and recent reports, journal articles, and relevant data.
3. Preliminary analysis of publicly available documents using a large language model (Co-Pilot 365, GPT 5 Version).
4. Validation of analysis through desktop review of resources and comparison against output of Step 3.
5. Review of preliminary technology lists (workshop #1) and preliminary analyses (workshop #2) by diverse industry and scientific experts via a series of targeted workshops and feedback on drafts (see Appendix D, for workshop descriptions).
6. Revision of analyses and summary tables developed based on outputs of Steps 4 and 5.
7. Peer review of sectoral sections by leading experts.

3.4 Assessment of Enablers

3.4.1 Technology archetypes

The technology assessment outputs were used to categorise technologies into one of seven archetypes (Table 3.4.1). Classification into archetypes (Oberlack et al., 2019) provides a diagnostic tool to help identify regularities across a portfolio of technologies, such as consistent barriers to and drivers of scaling. In this case, the archetype classifications were developed a priori, based on a classification by TRL / CRL for early stage technologies, then including key factors from the STA that constrain scaling. The approach was tested on the dataset once STAs were completed to ensure the method provide comprehensive coverage and reflected our expert assessment of where technologies sat on this transition spectrum. This approach helps to develop a line of sight between barriers and drivers, allowing identification of coordinated action or higher-level intervention and investment that may be necessary to scale multiple technologies.

Key advantages of the archetype approach:

- Firstly, it allows a better understanding of the portfolio of technologies (within a sector or across sectors), rather than focusing on each technology or practice individually. This helps define interventions and investments that ‘lift all boats’ within and across the transition phases outlined in Figure 3.2.1. For instance, public investment traditionally focuses on R&D in lower TRL technologies, but it may also be needed to overcome broader scaling constraints. For example, there may need to be investment in data infrastructure, or intervention in market functions necessary to provide confidence.
- Secondly, identification of archetype clusters within a technology portfolio can enable diagnosis of challenges to technology development and scaling. For example, if technologies are clustered in a specific transition phase (Figure 3.2.1) this may indicate a general weakness in related innovation system functions (discussed in section 3.4.3) and help define investment and intervention pathways and action.

Table 3.4.1. Definitions and classifications of archetypes used in this report, along with a rough association of phases of transition (see Figure 3.2.1). Note that A1-A4 are considered pre-scaling, but the foundations for scaling can be developed here. Boundaries of and overlap between phases are indicative and not meant to assume that just because a technology is classified as a particular archetype, that it will or will not scale.

PHASES		Early Emergence		Late Emergence			
					Diffusion		Reconfiguration
Technology Archetypes							
	Foundational research (A1)	Research and development (A2)	Development early (A3)	Development trialling (A4)	Scaling constrained (A5)	Scaling limited (A6)	Scaling ready (A7)
Definition	Basic research into mechanisms and foundational knowledge to support understanding of these	Technologies at early stages of development that are not yet being trialled	Technologies being developed in lab or research farm trials, experiments and modelling studies	Technologies being developed through plot or farm-scale trials	Technologies that are unlikely to scale without improved RoI, along with potentially addressing other barriers and risks	Technologies that could scale with intervention that removes barriers or technologies that can only be extended to relatively small geographic areas or industries	Technologies that do/should scale within existing market, policy and other conditions, if there are effective extension, networks and advisory capacity
Classification using TA attributes	TRL 1-2	TRL 3-4	TRL 5	TRL 6-7, CRL ≤3, barriers medium to high	RoI negative, high TRL and CRL (>3), any enablers and/or co-benefits are not considered	RoI positive, high TRL and CRL (>3), but with limits on scaling because of other factors: either high barriers, or low breadth of application and/or low stacking potential	RoI positive, high TRL, CRL (>3) and stacking potential, breadth of application medium to high, barriers medium to low
Key Barriers	Largely technical barriers, often incommensurable	Specific R&D barriers that are often technical, and include foresight of potential early or emerging barriers and challenges	Technology-specific R&D barriers that are mostly technical but include system fit, social acceptability and others	Technical barriers associated with moving from trialling to commercialisation and scaling, alongside the above barriers	Costs relative to returns on application, high upfront costs, and other barriers to adoption and scaling	Diverse technology-specific barriers associated with applications, systems of use, incompatibility with farm systems, and limited contexts of application	Potentially no major barriers. Sometimes, knowledge, capacity and cultural constraints among farm managers and within advisory systems, farm system groups and other elements of the extension system

The above archetypes were developed deductively prior to analysis, with two additional archetypes developed after an initial analysis of all technologies, refle:

1. **Unlikely:** Technologies that have progressed along development pathways (TRL>5), but have low abatement potential relative to the target of abatement (<5% of the emissions targeted for abatement, e.g. from manure decomposition) are classified as 'unlikely' to be prospective.
2. **Low abatement/high co-benefit:** Similar to above, but technologies that may be worth developing and/or scaling because they have high co-benefits, and emissions reductions are considered a secondary benefit.

3.4.2 Enabling mechanisms

For each technology archetype, a variety of enabling mechanisms can assist in the scaling of the technologies it encompasses. These enabling mechanisms are interventions, distinct from the enabling characteristics of the technologies themselves (Section 3.3). Enabling mechanisms range from programs that build extension capacity, to infrastructure that supports information and data exchange, to basic research, to demand-side interventions that raise awareness or promote certain products, to market regulations and non-tariff trade barriers that create clear rules for investment and market function. Specific examples of enabling mechanisms are provided in Table 3.4.2. These mechanisms were identified through our background review of transitions and innovation literature (e.g. Hall et al., 2024; Hekkert et al., 2007; Jewell et al., 2026; Moallemi et al., 2025; Murphy et al., 2025; Sovacool et al., 2025). They are not intended as a comprehensive or prescriptive checklist, but as a strategic framework to guide decision-making and investment. By considering combinations of enabling mechanisms across the agriculture and food sectors, and the broader economy, this approach helps define sectoral investment pathways to support a pipeline of desirable, feasible, and scalable emissions reduction technologies. We return to actions in chapter 5, defining enabling actions under four intuitively accessible categories:

- a) Technology and infrastructure;
- b) Markets and regulation;
- c) Coordination and innovation; and
- d) Capability and extension.

These categorical alignments between groupings and mechanisms are included in Table 3.4.2, highlighting a general shift in mechanisms that are appropriate to different archetypes, which we discuss in the next section.

Table 3.4.2. Examples of enabling mechanisms appropriate for different technology archetypes, and associated with different groupings, which we return to in Chapter 5: a) Technology and infrastructure (T&I); b) Markets and regulation (M&R); c) Coordination and innovation (C&I); and d) Capability and extension (C&E).

Technology Archetype	Key objectives of enabling action	Enabling Mechanisms (examples only)
A1. Foundational Research (TRL 1-2)	Provide a foundational understanding necessary to facilitate the development of emissions reduction technologies and pathways for the future.	C&I: Challenge-focused innovation system actions. C&I: Long-term funding. T&I: Investment into R&D infrastructure and capability. C&I: Fore-sighting and anticipation. C&I: Collaborative research initiatives to pool expertise. C&I: Exploratory projects that improve fundamental understanding of mechanisms. C&I: Inter- and intra-national collaborations and science challenges.
A2. Research and development (TRL 3-4)	Develop prospective technologies and mobilise appropriate knowledge and expertise to assess and validate these, and overcome specific technical problems.	C&I: Competitive R&D grants focused on a promising concept. T&I: Prototype development funding to move from concept to lab prototype. C&I: Building of innovation system networking (interdisciplinarity). M&R: Crowd in investment (e.g. venture capital).
A3. Development Early (TRL 5)	Advance applied research and co-design with stakeholders to ensure system fit and acceptance, prototype testing & co-design.	T&I: Pilot studies on research farms to test technology in controlled real-world settings. C&I: Stakeholder workshops with producers, advisors, and regulators to gather feedback and align the innovation with on-farm realities (i.e trans-disciplinarity). C&I: Small-scale “innovation hub” trials that involve end-users early, fostering familiarity and trust in the technology.
A4. Development Trialling (TRL 6–7, CRL ≤3)	Create conditions for successful transition from trials to commercial readiness, through demonstration projects and coordination across actors; build trust in adoption population; create opportunity for transdisciplinary knowledge exchange; understand place-based or contextual matters that will impact scaling.	C&I: Deep technology commercialisation facilitation, incubation or accelerator programs to support startups/commercial entities bringing the tech to market, offering mentorship, business development, and regulatory navigation. C&E: Entrepreneurship and mentorship. C&I: Public–private partnerships (e.g. RDCs with agri-tech companies) to share costs and expertise in scaling up. C&E: Farm-scale demo trials in diverse regions to prove effectiveness and refine performance in different contexts and understand how technologies fit with existing enterprise systems. T&I: Providing common user infrastructure (such as footprint calculators, digital infrastructure such as soil attribute maps and regional emissions baselines or experimental monitoring facilities to test technologies).
A5. Scaling Constrained (ROI negative without incentives, high TRL/CRL, but med to high co-benefits)	Reduce costs and/or increase financial benefits, often through market creation and incentives and other interventions to improve economic viability and reduce risk.	M&R: Premium markets for low-emission products: develop small to medium market niches to provide premium prices, allowing economies of scale to reduce costs of technology. M&R: Direct payments and incentives: Use of public and/or private funds to incentivise and potentially scale uptake of emissions reduction technologies. M&R: Pricing or penalty mechanisms to create market demand supported by accounting and reporting requirements. M&R: Public procurement policy: using the scale of government to create niche markets for low-emissions technologies. M&R: Supply chain reporting rules facilitated by standard accounting methods that creates trusted evidence of different product credentials and may support procurement preferences or lead to down supply change pressure for performance improvement. C&E: Build regionally specific information on extent of co-benefits and how these impact the ROI.

A6. Scaling Limited (RoI positive, high CRL (>3) and TRL, no pronounced benefits, low to medium breadth of application)	Update outdated best practices and approaches. Improve siloed/narrow information availability. Address constraining industry/government/ research perspectives, remove subsidies for blocking technology that is more GHG-intensive.	C&E: Robust extension programs to update best practices and train advisors/producers in using the technology optimally, development of information that documents suitability for particular geographic and enterprise context. C&E: Cross-industry learning networks for sharing experiences and troubleshooting incompatibilities (e.g. user groups, field days). T&I: Targeted R&D for adaptation of the tech to new regions or farming systems (refine the innovation for broader contexts, bridging any remaining technical gaps). C&I: Working groups that bring together researchers, industry reps, and producers to align on improving system fit and build legitimacy and support. M&R: If extent limited by regulation or risk – robust evaluation of risks and investigation of mechanisms to reduce risk and communicate to consumers.
A7. Scaling Ready (RoI positive, high TRL, CRL (>3) and stacking potential, breadth of application medium to high, barriers medium to low)	Promote adoption of proven, mature and commercially ready technologies, removing remaining barriers and building wider capacity to embed, scale and re-orient, potential away from outmoded technologies (dis-adoption, exnovation).	C&E: Producer-led demonstration sites and case studies that show real-world success and fuel peer-to-peer learning. C&E: Extension investment M&R: Disincentives, norms and other interventions for phase out for replaced technologies

3.4.3 Innovation system functions

To accelerate sectoral abatement, the innovation system needs to possess a range of capabilities or ‘functions’. We use a set of innovation system functions developed through a recent research collaboration between CSIRO, ABARES and DAFF (see Hall et al., 2024), which sought to understand how different functions within an innovation system can catalyse diverse sustainability goals (Table 3.4.3). These draw from a long-standing tradition and analytical approach in innovation research (Hekkert et al., 2007). These functions span supply-side, intermediating, and demand-side capabilities. Each function represents the capability of the innovation system to deliver a range of mechanisms to catalyse progression of technologies across the transition phases in Figure 3.2.1. Identification of strong, weak or missing functions helps to understand where and scaling is supported or constrained across a technology portfolio. Similarly, if technologies are predominantly clustered in a specific archetype, we might diagnose a clearer demand for functions that are necessary in the related transition phase (Figure 3.2.1).

Table 3.4.3 Innovation system functions (i.e. capabilities) needed to catalyse sustainability transitions (based on Hall et al. (2024) and Hekkert et al. (2007)). Supply here refers to the development of resources and assets that enable innovation to meet demand from the market or policy audiences for these, where intermediating functions ensure this connection between supply and demand works effectively, efficiently, and legitimately, especially through direction-setting, coordination and learning across an innovation arena.

Supply-side functions (to enable the use of resources to create new solutions)	
SF1	Generate knowledge, ideas and technologies – The capability to develop the intellectual foundations for novel approaches and technologies.
SF2	Mobilise networks – The capability of diverse knowledge, rights and stakeholders to frame problems and bring the right expertise and experience to bear.
SF3	Resource mobilisation – The capability to mobilise financial capital and infrastructure to create new outputs and processes.

Intermediating functions (to support interaction and coherence across system elements and actions, including alignment to goals)	
IF1	Direction setting – The capability to articulate innovation goals that reflect national, community, and industry values.
IF2	Legitimizing – The capability to garner widespread support for innovation pathways and actions.
IF3	Coordinating and synchronising – The capability to reconfigure and coordinate action across actors, institutions, and scales, including niche protection.
IF4	Learning and improvement – The capability to generate insights to manage system performance and feed lessons back to stakeholders.
Demand-side functions (to enable the use of resources to build demand)	
DF1	Definition and activation of pathways – The capability to enable experimentation, de-risking, and entrepreneurial risk-taking.
DF2	Diffusion and uptake – The capability to facilitate interest in, access to, and adoption of novel outputs across networks.

The need to strengthen specific functions depends on three key factors: (1) the clustering of technologies within archetypes, and (2) the outcomes we aim to achieve, and (3) the investment capacity available. In other words, what we choose to do is shaped by the current state of the innovation system, our goals, and the levers of change we can activate.

If the goal is to build technologies that could scale in the future (given favourable market conditions such as higher carbon prices) then investment should focus on supply-side functions (especially SF1 and SF3). This builds a stack of technologies ready to deploy when conditions shift, with emphasis on the early stages of development (A1–A3).

If the goal is to scale technologies that are already delivering a financial return on investment under current market conditions, then intermediating functions (IF1–IF4) become more important, alongside continued supply-side support. This enables existing options to be adopted more widely and effectively.

If the goal is to reduce GHG emissions as rapidly as possible, then all functions will likely need to be activated, as all phases in a transition pathway would need to be well supported. This includes targeting multiple archetypes and investing in demand-side and intermediating functions—such as creating innovation niches, enabling experimental activity, and building incentives into the market to catalyse economies of scale through market demand (see Box 3.1).

Box 3.1. An overview of demand-side functions, mechanisms and the incentives they create

Demand-side functions can speed up adoption and scaling by creating credible, sustained “pull” for low-emissions solutions rather than relying on voluntary uptake via inherent private value (e.g. ROI) of a solution. These functions can help create innovation niches as a protected space, where early demand and learning-by-doing can be developed within incumbent market regimes (Smith and Raven, 2012). Governments can and often do shape markets via demand-side functions by setting directions and goals and using demand-side mechanisms such as strategic procurement policies, guidelines or standards to create such niches, and direct private investment and capability (Mazzucato, 2013). In Australia, for transition purposes, such mechanisms (including rebates, tax incentives and more) have effectively scaled solar PV, EV and home battery uptake over recent years.

Common mechanisms include: (1) Public procurement and purchasing standards or rules that create early demand (e.g., contracts specifying low-emissions performance across government agencies), reducing buyer risk and enabling suppliers to scale production (Murphy et al., 2025); (2) Standards and guidelines that define “acceptable” performance and claims (e.g., procurement specifications or value-chain rules), creating market-access and reputational incentives even where prices do not yet fully reward abatement (Murphy et al., 2025); (3) Outcome-based incentives—rebates, tax credits, feed-in style payments, or results-based contracts—that improve returns and accelerate diffusion by lowering effective costs and rewarding verified performance (Nuñez-Jimenez et al., 2022), and; (4) Demand-pull commitments (e.g., advance purchase commitments or milestone contracts) that de-risk investment and speed learning-by-doing, lowering costs and revealing delivery constraints early (Murphy et al., 2025).

In practice, these instruments work best as coordinated policy mixes that move quickly from pilots to wider efforts that combine near-term demand signals with credible measurement and standards, so uptake becomes repeatable and scalable (Geels, 2011).

Thus, innovation system functions are associated with sets of mechanisms that are variously enabling for technologies within differing archetype classes. Table 3.4.4 draws together and simplifies a rich set of theoretical and empirical contributions on socio-technical transitions and investment and interventions to scale them. It provides a useful tool for assessing alignment between existing technologies and investments and the sorts of goals outlined above. It is worth noting that different mechanisms take different forms when associated with different functions, or for different technology archetypes. For example, living lab models in early-stage development of technologies may be oriented to foresighting and understanding prospective risks and pathways; in commercialisation processes, they may be about prototyping and trialling. Similarly, public procurement can be a direction-setting initiative (IF1) to provide signals to markets as well as a means of activating technology and wider innovation pathways (DF1).

Table 3.4.4. A condensed set of mechanisms associated with differing technology archetypes and innovation system functions.

Technology archetype class	Supply-side functions (to enable the use of resources to create			Intermediating functions (to support interaction and coherence across system				Demand-side functions (to enable the use	
	SF1	SF2	SF3	IF1	IF2	IF3	IF4	DF1	DF2
A1. Foundational Research (TRL 1–2)	Long-term challenge-focused research programs; Investment in research infrastructure and capability; Exploratory fundamental research projects	Coordinated collaborative research initiatives	Long-term challenge-focused research programs Investment in research infrastructure and capability	Strategic foresighting and anticipatory research					
A2. Research and development (TRL 3–4)	Competitive R&D grants for promising concepts; Prototype development and concept-to-lab translation	Innovation-system networking to build interdisciplinary linkages	Competitive R&D grants for promising concepts Prototype development and concept-to-lab translation						
A3. Development Early (TRL 5)	On-farm pilot studies	Stakeholder co-design workshops Innovation-hub or living-lab models for early end-user engagement			Innovation-hub or living-lab models for early end-user engagement				
A4. Development Trialling (TRL 6–7, CRL ≤3)	Provision of common-use infrastructure			Cross-industry learning networks and user groups	Innovation-hub or living-lab models for early end-user engagement	Public-private partnerships for scaling and cost sharing Provision of common-use infrastructure		Deep tech commercialisation support (incubators, accelerators, mentoring)	Diverse farm-scale demonstrations/trials across regions and systems
A5. Scaling Constrained				Public procurement; Direct incentive payments and subsidies	Supply chain reporting and transparency	Public procurement		Creation of premium markets for low-emissions products; Direct incentive payments and subsidies; Pricing/penalty mechanisms; Public procurement; Supply chain reporting and transparency	
A6. Scaling Limited						Cross-industry learning networks and user groups	Cross-industry learning networks and user groups		Extension programs; Cross-industry learning networks and user groups
A7. Scaling Ready				Provision of common-use infrastructure			Cross-industry learning networks and user groups	Pricing/penalty mechanisms (replaced tech/practices)	Extension programs; Diverse farm-scale demonstrations/trials across regions and systems

3.5 System Interaction Analysis

System-level drivers of scaling beyond the farmgate will enable or constrain the effective deployment of technologies across regions and sectors. Identification and assessment of these system-level drivers by this project was largely qualitative, based on expert assessment that included input from participants in workshops and discussions (see Appendix D). While it does not form a major part of the report, it is recognised that technology pathways have often historically been significantly affected, for better or worse, by system-level drivers that were unexpected. Paying attention to and tracking these emerging drivers can help ensure technological pathways advance goals and avoid pitfalls and risks. The categories below were used to organise participant responses, and reflect a wider literature about systemic, structural and enabling considerations (Scoones et al., 2020).

Technological and infrastructure interactions: Technologies in agriculture will interact with a wider technological system. Some technologies require access to other enabling infrastructure for their widespread implementation – this might include green energy, high-speed internet, AI, rail links and costs of bulk commodity transport. Technological change outside of agriculture will structure technological pathways inside it. Similarly, technological change within agriculture can rapidly shift optionality. For instance, some technologies are mutually substitutive. If a methane vaccine could be effective and efficient, targeting the same emissions through more expensive feed supplements may no longer be necessary.

Cross-system and cross-sector interactions: Realisable abatement will inevitably be lower than the aggregated technical potential due to resource overlaps and substitution effects across technologies and sectors. Conversely, innovation in one sector may spill-in to agriculture, as it can spill across industries within agriculture. Examples of such inter-sectoral change are prospective growth in cell-cultured meat affecting traditional meat markets, or growing demand for bio-feedstocks for the manufacture of low-carbon liquid fuels shifting demands on cropping systems and wider land management.

System interactions among technologies, and with wider market, geopolitical and other shifts can be synergistic, leading to mutually positive outcomes, or antagonistic, leading to poor outcomes in one sector or geography while others benefit. Such outcomes are often very hard to predict but can be foreseen as potential scenarios and managed through pathways planning. Agriculture labour constraints and competition have historically been exacerbated by mining booms (and such dynamics have the potential to limit the application of emissions reduction technologies that require skilled labour on-farm).

Socio-cultural interaction: Various lock-ins and shifts in thinking, beliefs and practices across the innovation system can affect the development, adoption and scaling of technologies. These range from the views held by researchers and policy-makers about what the problems and solutions are, to producers' beliefs about best practice, to judgments among social networks and consumers about technologies, risk and outcomes. Resistance to policies, methods, or technologies may arise from competing values or perspectives. These tensions can reduce social acceptability and hinder widespread adoption, or specific development pathways. They will be reinforced by any lack of internal consistency between claims, methods, and the technologies or practices implemented,

which can undermine the credibility and legitimacy of initiatives, especially at scale. Social acceptance is shaped by prevailing values, identities, and skills. While these factors are difficult to predict or directly influence, work to build alignment between economic, environmental, and social value can accelerate scaling, and needs to be taken seriously in any realistic change process.

Cross-sectoral transformation effects: Structural changes, such as the growth of firmed renewable energy, can enable the adoption of complementary technologies (e.g. electric farm equipment), by altering infrastructure, cost structures, and system dynamics. The integration and alignment of production and consumption systems (e.g. food, energy, materials) can create new synergies or barriers, depending on whether interdependencies support or conflict with adoption goals.

3.6 Investment and Prioritisation Assessment

The penultimate assessment uses data from previous analyses to identify where and why high-potential technologies are and are not receiving sufficient investment to achieve their potential. This analysis involved four steps:

3.6.1 Classification of absolute abatement potential

High-potential technologies are those that can reduce scope 1 emissions significantly within the next decade. To reflect the high degree of uncertainty and wide range in absolute abatement potential, especially for low TRL technologies, absolute abatement potential was classified on a three-point ordinal range. The classification is based on the percentage of total agriculture sector emissions that could be mitigated by the technology. This rating is calculated by dividing the maximum feasible abatement (see Table 3.3.1) by the total farm-level emissions, based on NGGI (2025) figures (79 Mt CO₂-e/year). Three classes that make intuitive sense in discrimination across the frequency distribution were used as follows:

- Low – <1% of all agricultural scope 1 emissions (0.01 x 79 Mt CO₂-e/year =<790 kt CO₂-e/year)
- Medium – 1-2% of all agricultural scope 1 emissions (790 -1580 kt CO₂-e/year)
- High – > 2% of all agricultural scope 1 emissions (>1580 kt CO₂-e/year)

3.6.2 Classification of sub-sectoral abatement contribution

Classification of absolute abatement (above) is important for consideration of agriculture's contribution to national emissions. It is also crucial for individual sectors to improve their own footprints and emissions intensity of products. The ability of any given technology to contribute to sub-sectoral emissions reduction, within 10 years, is estimated using a similar three-point ordinal range as above, this time calculating the proportion of total annual emissions of a given industry relative to the technology's maximum feasible abatement potential. Again, three classes were defined through the distribution of the results into intuitively sensible groupings:

- Low – abatement potential less than 1% of annual sub-sectoral emissions
- Medium – between 1-10% of annual sub-sectoral emissions

- High – greater than or equal to 10% of annual sub-sectoral emissions

3.6.3 Confidence assessment

A simple assessment of confidence is given by the ratio of the lower and upper estimates of feasible abatement for each technology. These ratios provide a tercile range:

- Low – lowest tercile (0 – 0.33)
- Medium- middle tercile (0.33 – 0.66)
- High – highest tercile (0.66 – 1.0)

These classifications provide an approximation of the degree to which feasible abatement can be accurately assessed based on currently available data and research, and therefore an assessment of confidence in the abatement ratings above.

3.6.4 Analysis of current investment

Public and private resources are currently being directed across a range of low-emissions agriculture technologies to address various enablers and constraints facing existing and prospective options. A preliminary investment analysis was undertaken to develop a snapshot of the investment landscape in terms of overarching direction of investment.

A full analysis of investments would evaluate public and private sector efforts and relevant investments in innovation system functions and wider capabilities to advance emissions reduction. This could include, for example, public sector development of carbon markets (e.g. The ACCU Scheme, Safeguard Mechanism) and incentives, capacity building initiatives, and frameworks and data infrastructure for supply-chain transparency and accountability. This would inform the most efficient deployment of resources to address the creation and scaling of technologies.

Within the limited scope of this project and the wide range of technologies identified, the investment analysis focused on: a) defining a set of potentially impactful technologies across the range of archetypes in Table 3.4.1 for each industry sector addressed by the project; b) classifying each priority technology in terms of existing investment, and; c) rating existing investment relative to the abatement potential of the technology (high, medium, low – see Table 3.6.1) .

For each of the identified priority technologies, we gauged the scale of overall Australian and international investment in research, development and commercialisation, via:

- Preliminary assessment of the quantum of funding associated with each technology in Australia and internationally, employing the assistance of artificial intelligence to undertake a scan of publicly available online information.
- Assessing available data on domestic RD&E ecosystem investment in these priority technologies and their associated enablers.

For the latter a list of investments and grants was sourced from the Council of RDCs which provides an indicative picture of investment across three financial years, 2022/23, 23/24, and 24/25. These data were sought for RDC projects that had a primary focus on emissions reduction and provide an aggregated picture of RDC investment across key drivers/ opportunities in

emissions reduction. Data were collated for the desktop stocktake, for DAFF internal purposes only. While this high-level, indicative information is not completely up-to-date, or comprehensive, or developed for this report, it provides a reasonable approximation of where effort is concentrated across the Australian RDC system, which comprises about half of the total annual investment in agricultural RD&E (Chancellor, 2023). RDC data was supplemented with investments by ZNE-Ag CRC, as published on their website on 01/03/2026. While these are not an ideal set of investment information, they provide a relevant snapshot of the direction of investment and prioritisation at the outset of this project.

Each identified investment / project was classified via project descriptions, to estimate how much investment within the sample was being directed to: different industries, innovation system functions, enabling mechanisms and technologies. Classification was done via reading project descriptions and labelling each project by industry, innovation function, enabling mechanism and technology. Where projects were aligned with more than one of any of these, investment was allocated as follows:

- Industry: up to two coded, all investment allocated to each industry assuming equal applicability/benefit
- Innovation function: up to two coded, investment split evenly across these (i.e. 50:50)
- Mechanism: up to three coded, investment split evenly across these (i.e. 33:33:33)
- Technologies: up to four coded, investment split evenly across these (i.e. 25:25:25:25)

Investment in technologies is rated in ranges: \$0-100K, \$100K – \$500K, \$500K-\$1mill, \$1- \$5mill, \$5- \$10mill, and then in steps of \$10,000,000.

This resulted in tables that split overall investment within the sample by the above categories, allowing for indicative analysis of where resources were flowing to.

Using investment and maximum feasible abatement potential ratings above, a simple classification was used to rate technologies in terms of alignment between the relative scale of investment and the technology's abatement potential. This classification does not indicate whether investment should be higher or lower, as the classification reflects only two parameters. There are many other reasons why investment may be high. Chiefly, many technologies that have potential profitability or productivity benefits may receive high investment despite relative low projected emissions reduction benefits ("Other investment goals?" in Table 3.6.1). For this classification, each technology is allocated to one of nine cells (Table 3.6.1). This provides an entry point for more targeted analysis, deliberation and debate about investment options and opportunities.

Because classification relied on project descriptions and the dataset primarily covered projects with an explicit emissions-reduction focus, the analysis may not capture broader investment in genetics, productivity, feedbase, animal health, adoption, extension and enabling infrastructure that also contributes to emissions outcomes. Absence of identifiable investment in a technology category should therefore not be interpreted as absence of relevant investment.

Table 3.6.1. Framework for the classification of technologies in terms of relative investment and abatement potential within the sample. Where data were available, the framework was applied to classify technologies in terms of both absolute abatement potential (section 3.6.1, above) and sub-sectoral abatement (section 3.6.2).

	Low potential abatement	Med potential abatement	High potential abatement
Low investment	Benign neglect	Untapped potential	Missed opportunity
Medium investment	Other investment goals?	Well-supported	Untapped potential
High investment	Other investment goals?	Well-supported	Well-supported

3.7 Scaling pathways for sub-sectors and sectors

The final analysis presented for each sub-sector in Chapter 4 is a synthesis of opportunities to focus investment. This analysis draws on previous sections to:

- Identify and address priority barriers (identified in the technology assessment) and key risks (systems interactions)
- Identify and enhance critical enabling mechanisms
- Define and capitalise on opportunities, or
- Clarify reasons that the investment/intervention may not be warranted

For each sub-sector, a logic is presented that links these barriers and opportunities to a set of actions or areas of activity, framed in terms of three time-horizons that align with the objectives and timelines of the Agriculture & Land Sector Plan:

- Horizon 1 (now- 2030):** The actions, investments and interventions that are best focused on between now and 2030, including scaling of win-win technologies and building the foundational capacity, infrastructure and resources to ensure agriculture can appropriately build pathways to low-emissions production in the 2030s.
- Horizon 2 (2030-35):** The actions, investments and interventions that are likely to be the key focus in the early 2030s, and would enable more rapid development and scaling of technologies in the latter part of that decade.
- Horizon 3 (2035 onwards):** The actions, investments and interventions post-2035 that would support a more rapid scaling of developed technologies and maintenance of progress on low-emissions options and pathways into the future

While progress may move faster or slower than projected, with high potential for unexpected and emergent events and technologies to re-orient priorities in this timeframe, these horizons provide a rationale around sequencing and prioritisation. As explored, differing government and industry goals will imply weighing actions and investments differently.

3.8 Limitations of method and design

The approach developed in this chapter provides a structured framework for assessing and prioritising investments across technology pathways. It draws on, and extends contemporary theory and methods from agricultural adoption research, sociotechnical transitions, and systems innovation studies. In the absence of readily applicable approaches in the published literature, the framework was developed and applied within this report to meet the objectives set out in the project scope (see Section 1.2).

Three key limitations of the approach should be noted from the outset.

1. Data availability, comparability and robustness.

Many of the data required to undertake the assessments and analyses outlined in this chapter are unavailable, incomplete, difficult to validate, or derived from contexts that do not align well with the national focus of the project. This reflects the relative novelty of research on agricultural emissions-reduction technologies at scale, the complexity of the underlying drivers, and the limited formal evaluation of individual technologies. In some cases, relevant information—particularly on costs, returns, and R&D investment—is commercially confidential. Critically, data on adoptability and scalability, which underpin estimates of feasible abatement, are very scarce and rarely available at the national scale.

There are also issues of data consistency and comparability, which can create significant confusion and contestation. For example, estimated emissions for N fertiliser use for non-irrigated crops in 2020 based on top-down data from Australian National Greenhouse Accounts are based on approximately half the weight of N compared to analysis of bottom-up data, such as can be aggregated from farm surveys (Sevenster and Burrett, 2024). Such data issues require attention of experts to resolve which data are most appropriately used, where, and why and industry, and government coordination to ensure appropriate application is supported across systems.

2. Intelligence and foresight gaps.

The deployment of technological change is shaped by future conditions that are inherently uncertain, particularly where markets, geopolitics and investment environments interact in complex ways. Foresight methods can help manage such uncertainty by testing the robustness of pathways across multiple scenarios. However, given the breadth of sectors, technologies and drivers considered in this project, systematic foresight analysis could not be undertaken to any significant degree. These issues are only minimally addressed through the consideration of system interactions. We have attempted to mitigate this risk through engagement of participants in a simple foresighting activity to highlight some trends and future risks, and used this in our analysis.

3. Challenges of scale.

A national focus presents inherent challenges for assessing technology pathways, as the relevance and potential value of individual technologies vary substantially across regions and farming

systems. A technology assessed as low value at the national scale may nonetheless be transformative within a particular region or locality. As a result, the level of analytical granularity is often insufficient to capture these localised dynamics. This limitation also affects assumptions about adoptability, which arguably cannot be meaningfully assessed at national scale, as adoption depends on the preferences, constraints and objectives of specific farming populations and production systems (see Section 2.2). Consequently, some assumptions and estimates necessarily rely on limited evidence. This risk remains relatively unresolved though we have looked for congruence between what we have done at a national level of assessment and what was recently completed in at the state level by NSW (Cowie et al., 2025).

Despite these limitations, we suggest that the approach provides a robust and transparent framework for analysis. In Chapter 6, we revisit these limitations, reflecting on the performance of the framework and identifying opportunities for future improvement and for embedding it more effectively in deliberative and decision-making processes.

Further criteria for prioritisation that are worthy of investigation in subsequent attempts to prioritise include: the likelihood of the technology ‘moving up’ the archetype ladder in 2-3 years (i.e. the tractability of barriers), and the relative alignment with policy objectives, where these are clearly articulated (e.g. state, federal and industry priorities). Presence of significant co-benefits is a clear example of where relatively low abatement potential technologies receive significant investment due to their contribution to profitability, productivity, improved soil health or other non-abatement-related benefits.

3.9 Summary

The analysis method described in this chapter spans assessment of individual technologies, right through to a diagnosis of where innovation system investment needs to be strengthened to build the collective capacity required for transformational change. This approach highlights where targeted investment and coordinated institutional change can most effectively enhance system performance. When including preliminary assessment of current investment, it allows for identification of where investment is well-targeted, as well as where there may be missed opportunities or over-investment.

In all, this approach enables decision makers to both target specific technologies and intentionally shape the innovation environment by aligning goals, improving coherence across actors, and expanding the system’s ability to generate, scale, and normalise new practices and technologies. It is proposed as a foundation for directing innovation system investment toward shared national outcomes and building the long-term capacity for the low-emissions agriculture transition articulated in the Agriculture and Land Sector Plan.

To recap:

- 1) The assessment of technologies using a combination of the technology assessment framework and the analysis of enablers can help to classify technologies, compare them across a multi-criteria prioritisation, and identify capabilities and mechanisms that would be needed to drive adoptability and scaling.

- 2) Classification of individual technologies into archetypes supports comparative analysis for prioritisation. It enables further interrogation about what investment might be needed and a framework to support discussion and debate in prioritisation of technologies to invest in, barriers to address and enablers to enhance.
- 3) Portfolio analysis of technology archetypes identifies the forms of expected system innovation functions and enabling mechanisms that are likely to be needed to advance different policy goals across the public and private sectors.
- 4) This analysis approach is limited by data availability, limited inclusion of foresighting, and challenge with scale and granularity.
- 5) Nevertheless, the analysis provides a foundation to structure informed deliberation and elicit stakeholder and expert perspectives on what is needed, where, and why. Integration of formal analysis with expert and stakeholder perspectives provides a rich, structured dataset and sound policy logic for coordinated public and private sector investment and action to enable rapid and orderly shifts to low-emissions agriculture in Australia. Balancing a focus on technologies, enablers, barriers and system risks supports the development of clear and easily communicable and effective industry pathways.

Part II Analysis of options



4 Sectoral technology assessment of options, enablers, gaps and priorities

This chapter illustrates the current state of play for emissions reduction technologies across the focal agricultural industries by providing an overview of the sectoral technology assessments (STAs) presented in Appendix C. As the chapter largely produces a summary analysis of detailed material in the STAs, it uses references sparingly. Readers interested in following up on claims should refer to specific STAs. Each section, with a sub-sector focus, follows the structure of the methods (Chapter 3).

Overall, agriculture's scope 1 emissions have changed little from the 2004-05 baseline, remaining between 70 and 80 Mt CO₂-e / year, with approximately 80% arising from methane, 15% from N₂O and the remaining 5% from carbon dioxide emissions (National Inventory Report, 2026 (data from 2024); Mayberry, 2024; Sevenster and Burrett, 2025). This variation in emissions is mostly driven by enteric methane emissions (National Inventory Report, 2026; Figure 5.3) as a function of climatic conditions and change in animal numbers.

In addition to identifying current and emerging technological contributions to emission reductions, the assessment sought to understand the main barriers and gaps in scaling technology adoption. Conversely, it also examined potential enablers of adoption and trends influencing uptake across the six industries.

Finally, this chapter outlines indicative investment pathways for technology scaling for different planning horizons, including options deliverable by 2030 that have potential emerging in 2030-35, and longer-term opportunities beyond 2035.

4.1 Red meat and sheep

4.1.1 Background: Emissions contribution, distribution, trends and drivers

According to Mayberry (Mayberry, 2024), total emissions from the red meat sector in 2023 were 53.76 Mt CO₂e (approximately 11% of national emissions of 465.2 Mt CO₂e, and approximately 69% of Agriculture's emission total of 82.2 Mt CO₂e) and this was offset by -22.68 Mt CO₂e from attributed land use and land use change and forestry (LULUCF), resulting in net GHG emissions of 31.08 Mt CO₂e. On farm, emissions have remained almost unchanged since 2005, however net emissions have dropped markedly due to LULUCF on lands used for grazing. Processing emissions are not included in these graphs.

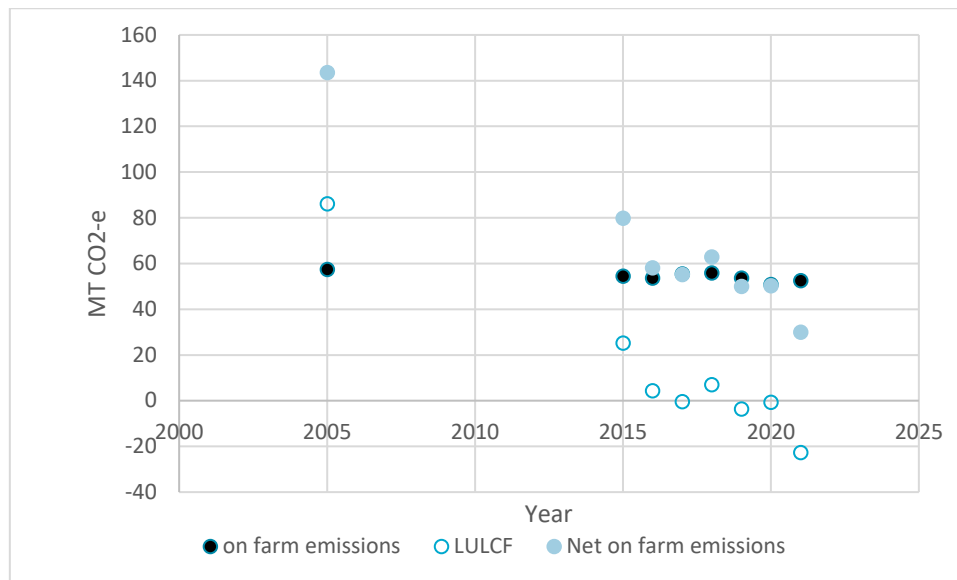


Figure 4.1.1. On farm emissions and net emissions from Australia's livestock sector (Mayberry 2024).

The composition of emissions is as follows (Australian Government, 2024)

- Enteric methane: 80%
- Manure Management: 7%
- Agricultural soils: 11%
- Burning of field residues: 0.2%
- Liming and urea: 1%
- Farm and feedlot energy use: 2%

Regional variability and the nature of emissions

Emissions intensity in red meat and sheep systems varies substantially across regions and production systems, reflecting differences in feedbase quality, climate, and biological processes rather than management choices alone. Enteric methane intensity is lowest in systems with higher forage digestibility and animal productivity, and highest in extensive or variable feedbase systems where seasonal pasture quality constrains intake efficiency. Climate and seasonality are central drivers: drought reduces pasture availability and elevates methane intensity through lower-quality forage and supplementation, while high-rainfall periods can reduce pasture quality and increase nitrogen losses.

The structure of emissions is also shaped by production context. Manure methane emissions are generally minor in extensive grazing systems, but become more material in feedlots and processing nodes, particularly in warmer climates where anaerobic conditions prevail. Nitrous oxide emissions from soils exhibit strong spatial and temporal variability driven by soil moisture, temperature, and nitrogen inputs, contributing to pronounced inter-annual fluctuations that complicate attribution of year-to-year change.

In addition to regional drivers, substantial animal-to-animal variation in methane emissions exists within herds and flocks, even under similar diets and management. Individual animals can differ markedly in methane yield per unit of intake due to differences in rumen microbial communities, digestion efficiency, intake behaviour, and host genetics. As a result, emissions at herd or flock

level reflect the aggregation of many heterogeneous biological responses rather than a single representative animal and is the appropriate scale of assessment.

Measurement constraints further shape how emissions are understood. Direct measurement methods provide high-quality data but are confined to research settings, meaning that most emissions characterisation relies on proxies and model-based approaches that average across animals, seasons, and systems. Short-term or individual-animal measurements therefore provide limited insight into longer-term herd- or regional-scale emissions outcomes. Taken together, these factors mean that emissions in red meat and sheep systems are best understood as biologically driven, spatially heterogeneous, and temporally variable, with reductions emerging gradually through cumulative system-level change rather than rapid, discrete shifts.

4.1.2 Technology assessment

The assessment of individual technologies (Appendix C.1) is summarised in Table 4.1.1. A high-level summary is below

Table 4.1.1. High-level summary of red meat and sheep emissions reduction technologies. Abatement potential ratings are the maximum plausible abatement 10 years from now (2036)

Technology name	Archetype	Current investment	Industry abatement potential	Ag Sector abatement potential	Confidence	Key issues
Ionophore antibiotic (Monensin)	Unlikely	LOW	LOW	LOW	HIGH	Regulatory constraints & market access; Modest/short-lived abatement
Biochar feed supplementation	Unlikely	LOW	LOW	LOW	HIGH	Lack of reproducible methane reduction evidence
Low-emission farm machinery	Unlikely	LOW	LOW	LOW	LOW	High capital cost & supporting infrastructure (fuel/charging); Service/supply chain availability in regional areas
Grape marc	Unlikely	LOW	LOW	LOW	HIGH	Energy dilution/productivity trade-offs; Inconsistent methane benefits
Probiotics & directed microbes	Low abatement/High co-benefit	LOW	LOW	LOW	HIGH	High barriers (incl. regulatory/practical); Low/uncertain methane efficacy in vivo;
3-Nitrooxypropanol (3-NOP) – rumen methane inhibitor	A7 - Scaling Ready	MEDIUM	LOW*	LOW	LOW	Delivery in extensive grazing (consistent dosing); Economics/ROI and incentives for adoption
Lipid /fat supplementation	A7 - Scaling Ready	LOW	LOW	LOW	LOW	Economics/ROI and feed cost volatility; Animal performance trade-offs (intake, production); high levels of existing adoption
Phytochemicals – Pasture species (e.g. tannin-rich legumes)	A7 - Scaling Ready	HIGH	MEDIUM	MEDIUM	LOW	Variable efficacy across seasons/regions; Seed supply, persistence & grazing management;
Phytochemicals – extracts added to	A7 - Scaling Ready	MEDIUM	LOW	LOW	LOW	Variable in vivo efficacy / adaptation; Cost/ROI vs modest abatement

diet (e.g., essential oils)						
Herd management	A7 - Scaling Ready	LOW	MEDIUM	MEDIUM	LOW	Management complexity, labour/time and skills; MRV/attribution of gains and additionality
Nitrate supplementation in feed	A6 - Scaling Limited	MEDIUM	LOW	LOW	LOW	Safety management (nitrite toxicity) and protocols; Delivery control in extensive systems; Market/regulatory acceptance & MRV
Covered anaerobic lagoons and anaerobic digesters (biogas capture)	A6 - Scaling Limited	LOW	LOW	LOW	LOW	High capex/Opex; viable mainly for larger intensive sites; Fugitive emissions, monitoring and methodology/MRV
Red seaweed (<i>Asparagopsis</i>) and extracts from seaweed as feed additive	A4 - Development trialling	MEDIUM	MEDIUM	LOW	LOW	Supply-chain scalability & product standardisation; Delivery in grazing (pulse feeding/lick blocks); Regulatory/residue considerations and market acceptance
Garlic & citrus extract (e.g. Mootral)	A4 - Development trialling	MEDIUM	LOW	LOW	LOW	High barriers (incl. regulatory/practical); Cost/ROI at required dose; Evidence variability under commercial conditions
Selective breeding for low methane	A4 - Development trialling	HIGH	MEDIUM	HIGH	LOW	Phenotyping/proxy measurement capacity; Time lag to realise gains
Early-life rumen programming	A3 - Development early	LOW	LOW	LOW	LOW	Durability of effect and practical protocols; Needs controlled early-life feeding systems
Synthetic bromoform and various 2nd generation haloform anti-methanogenic feed supplements	A2 - Research and Development	LOW	MEDIUM	LOW	LOW	Regulatory approval pathway & residue/toxicology; Commercialisation maturity & supply chain; Evidence base and safety/acceptability
Anti-methanogen vaccine (in development)	A2 - Research and Development	LOW	MEDIUM	HIGH	LOW	Demonstrate durable in vivo efficacy; Regulatory pathway for biologicals; Long timelines and high uncertainty
*n.b. DSM has set an upper dose limit that restricts reduction to ~ 30 - 40 % on propriety releases. The product can achieve 90 -100% at higher dose which would bump the technology to the MED category						

In this assessment, 'scaling ready' (A7) denotes technical maturity under defined delivery conditions; it does not imply universal deployability across extensive grazing systems.

The portfolio contains a small set of scaling-ready (A7) options that can expand under current settings with targeted extension and decision support. For many of these, however, the potential abatement remains uncertain; that is, we know they work, but there remains some uncertainty about how effective they will be when deployed and/or there remains uncertainty about the extent to which they are deployable across enterprise contexts. Some of the most prospective technologies with high breadth of application and high potential abatement (such as vaccines)

remain in early-stage development (A2-A4). There is a broad set of scaling-constrained and scaling-limited due to delivery constraints, weak ROI, or unresolved assurance and MRV requirements. For extensive systems, the limiting constraint is often delivery and transaction cost rather than technical efficacy.

Table 4.1.1 and the detailed sectoral technology assessment (Appendix C.1) reveals:

- **ROI constraints affect many technologies:** Many red meat and sheep options remain scaling-limited or development-stage, rather than purely scaling-constrained. While some technologies (e.g. herd management, pasture-based phytochemicals, selective breeding) show positive or near-neutral ROI, most enteric methane inhibitors (e.g. *Asparagopsis*, garlic/citrus extracts) and manure options do not pay for themselves under current extensive grazing economics without premiums, insetting, procurement, energy revenue, or carbon crediting. The issue is less “technology immaturity” and more misalignment between costs, delivery feasibility, and value capture.
- **System fit and regional delivery are decisive:** Technology performance and feasibility are highly contingent on production system (extensive grazing vs confined or semi-confined systems), regional climate, and seasonality. For red meat and sheep, where most emissions occur in extensive pasture systems, delivery constraints dominate outcomes. Stacking and timing remain critical, particularly where nitrogen-related emissions or seasonal feed quality interact with enteric mitigation, but the primary constraint is physical delivery to grazing animals, not agronomic optimisation as in dairy.
- **No single universally scalable mitigation option exists today:** Red meat and sheep systems do not have a small set of universally scalable technologies. The most broadly applicable options at present are selective breeding for low methane and herd management practices, both of which together offer cumulative, system-wide benefits but deliver gradual emissions reductions. Pasture-based phytochemical strategies are promising and broadly applicable but still depend on agronomic support and regional suitability. Most feed-based enteric inhibitors are not universally scalable under current grazing conditions.
- **Adoption pathways for scaling-limited and scaling-constrained options could be assisted by market and system activation:** Several technologies have high TRL and reasonable technical performance but remain stuck in pilot or trial phases because ROI is weak and MRV, assurance, and delivery costs add friction. For red meat and sheep, market creation (premiums, insetting, procurement) and low-friction, herd-level MRV are pre-conditions for scale, particularly in extensive systems where per-animal margins are thin.
- **Emerging and development-stage options could unlock future abatement, but not without further system work:** Long-acting or slow-release delivery systems (e.g. bolus or water-based approaches for 3-NOP), vaccines, and synthetic haloforms could materially expand abatement potential in grazing systems over the medium-term. However, these options require translational farm-system trials, delivery validation at herd scale, residue and safety frameworks, and a clear route to claimable abatement before they can move beyond development trialling or early R&D.
- **Delivery, not efficacy, is the dominant scaling barrier for enteric mitigation:** Across the red meat and sheep portfolio, the principal constraint on scaling enteric emissions reduction technologies is not biological efficacy, but how reliably, cheaply, and credibly they can be

delivered and measured in extensive grazing systems. Without solutions to delivery and MRV, even highly effective technologies will remain confined to niche or intensive contexts.

- **Overcoming scaling constraints.** The first step is to unlock scaling-ready technologies (A7). In red meat and sheep systems, A7 options are primarily herd management and some pasture-based phytochemical strategies, rather than feed-based enteric inhibitors. These options are mainly held back by knowledge, capability, and confidence constraints rather than technology readiness. Trusted advisers, effective extension, and regionally credible trials are the decisive levers. Decision tools and local demonstrations remain the quickest path to uptake, particularly where benefits are cumulative and system-wide rather than immediately visible at animal level.

The remaining portfolio of red meat and sheep technologies highlights a familiar but more acute bottleneck than in dairy: solutions with high technical potential but weak system fit or delivery feasibility in extensive grazing systems. This includes *Asparagopsis* and other high-efficacy inhibitors, nitrate supplementation, garlic/citrus extracts, and manure methane options in intensive nodes. In these cases, two levers are decisive:

1. Reduce effective cost — through concessional finance (e.g. such as provided by the CEFC), service-based or turnkey delivery models (where applicable, such as methane to energy projects), and supply-chain standardisation (e.g. QA and logistics for seaweed products; agronomic seed and advisory systems for pasture-based phytochemicals).
 2. Create product value — via processor or retailer premiums, supply-shed insetting, use of public procurement of low-emissions products to help build market scale, and carbon crediting or equivalent mechanisms for enteric and manure interventions, contingent on credible and low-friction MRV. For extensive systems, value creation is a prerequisite for adoption, not an optional accelerator.
- **Overcoming MRV challenges.** Red meat and sheep systems require MRV that is credible, low-cost, and workable at herd or flock scale. Without MRV, incentives cannot be directed and markets cannot operate efficiently to support scaling. In extensive grazing systems, enteric methane mitigation requires sampling-based, model-informed, herd-level approaches that are acceptable to processors, insetting arrangements, and emerging carbon frameworks. High-precision, individual-animal measurement is neither feasible nor necessary for scaling. Where manure methane options apply (e.g. feedlots or processing nodes), MRV must explicitly address leakage, uptime, and operational performance, rather than theoretical abatement. Regional demonstration and modelling are priorities, with accuracy sufficient for payments and supply-chain claims, not research-grade precision.
 - **Regulatory assurance, product evidence and emissions claims (APVMA/FSANZ and ERAC).** For feed-based enteric methane inhibitors, regulatory requirements depend on the nature of the product, its intended use and the claims made. Where a product falls within APVMA regulation, evidence may be required to support relevant claims, including productivity or performance claims, alongside requirements relating to animal and human safety, residues, product quality and manufacturing. Current APVMA requirements should not, however, be assumed to provide regulatory verification of methane-reduction efficacy itself. Methane-abatement evidence therefore needs to be considered separately against

the requirements associated with the intended emissions claim or accounting framework. Where use of a product is intended to generate ACCUs, the project must also meet the eligibility, measurement, monitoring, reporting and other requirements of the applicable ACCU Scheme method and the Scheme's integrity requirements. Although these regulatory and emissions-assurance pathways serve different purposes, they can draw on overlapping evidence, particularly around product performance under defined conditions of use. Better alignment and earlier clarity about evidence requirements could therefore reduce unnecessary duplication and development costs, while maintaining regulatory and scientific rigour. This is particularly important for startups and emerging technology developers as Australia continues to consider the regulatory treatment of agricultural emissions inhibitors

- Role of shared measurement infrastructure and standards:** A critical accelerator for scaling is the development of common-user measurement and testing infrastructure, alongside standardised protocols for trials, residues, emissions measurement and modelling. Shared facilities (e.g. respiration chambers, tracer platforms, controlled feeding and grazing trial sites) and agreed protocols can reduce duplication, lower costs and improve comparability across products and regions. Facilities may need to be deployed to capture regional differences in feedbase, genetics and climate. Consistent standards and testing frameworks can also make evidence generation more efficient and increase the potential for well-designed studies to inform multiple requirements, including relevant APVMA submissions, the evidence base for emissions-accounting methods and supply-chain assurance. While these pathways have different purposes and evidence requirements, earlier alignment of measurement approaches can reduce unnecessary duplication. In practice, investment in shared infrastructure and standards can shift effort from repeated proof-of-concept testing towards faster, lower-risk progression from development to scalable deployment.
- Regional embedding and capability building:** Adoption hinges on trusted advisers, producer groups, and regionally credible trials that integrate technology stacks appropriate to extensive systems (e.g. selective breeding combined with pasture management and, where feasible, enteric mitigation). Embedding technologies within whole-of-system management—rather than promoting stand-alone interventions—reduces perceived risk, clarifies ROI under local conditions, and accelerates diffusion. A critical enabler is not simply technology availability, but the strength of regional innovation and advisory systems that translate potential into practice.
- Choosing when and how to partner on high-risk long-term technologies:** For technologies like vaccines, the centre of research may be overseas, and it makes little sense to replicate this in Australia. However, it is critical that Australia remain connected to this research so that the research develops products suitable for our systems (i.e., for vaccines, they are effective against the suite of rumen microbes found in our livestock) and so that Australia can be an early recipient of technology once developed.

4.1.3 Portfolio analysis

The red meat and sheep emissions-reduction technologies reviewed in this study span the full transition pathway, from research and early development through to scaling-ready options. However, portfolio coverage does not equate to the system's ability to deploy them at scale. Across most technologies, industry-wide uptake remains low, with constraints arising less from technical feasibility than from system fit, delivery mechanisms, economics, and assurance. In extensive grazing systems in particular, system-level enablers, including incentives, credible and low-friction MRV, access to finance, regulatory clarity, and supply-chain alignment, are often more limiting than technology performance itself.

High-level summary of actions:

- **Scaling ready (A7):** A small subset of options is broadly scaling-ready, but with important limits on their likely contribution to sector-wide abatement. Herd management practices, and pasture-based phytochemical approaches (e.g. tannin-rich legumes) represent the most broadly applicable options in extensive systems, with medium industry-level abatement potential. These technologies can scale primarily through extension, on-farm decision tools, trusted advisory capability, and regionally credible demonstrations, though confidence in outcomes remains variable, and additionality and attribution need to be resolved through improved MRV. Feed-based enteric inhibitors such as 3-NOP are also classified as scaling-ready, but only in confined or semi-confined systems where consistent delivery and dosing control are feasible. Their contribution across extensive grazing systems is expected to remain limited due to delivery constraints, economics, and low confidence in scalable application under grazing conditions. Lipid supplementation and dietary phytochemical extracts face similar limitations, with modest abatement potential and sensitivity to feed costs and animal performance trade-offs. Selective breeding (as a cumulative, system-wide strategy), is mainstreamed as a livestock improvement mechanism, and while evidence that methane traits are heritable exist, there is still development trialling (A4) work to do for a commercially deployable Australian methane-specific breeding pathway with sufficiently accurate EBVs/GEBVs integrated into mainstream selection indexes
- **Scaling limited (A6):** Technologies such as nitrate supplementation, garlic and citrus extracts, lipid supplementation, and manure methane options in intensive nodes are technically mature and capable of positive returns in specific contexts but face high barriers to broader adoption due to delivery risks, safety requirements, system incompatibility, limited breadth of application, and constrained stacking potential. For these options, adoption is unlikely to extend beyond bounded geographies or production systems without targeted intervention to remove specific barriers, including refined protocols, regulatory guidance, and practical system integration. Even with intervention, these technologies should be treated as complementary, locally applicable contributions rather than core sector-wide pathways.
- **Development trialling (A4):** Technologies such as *Asparagopsis* and other high-efficacy enteric inhibitors, along with selective breeding approaches focused on methane trait proxies and index integration, have high technical potential but require further effort to

transition from trials into routine, investable practice. The dominant constraints at this stage are system fit, delivery in grazing systems, regulatory and assurance requirements, and the absence of a clear pathway to claimable abatement, rather than efficacy per se. Increasing adoption depends on coordinated farm-scale demonstration across regions, refinement of delivery mechanisms, assurance and regulatory co-design, commercialisation support, and shared infrastructure (e.g. data, baselines, monitoring tools) to reduce friction and build trust among adopters.

- Research/foundational (A1–A3): Vaccines, synthetic and second-generation haloforms, and early-life rumen programming remain longer-horizon options at the research and early development stages. These approaches require sustained R&D investment, early attention to safety, durability, delivery protocols, regulatory pathways, and social licence, and continued engagement with international research efforts. These technologies should be viewed as preserving future option value rather than contributing materially to near-term emissions reduction targets.
- Some technologies deliver little or no material methane abatement in red meat and sheep systems (e.g. biochar feed supplementation), while others provide productivity or system co-benefits with only incidental methane reductions (e.g. ionophores, probiotics, and directed microbials). While these options may play supporting roles in broader system performance or resilience, they should not be relied upon as core emissions-reduction strategies in sectoral pathways.

4.1.4 System interactions: risks and opportunities

Technological & infrastructure interactions. Innovation in delivery mechanisms (e.g. bolus, slow-release, water-based or long-acting carriers for enteric inhibitors) and the availability of low-friction MRV are pivotal for uptake of low-emissions technologies in extensive grazing systems, where most emissions occur. Without practical delivery at herd or flock scale, even high-efficacy technologies remain confined to pilots or intensive niches. In intensive nodes (e.g. feedlots or processors), energy system integration—including renewables, biomethane capture, renewable energy generation and storage, and electrification of equipment—can materially improve the business case for manure methane abatement and contribute to Scope 2 and Scope 3 reductions. These interactions typically require scale, aggregation, or locality-based systems to achieve acceptable returns. Another consideration is that abatement is not always additive across technologies targeting the same emission source; resource competition and overlapping claims can limit simultaneous deployment. There is a clear role for clarity on stacking options that can create a portfolio of actions with clearly defined abatement outcomes tailored for geographies.

Cross system & cross sector interactions. Red meat and sheep production interacts with energy, transport, and processing systems in ways that can shift ROI for certain mitigation options. For example, biomethane from covered lagoons or waste streams and on-site renewable energy can improve project viability where sufficient throughput exists. At the same time, supply-chain emissions reporting (Scope 3) is emerging as a key coordination mechanism, enabling processors to valorise on-farm abatement through inseting or premiums, provided MRV and assurance are

credible and proportionate. These interactions create opportunities for system-level optimisation but also increase coordination requirements across farms, processors and energy providers.

Socio-cultural interactions. As in many sub-sectors, there is a risk that new expectations placed on producers through regulation or markets without equitable cost-sharing or clear value propositions could lead to resistance and disengagement. This risk is heightened for feed additives and animal interventions that attract public scrutiny. Successful scaling depends on trusted advisers, transparent communication about benefits and risks, and assurance frameworks that address safety, residues and animal welfare alongside emissions outcomes. High (and appropriate) regulatory hurdles for demonstration of safety can impose significant scaling delays.

Cross-sectoral transformation effects. Shifts in retail, consumer and export market requirements may unlock premiums for low-emissions red meat and sheep products, particularly where claims are simple, credible and comparable. Conversely, if certain additives or practices become implicit or explicit conditions of market access, feed supply chains, delivery logistics, and advisory systems will need to scale rapidly to avoid creating bottlenecks or inequities between regions and production systems.

Red meat and sheep specific headwinds. Dependence on imported inputs (e.g. certain bioactives or inhibitors) and limited domestic manufacturing capacity can constrain access and raise adoption costs. In parallel, the administrative burden of climate disclosures and Scope 3 reporting risks creating friction and resistance if requirements are complex or poorly aligned across buyers. Simplification, automation, and the use of consistent templates and data pipelines through processors are therefore critical to reducing transaction costs and enabling broader participation in low-emissions pathways.

4.1.5 Investment assessment

Table 4.1.2. Indicative assessment of RDC investment in different technologies in the period 2022-2025 (note activities under the NLMP on grape marc and nitrate supplementation precede this interval). NB: Investments here are a limited subset of all investments focused on technologies; they may be related to technologies that span sectors and may not primarily be targeted to cropping. See Section 3.6. for details on data. “No data sourced” means there were no investment data in the dataset for this category.

Technology category	Investment (\$)	Classification
Ionophore antibiotic (Monensin)	\$843,755	\$500K-\$1mill
Biochar feed supplementation	316,228	\$500K-\$1mill
Low-emission farm machinery	\$3,220,000	\$1-5mill
Grape marc	no data sourced	no data sourced
Probiotics & directed microbials	\$978,864	\$500K-\$1mill
3-Nitrooxypropanol (3-NOP) – rumen methane inhibitor	\$8,917,056	\$5-10mill
Lipid /fat supplementation	\$843,755	\$500K-\$1mill
Phytochemicals – Pasture species (e.g. tannin-rich legumes)	\$21,550,000	\$20-30mill
Phytochemicals – extracts added to diet (e.g., essential oils)	\$6,054,668	\$5-10mill

Herd management	no data sourced	no data sourced
Nitrate supplementation in feed	no data sourced	no data sourced
Covered anaerobic lagoons and anaerobic digesters (biogas capture)	\$900,000	\$500K-\$1mill
Red seaweed (<i>Asparagopsis</i>) and extracts from seaweed as feed additive	\$7,359,712	\$5-10mill
Garlic & citrus extract (e.g. Mootral)	no data sourced	no data sourced
Selective breeding for low methane	\$38,465,762	\$20-30mill
Early-life rumen programming	1,358,566*	\$1-5mill
Synthetic bromoform and various 2nd generation haloform anti-methanogenic feed supplements	\$3,856,970	\$5-10mill
Anti-methanogen vaccine (in development)	no data sourced	no data sourced

*n.b. additional investment through ZNE-Ag CRC in integrated program is occurring

In interpreting table 4.1.2 it is worth noting that broader investment in genetics, productivity, feedbase and nutrition, animal health, adoption, extension and enabling systems may contribute to emissions outcomes without being attributed to the individual technology categories shown. “No data sourced” means that no investment was identified in the dataset for that category; it does not mean that no relevant investment occurred. See Section 3.6 for details.

Investment identified within the sample of red meat and sheep emissions-reduction projects is unevenly distributed across technology categories. Of the approximately \$93 million attributable to the categories in Table 4.1.2, the largest identified investments are in selective breeding for low methane (\$38.5 million) and pasture-based phytochemical strategies (\$21.6 million). A second tier covers enteric methane inhibitors, including 3-NOP (\$8.9 million) and *Asparagopsis* and related seaweed products (\$7.4 million), together with dietary phytochemical extracts (\$6.1 million) and second-generation haloforms (\$3.9 million). These results are consistent with substantial deliberate investment in genetics and methane-reducing feed technologies.

For several other categories, including herd management, nitrate supplementation, garlic and citrus extracts, vaccines and some infrastructure-based options, little or no investment was identifiable from the available project descriptions. This should not be interpreted as evidence of little or no relevant investment across the wider red meat and sheep portfolio. Broader programs addressing productivity and herd performance, feedbase and nutrition, animal health, producer adoption, extension and enabling infrastructure may contribute to emissions-reduction or emissions-intensity outcomes without being attributed to the specific technology categories used in Table 4.1.2. Early-life rumen programming and biochar were not absent from the sample, with approximately \$1.36 million and \$0.32 million, respectively, identified against these categories. A small share of the approximately \$93 million total, including investment associated with machinery electrification and biogas systems, also originates from cross-sectoral programs whose primary focus extends beyond red meat and sheep but remains applicable to livestock systems. The figures should therefore be interpreted as an indicative snapshot of investment identifiable

against specific technology categories, rather than a comprehensive estimate of investment contributing to livestock emissions outcomes.

The red meat and sheep-tagged RDC project set shows a strong concentration of activity in SF1 (knowledge generation), particularly for enteric feed-based options such as *Asparagopsis*, 3-NOP, and phytochemical extracts. This reflects a portfolio emphasis on efficacy testing, dose–response relationships, delivery feasibility (including grazing-system concepts), residue and safety assurance, and measurement foundations.

At the same time, the portfolio is characterised by very high investment in selective breeding for low methane, which represents the single largest investment line in the red meat and sheep mitigation portfolio. However, despite this scale of investment, breeding activity also appears predominantly in research and development, focused on phenotyping, proxy development, genomic tools, and index integration, rather than in diffusion-oriented functions. While some projects and program (e.g. ZNE-Ag CRC) have elements of diffusion via commercial studs, the R&D focus reflects the long lead times and cumulative nature of genetic abatement, where large upfront investment is required before impacts materialise, and where deployment is mediated through existing breeding and seedstock systems rather than discrete technology adoption events.

The only technology cluster where learning (IF4) and diffusion-oriented activity (DF2) appear together in the red meat and sheep-tagged project set is nitrogen management, reflecting uptake-oriented work embedded within broader cross-industry nitrogen programs. These programs explicitly combine evaluation, advisory engagement, and practice change, and therefore exhibit a more complete innovation-function profile than either feed additives or breeding, despite receiving substantially lower total investment.

Across the red meat and sheep-tagged project set, IF3 coordination and synchronisation was not explicitly identified in the coded project descriptions. This may partly reflect the limitations of classifying investment from project descriptions, where coordination can be embedded within technically framed projects, delivered through program and portfolio governance, or undertaken outside the sampled RDC investments. It should therefore not be interpreted as an absence of coordination across the wider red meat and sheep innovation system.

MLA and other peak bodies have coordinated substantial programs over time. RERLP (2009–2012) and NLMP (2012–2015) supported coordinated research addressing knowledge gaps around prospective products and measurement approaches across different production systems. Later initiatives, including MLA’s CN30 program and MERiL, have extended this work with greater attention to feasibility and scaling constraints. Coordination is also occurring through value-chain operators and aggregators working with supplier networks to support lower-emissions production, including Woolworths’ SeaFeed initiative, the Coles Nature Fund, and McDonald’s supply-chain actions. These activities may perform coordination, market activation and diffusion functions that are not visible in project-level RD&E coding.

Within these limitations, the identifiable project-level investment remains weighted towards knowledge generation and early validation, including for technologies assessed as scaling ready or in development trialling. For enteric inhibitors, this includes evidence on efficacy, safety, residues, delivery and measurement needed to support further development and use. For selective

breeding, it includes phenotyping, measurement proxies, genomic tools and integration into breeding systems. The analysis therefore identifies limited visibility of coordination, market activation and diffusion functions in the coded project set, rather than demonstrating that these functions are absent or underfunded across the wider system. It nevertheless points to the growing importance of connecting technical investment with existing RD&E coordination, value-chain initiatives, regulatory and measurement arrangements, and practical delivery systems to convert technological progress into observable sector-level emissions outcomes.

Table 4.1.3. Red Meat and Sheep emission reduction technologies, associated archetypes, and functions aligned to funded activity. This table identifies the number of investments (i.e. projects in our sample) aligned with specific technologies and functions. For example, four projects had at least a partial focus on 3-NOP and SF1 (Knowledge generation). NB: Projects could be classified as aligned with up to four technologies and up to 2 functions.

Technology	Archetype	SF1: Knowledge	SF2: Networks	SF3: Resources	IF1: Direction Setting	IF2: Legitimizing	IF3: Coordination	IF4: Learning	DF1: Activation	DF2: Diffusion
3-Nitrooxypropanol (3-NOP) – rumen methane inhibitor	A7 - Scaling Ready	4	1	0	0	0	0	0	1	0
Red seaweed (Asparagopsis) and extracts from seaweed as feed additive	A4 - Development trialling	4	0	0	0	0	0	0	0	0
Synthetic bromoform and various 2nd generation haloform anti-methanogenic feed supplements	A2 - Research and Development	3	0	0	0	0	0	0	0	0
Lipid /fat supplementation	A7 - Scaling Ready	1	0	0	0	0	0	0	0	0
Phytochemicals – Pasture species (e.g. tannin-rich legumes)	A7 - Scaling Ready	0	0	0	0	0	0	0	0	0
Phytochemicals – extracts added to diet (e.g., essential oils)	A7 - Scaling Ready	2	0	0	0	0	0	0	0	0
Nitrate supplementation in feed	A6 - Scaling Limited	0	0	0	0	0	0	0	0	0

Garlic & citrus extract (e.g. Mootral)	A4 - Development trialling	0	0	0	0	0	0	0	0	0
Ionophore antibiotic (Monensin)	Unlikely	1	0	0	0	0	0	0	0	0
Probiotics & directed microbials	Low abatement/High co-benefit	1	0	0	0	0	0	0	0	0
Anti-methanogen vaccine (in development)	A2 - Research and Development	0	0	0	0	0	0	0	0	0
Early-life rumen programming	A3- Development early	0	0	0	0	0	0	0	0	0
Selective breeding for low methane	A4 - Development trialling	5	0	0	0	0	0	0	0	0
Covered anaerobic lagoons and anaerobic digesters (biogas capture)	A6 - Scaling Limited	0	0	0	0	2	0	0	0	0
Biochar feed supplementation	Unlikely	0	0	0	0	0	0	0	0	0
Low-emission farm machinery	Unlikely	0	0	0	0	0	0	0	0	0
Grape marc	Unlikely	0	0	0	0	0	0	0	0	0
Herd management	A7 - Scaling Ready	0	0	0	0	0	0	0	0	0

4.1.6 Prioritisation analysis

The following analysis compares abatement potential with investment identifiable within the available dataset. It is a screening and discussion tool, not a comprehensive assessment of investment adequacy. Matrix positions may change if broader productivity, adoption, infrastructure, private-sector or earlier-period investments are included.

The analysis highlights several priority issues for the red meat and sheep mitigation portfolio. First, selective breeding for low methane has by far the highest level of investment yet remains classified as development trialling (A4). This reflects a concentration of investment on measurement infrastructure, proxy development, genomic tools, and integration into breeding indices, rather than on diffusion or market deployment. While the scale of investment is broadly proportionate to the long-term abatement potential, impacts will materialise slowly due to biological lags and the cumulative nature of genetic change (and of course all of which can be lost in extensive systems if “unwanted” genetics from feral bulls access the herd). Moreover, unless demand-side incentives, MRV recognition, and claims frameworks are put in place, much of the benefit is likely to be realised as emissions-intensity improvements, rather than absolute emissions reduction, since genetic improvements like improved feed conversion efficiency may create animal level emissions reduction which might be lost if stocking increased. This implies that, alongside continued supply-side R&D, greater emphasis on intermediating and demand-shaping functions—including MRV frameworks that recognise genetic gains, alignment of breeding

objectives with market signals, and insetting or procurement mechanisms—is required to unlock the full value of existing investment.

Second, the enteric feed additive portfolio spans multiple transition phases, with 3-NOP assessed as scaling ready (A7) in confined or semi-confined systems, *Asparagopsis* in development trialling (A4), and synthetic haloforms in early R&D (A2). This pattern indicates that delivery, regulatory approval, and assurance constraints, rather than efficacy, are the dominant focus of current investment. While some technologies could be deployed today in specific contexts, the portfolio continues to prioritise de-risking future options—through work on delivery mechanisms, safety, residues, MRV, and regulatory readiness—rather than driving immediate, broad adoption across extensive grazing systems. This reflects persistent concerns about system fit, supply reliability, cost of goods, and social licence for first-generation feed additives.

Conversely, several technologies that are technically mature but scaling-limited, including manure methane options in intensive operations and certain infrastructure-based measures, show low or nil identifiable RDC investment in the extracted classification. This suggests that either investment is occurring—or needs to occur—outside traditional RDC mechanisms (e.g. via energy, infrastructure, or private capital channels), or that these options remain under-served relative to their potential in suitable niches, largely because their barriers are economic, organisational, or regulatory, rather than technical.

Finally, vaccines which have medium to high long-term abatement potential at both sectoral and whole-of-agriculture levels currently attracts low domestic investment. Given that major centres of activity are located overseas (notably New Zealand and the United States), this appears to be a reasonable portfolio balance at present. However, Australia should remain actively engaged, ensuring that emerging solutions are compatible with local rumen biology, production systems, and regulatory settings, and that pathways exist for access and deployment as these technologies mature. In practice, this implies less emphasis on duplicative domestic R&D and greater emphasis on international collaboration, monitoring, and early system-readiness and regulatory preparedness.

Table 4.1.4. Industry-level assessment of adequacy of current investment coverage (red meat and sheep) comparing level of investment against whole of agriculture abatement potential (see Section 3.6 for method). Light Grey = Benign neglect; Dark Grey = overinvestment/ other investment goals?; Blue = Untapped potential; Pink = Well-supported; Purple = Missed opportunity.

	Low potential abatement	Medium potential abatement	High potential abatement
Low investment (or data not found)	Lipid /fat supplementation; Nitrate supplementation in feed; Garlic & citrus extract (e.g. Mootral); Ionophore antibiotic (Monensin); Probiotics & directed microbes; Early-life rumen programming; Covered anaerobic lagoons and anaerobic digesters (biogas capture); Biochar feed supplementation; Low-emission farm machinery; Grape marc	Synthetic bromoform and various 2nd generation haloform anti-methanogenic feed supplements; Anti-methanogen vaccine (in development); Herd management	
Medium investment	3-Nitrooxypropanol (3-NOP) – rumen methane inhibitor; Phytochemicals – extracts added to diet (e.g., essential oils)	Red seaweed (Asparagopsis) and extracts from seaweed as feed additive	
High investment		Phytochemicals – Pasture species (e.g. tannin-rich legumes); Selective breeding for low methane	

Table 4.1.5. Agricultural sector-level assessment of adequacy of current investment coverage (Red meat and sheep) comparing level of investment against whole of agriculture abatement potential (see Section 3.6 for method). Light Grey = Benign neglect; Dark Grey = overinvestment? / other investment goals? ; Blue = Untapped potential; Pink = Well-supported; Purple = Missed opportunity.

	Low potential abatement	Medium potential abatement	High potential abatement
Low investment (or data not found)	Synthetic bromoform and various 2nd generation haloform anti-methanogenic feed supplements; Lipid /fat supplementation; Nitrate supplementation in feed; Garlic & citrus extract (e.g. Mootral); Ionophore antibiotic (Monensin); Probiotics & directed microbials; Early-life rumen programming; Covered anaerobic lagoons and anaerobic digesters (biogas capture); Biochar feed supplementation; Low-emission farm machinery; Grape marc	Herd management	Anti-methanogen vaccine (in development)
Medium investment	3-Nitrooxypropanol (3-NOP) – rumen methane inhibitor; Red seaweed (Asparagopsis) and extracts from seaweed as feed additive; Phytochemicals – extracts added to diet (e.g., essential oils)		
High investment		Phytochemicals – Pasture species (e.g. tannin-rich legumes)	Selective breeding for low methane

Taken together, the investment–abatement matrices show that investment identifiable within the sample is concentrated in a relatively small number of technology categories. Selective breeding for low methane and pasture-based phytochemicals sit in the “well-supported” cells, reflecting substantial investment relative to their assessed abatement potential. These are credible long-term pathways, particularly at the whole-of-agriculture level. However, their future contribution will depend not only on continued technical development but also on translation into adoption and measurable emissions outcomes. This includes recognition within MRV and claims frameworks, alignment with breeding and production systems, supportive market signals, and supply-chain uptake. Without these conditions, some of the benefits may be realised primarily as improvements in emissions intensity rather than reductions in absolute emissions.

The low-identifiable-investment and medium-to-high-abatement cells also warrant attention, but they require careful interpretation. For herd management, the matrix reflects little investment directly attributed to that category in the available project descriptions, rather than demonstrating low investment across the broader portfolio. Substantial relevant activity may be embedded in programs addressing productivity, genetics, feedbase and nutrition, animal health, producer adoption and extension. The opportunity is therefore less clearly one of additional technology R&D and more one of ensuring that relevant existing investment is connected to advisory delivery, appropriate MRV and explicit emissions outcomes where feasible. Herd management may also

scale most effectively through its productivity and profitability benefits, with emissions-intensity improvement recognised as a consequential benefit rather than its sole rationale.

Anti-methanogen vaccines present a different signal. They have high assessed long-term abatement potential at the whole-of-agriculture level, but low identifiable domestic investment and remain technologically uncertain. Given substantial international activity and long development timelines, this should not automatically be interpreted as a missed opportunity or a case for major domestic investment. It instead supports continued international engagement, strategic monitoring and Australian system readiness so that effective products can be evaluated, accessed and deployed efficiently if they mature.

At the whole-of-agriculture level, several feed-based enteric inhibitors fall into cells labelled “possible over-investment”. This classification reflects relatively high identifiable investment compared with their currently assessed feasible abatement across Australian agriculture; it is not, by itself, evidence that these technologies are over-invested. Their application is constrained by delivery, cost and measurement challenges in extensive grazing systems, but they may be highly effective in feedlots and other controlled or semi-controlled production systems. The practical implication is to scrutinise the balance of future investment, progressively moving beyond efficacy testing where evidence is sufficient and focusing effort on delivery mechanisms, cost reduction, safety and regulatory requirements, proportionate MRV, and deployment in systems where use is feasible. Continued upstream R&D may remain justified where it addresses these constraints or preserves valuable longer-term options.

Overall, the matrices provide directional signals for further portfolio deliberation rather than definitive judgements of investment adequacy. They suggest value in improving the translation of existing technology and broader productivity investments into measurable emissions outcomes; examining categories where potentially relevant investment was not visible in the project coding; and maintaining targeted development of longer-term, higher-risk options. For red meat and sheep, progress over the next decade is likely to depend on combining continued technology development with stronger delivery systems, supply-chain coordination, proportionate MRV and market mechanisms suited to extensive grazing and more controlled production systems

4.1.7 Pathways for Red Meat and Sheep

Methane from extensive livestock systems remains the single largest source of agricultural emissions, with most of these emissions produced in extensive grazing systems and a far smaller proportion in controlled feeding or close to barn situations. The livestock mitigation portfolio is dominated by technologies at various stages of maturity, but is characterised by delivery, measurement, coordination, and value-capture constraints. High abatement solutions exist across breeding, management, feed additives and emerging vaccines, but most cannot scale without system-level foundations that assist their adoption or improve the return on investment from their use.

The sequencing logic for actions that is outlined below focuses on the longer-term goal of tackling emissions in extensive grazing systems drawing on the previous analysis:

- Horizon 1 (now–2030) focuses on unlocking existing options—especially herd management and advancing the readiness of selective breeding—by building low-friction MRV, clarifying

stacking rules, investing in supply chain, and research direction setting coordination capacity, and enabling targeted uptake of delivery-feasible options in intensive and semi-intensive systems. In this phase more controlled situations such as feedlots can be used for early entry of technologies for which R&D into delivery mechanisms for extensive grazing will delay general uptake. Near-term abatement is modest, but system readiness increases substantially.

- Horizon 2 (2030–2035) uses those foundations to scale integrated mitigation pathways where they fit, including broader recognition of genetic gains, expansion of deliverable inhibitors, and stronger demand-side signals through insetting and procurement. Support aggregation models and supply-chain incentive programs that enable deployment of proven interventions across extensive production systems.
- Horizon 3 (post-2035) enables rapid uptake of breakthrough options (e.g. vaccines, long-acting delivery systems) precisely because MRV, regulatory, delivery and coordination infrastructures are already in place.

The Horizon (H1) actions for the livestock sector do not chase volume abatement but rather focus on reducing transaction costs, coordination failure and delivery risk, and in doing so builds pathways for higher levels of abatement in H2 and H3.

Key drivers and constraints for the scaling of the existing suite of technologies are synthesised in Table 4.1.6.

Table 4.1.6. Key barriers (B), enablers (E), opportunities (O) and non-investment signals (N) for red meat and sheep, synthesised from previous sections, and underpinning action areas in Table 4.1.7.

Item	Description
B1. Delivery constraints in extensive grazing	Most enteric feed supplement mitigation options require frequent or controlled delivery; extensive grazing systems lack practical, low-cost delivery mechanisms. Efficacy is not the constraint (though long term efficiency and rumen biota adaptation requires further study).
B2. High transaction costs relative to margins	Thin per-animal margins in extensive systems mean that even modest recurring costs, labour or complexity deter adoption without offsetting value.
B3. Weak or absent MRV fit-for-purpose	Existing measurement approaches are either costly, focussed on individual animals and not herds, assume additivity of effect on methane reduction, or are poorly suited to herd-level claims in extensive systems, preventing incentives, inseting and procurement from operating at scale. Difficulties are exacerbated by the known effects of feed base or animal condition of emissions per unit feed intake making generalisation hard.
B4. Misalignment between breeding gains and market recognition	Significant investment in low-methane genetics risks delivering only emissions-intensity gains unless incentives exist to translate these into absolute emissions reduction.
B5. Regulatory and assurance bottlenecks	APVMA registration, residue assurance and ERAC requirements can be slow (in the sense of requiring significant dossiers of information that require scarce scientific infrastructure) and sequential, and high cost, resulting in it being costly to develop a sufficient evidence base, creating slowing delivery of innovations.
E1. Mature, “no-regrets” herd management options	Herd management and productivity improvements are scaling-ready, broadly applicable and can deliver cumulative emissions-intensity benefits with positive or neutral ROI.
E2. Strong sunk investment in breeding platforms	Extensive investment in phenotyping, proxies and genomic tools provides a strong foundation for long-term, system-wide methane reduction if properly integrated with claims frameworks.
E3. Supply-chain demand emerging via Scope 3	Processors and downstream buyers increasingly require emissions data, creating potential demand-side pull through inseting, procurement and premiums if MRV is workable.
E4. International progress on vaccines and delivery systems	Major R&D activity overseas reduces the need for full domestic replication and creates opportunities for early system readiness and alignment.

O1. Low-friction MRV as shared infrastructure	Further developing herd-level, fit-for-purpose MRV that handles stacking and interaction effects would unlock mechanisms for incentives to flow through supply chains and finance.
O2. Converting breeding into claimable abatement	Aligning MRV and procurement frameworks with progress in low-methane genetics could unlock system-wide abatement from existing investment with low marginal cost.
O3. Regulatory acceleration via shared testing	Common-user testing infrastructure and standardised protocols could materially shorten time-to-market for multiple feed-based and delivery technologies.
O4. Targeted market activation in feasible niches	Confined, semi-confined and intensive production systems offer realistic early markets for high-efficacy inhibitors without forcing premature deployment in extensive systems.
N1. Premature scaling of delivery-infeasible technologies	Pushing widespread uptake of high-efficacy additives without delivery or MRV solutions risks backlash, stranded investment and loss of trust.

Action areas proposed from this research for the horizon logic is consistent with Section 3.7: first addressing constraints and preconditions for scale, then enabling selective uptake, and later positioning the system to absorb breakthrough options, which are developed through ongoing Australian participation in international R&D efforts (Table 4.1.7). That is, the pathway below is not organised around individual technologies alone. Instead, it translates the identified barriers, enablers, opportunities and non-investment signals listed in Table 4.1.6 into a manageable number of system-level investment pathways that sequence action across horizons to sustain effort and advance long-term impact. Some elements of the above table are not best addressed at a sectoral level, but through cross-sector/ systems level interventions (see Chapter 5).

Table 4.1.7. Pathway of investment action areas and associated problems (with links to barriers etc from the previous table) for Red Meat and Sheep (with explicit issue linkages). Notes: 1) Numbers are not associated with importance, order or priority, but simply to allow cross-reference of ‘aligned action areas’ with best action in use Table 4.1.8.

Action areas	Problem / Risk Addressed (linked to Table 4.1.6)	Indicators of Success	Indicators of Failure	Prioritised Actions aligned to horizons
1. Build low-friction MRV that handles stacking and interaction effects	MRV constraints (B3) prevent incentives, claims and stacking across breeding, feed additives and management; lack of representation of potential antagonisms and synergies in	Herd/flock-level MRV adopted that explicitly handles stacked measures; clear rules for additive, synergistic	MRV challenged or rejected by regulators or markets; it becomes apparent that stacking of	H1: Develop MRV approaches that assist scaling of technologies at low cost and harmonise top-down/national accounting and the diversity and combinations of practices in paddock ; capture interaction effects into calculations; publish stacking rules; upskill advisors in the opportunities of combining and stacking technologies.

	MRV processes inhibit accurate accounting with stacks of technologies; lack of shared MRV infrastructure limits value capture despite strong enablers (E3, O1).	and non-additive effects; acceptance by processors, regulators and markets.	abatement options leads to under- or over-credited; high transaction costs deter participation.	H2/H3: Standardise and automate MRV; integrate with supply-chain claims, insetting and finance; Maintain and update MRV to accommodate new delivery technologies and breakthrough options (e.g. vaccines).
2. Convert high breeding investment into claimable, system-level abatement	High breeding investment risks delivering only intensity gains (B4), despite strong enabling base (E2) and clear opportunity for low-cost system abatement (O2).	Methane traits embedded in breeding indices; breeding gains recognised in MRV, insetting or procurement frameworks; long-term incentives for genetic progress.	Breeding gains invisible to markets; weak incentives; erosion of confidence in breeding pathway.	H1: Invest in proxy validation and herd-level accounting approaches. Align breeding objectives with MRV and claims frameworks H2/H3: Link verified genetic gains to supply-chain insetting, procurement and premiums.
3. Reduce regulatory pathway timelines via shared testing infrastructure	Regulatory and assurance processes are onerous to ensure safety and integrity but (B5) can delay technologies, particularly feed-based enteric methane inhibitors where regulatory approval, MRV and abatement claims are inseparable and claims about productivity may be integral to ROI. The ability of products to make claims about productivity change is material to market capture but may impact APVMA pathway. Shared infrastructure represents a cross-cutting opportunity (O3)	Good access to testing facilities assists product development and increases confidence with solid data of dose and effects. APVMA (where required)- and ERAC-ready dossiers built from shared datasets;	Long approval timelines persist; duplicative trials; promising products abandoned due to regulatory burden.	H1: Australia has common-user testing facilities (supporting testing of efficacy, residues, MRV to regulatory standard); standardise and publish protocols and standards for key feed supplements and measurement of active ingredient aligned with regulators; develop omnibus methods for classes of technologies that only require technology specific information in addition to standard requirements H2/H3: Maintain infrastructure and update standards as new classes of products emerge.

4. Enable long-acting delivery for enteric inhibitors in grazing systems	Delivery feasibility is the dominant constraint (B1), compounded by transaction costs (B2); success depends on pairing delivery innovation with MRV readiness (B3, O1).	Sustained 20–30% CH ₄ reductions in grazing herds/flocks over >90 days; delivery systems validated under commercial conditions.	Delivery failure; residue or animal-health concerns halt deployment.	H1: Invest in delivery mechanisms for promising feed supplements, and support work on MRV and safety assurance of these technologies. Focus success criteria initially on delivery success and safety, and less on abatement efficacy H2: Optimise efficacy once delivery and MRV are validated, including persistence under grazing conditions and dose/response under variable feedbases Establish processor- or supply-shed-led regional pilots that integrate supplement delivery, low-friction herd-level MRV, and a clear value signal (premium or insetting): focus on supply-chain enablement. Embed supplements into managed service models that normalise abatement and are funded through supply-chain demand. H3: Enable breakthrough option delivery (e.g. vaccines) using international partnerships where that is efficient and provides rapid access to know-how and emerging technologies.
5. Create targeted market signals where delivery is feasible	Weak ROI and mis-targeted incentives (B2) risk waste or backlash; opportunities exist in confined production system niches (O4) that align with emerging demand (E3).	Uptake in confined production systems and intensive production systems; private capital co-investment; limited deadweight loss or failed start-ups in promising technologies.	Broad incentives with low uptake; pressure to mandate delivery-limited technologies; promising technologies fail to achieve commercialisation.	H1: Look into incentive schemes that target farm-level or supply-chain emissions reduction outcomes. Where technologies are assessed as low risk, high probability of scalability but with weak ROI investigate targeted R&D to reduce cost of goods or delivery. Prioritise confined/semi-confined production systems and supply-shed pilots where MRV and delivery are feasible; avoid broad incentives that force technologies for extensive systems technologies prematurely. H2/ H3: Support aggregation models and supply-chain incentive programs that enable deployment of proven interventions across extensive production systems. Private capital is mobilised to finance large-scale deployment of verified low-emissions livestock systems. Target sub-sectors where early-stage technologies have not addressed abatement needs.

6. Align claims, MRV and residue standards to protect exports	Fragmented domestic and international assurance frameworks (B5) threaten export access and increase compliance costs; alignment is necessary to safely scale validated options.	Mutual recognition across key markets; portable claims; reduced duplication.	Dual compliance; rising costs; loss of market access or credibility.	H1: Market requirements will vary in data type and scale. Wherever possible, prioritise the reuse of existing data—such as proxy measures, remote sensing, and modelled data—to meet multiple evidence needs. This reduces reporting burden on farmers while still supporting downstream market and regulatory requirements. Provide access to shared data layers and benchmarks that underpin claims, and invest in modelling and remote and proximal sensing platforms to build a low-cost, reusable evidence base that can be repurposed as market needs evolve. H2/H3: Maintain infrastructure and update standards and common data availability as new classes of products emerge. Look at the extent to which farm input measures combined with models can create sound evidence on emissions per animal/area/unit product to support markets
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Best-bet actions for red meat and sheep, mapped to aligned action areas are identified and detailed in Table 4.1.8. These actions are considered to be the sub-sectoral investment priorities to strategically advance the sub-sector's contribution to a low-emissions future, and combine a variety of mechanisms and functions beyond R&D to build a foundation for speeding up low-emissions transitions for red meat and sheep post-2030, and ensuring accountability and MRV are integral to investment, market access and social licence.

Table 4.1.8. Best-bet actions for red meat and sheep, matching action area order in the table above. Note: The order of the best-bet actions in this table does not indicate their level of importance or priority. A low priority does not indicate that an action is not worth pursuing just that it has low leverage for emissions reduction.

Best-bet actions	Aligned action areas.	Rationale (why this action is needed)	Description of the priority action	Level of Priority
Improve herd efficiency, pasture and operational management, embedded in advisory systems and MRV recognition.	1, 2, 5	These actions are broadly applicable, often ROI positive, and deliver cumulative emissions intensity reductions. Their system-level impact depends on trusted advisory	Focus investment on integrated management uplift—animal health, fertility, mortality reduction, herd/flock structure, pasture utilisation, energy use and logistics—delivered through regionally credible advisory systems. Prioritise benchmarking and simple measurement so gains are sustained and recognised in MRV and supply-chain	Priority high: Scaling-ready, broadly applicable, low-risk actions delivering cumulative impact now when embedded in advisory systems and MRV recognition.

		delivery and explicit recognition within MRV and claims frameworks, rather than standalone productivity programs.	claims. Consider the development of demonstrator farm networks and virtual farm networks to encourage co-learning and experimentation.	
Develop MRV approaches that are credible for extensive, variable landscapes and capable of handling stacked and interacting mitigation measures.	1	Low-friction herd/flock-level MRV is a limiting system precondition. Without it, incentives, markets, coordination and private investment cannot function at scale in extensive grazing systems.	Design herd- or flock-level emissions measurement approaches that tolerate seasonal and regional variability and explicitly handle multiple practices used together. Focus on proportional levels of accuracy aligned to incentives and claims, and embed MRV into processor and advisory workflows to minimise farmer burden and transaction costs. Invest in low cost N ₂ O and methane measurement technologies to support this.	Priority High: Foundational system precondition; without low-friction herd/flock MRV, incentives, markets, stacking and coordination cannot function at scale.
Improve farm operational efficiency (energy use, logistics, management practices).	5	Lowering costs and complexity makes participation in emissions initiatives more attractive and feasible, especially where margins are thin.	Encourage practical efficiency gains such as reduced fuel use, better logistics, streamlined management practices and improved farm operations. These actions strengthen the business case for emissions reduction by lowering overheads and freeing up capacity. They also prepare businesses to engage with future market incentives or reporting requirements without adding administrative burden.	Priority Low: Strengthens business viability and participation but delivers limited direct methane abatement in red meat and sheep systems
Conduct selective piloting of existing feed supplements where logistics allow (e.g. feedlots), including preparation of carbon-credit method and claims evidence where appropriate.	1, 3, 5	Controlled pilots allow learning and evidence generation without forcing premature uptake in systems where delivery is infeasible. They also support regulatory, MRV and market readiness.	Run targeted trials of methane-reducing feed supplements in delivery-feasible settings (e.g. feedlots or semi-confined systems). Use pilots to test delivery reliability, costs, animal outcomes, MRV workflows and regulatory/assurance pathways. The aim is to generate credible, reusable evidence—not immediate widescale deployment.	Priority High: Necessary precursor to delivery platform design: de-risks delivery assumptions, generates MRV and regulatory evidence, and informs grazing-system delivery requirements.

Improve access to measurement infrastructure to support feed supplement testing and dossier preparation.	3	Limited access to shared infrastructure slows regulatory approval, raises costs and creates duplication, particularly for new entrants and emerging products.	Invest in shared facilities and capabilities (e.g. testing, sampling, measurement platforms) that multiple technologies can use to generate evidence on efficacy, residues and emissions outcomes. This reduces duplication, shortens approval timelines and lowers costs for innovators, while maintaining high safety and assurance standards.	Priority high: Cross-cutting system enabler that accelerates multiple technologies in parallel by reducing regulatory, assurance and cost barriers.
Develop methane-reducing feed interventions suitable for grazing systems, with focus on delivery, persistence, cost and safety.	1, 4, 5	In extensive grazing systems, delivery feasibility and transaction cost—not efficacy alone—are the dominant barriers to scale.	Prioritise R&D and translational trials on practical grazing-compatible delivery approaches (e.g. slow-release systems, blocks/licks, water-based delivery). Define early success by persistence, safety and affordability, alongside herd-level MRV design, before optimising abatement performance	Priority High: Essential pathway to large-scale abatement in extensive systems; delivery feasibility is the dominant long-term constraint.
Develop genetic and breeding approaches targeting emissions intensity with long biological lead times.	2, 1	Breeding provides durable, system-wide abatement potential, but only if genetic gains are visible, verifiable and valued within MRV and market frameworks.	Continue improving breeding values and selection tools that favour lower methane emissions or higher productivity. Because results accumulate slowly, this effort must be sustained over time and paired with systems that recognise and reward genetic progress. The goal is steady, long-term reduction in emissions intensity across the national herd, not rapid short-term abatement.	Priority High: Very high long-term potential, but slow to materialise and dependent on MRV/claims recognition to avoid intensity-only outcomes.
Develop integrated nutrition–genetics–management stack designs for different grazing systems.	1, 2, 4	No single technology delivers large abatement; outcomes depend on how measures interact within real systems.	Develop practical “packages” of actions that combine feeding strategies, genetics and management suited to different grazing contexts. These stacks help producers understand what works together, reduce risk from trial-and-error, and support advisory delivery.	Priority medium: Enables uptake, risk reduction and interaction management, but impact is indirect and realised through other measures.
Partner internationally on high-upside biological solutions (e.g. vaccines, novel interventions).	4, 7	Major R&D is occurring offshore; Australia benefits most by being ready to adopt, and making meaningful contributions, not duplicating effort.	Engage with international research programs developing vaccines and other breakthrough technologies to ensure Australian systems are considered. Focus domestically on readiness—regulatory understanding, MRV compatibility, system fit and access pathways—so promising solutions can be evaluated and adopted quickly if they mature, without waiting years to catch up.	Priority Low: Potentially transformational but long-dated and uncertain; priority is system readiness rather than near-term abatement.

4.2 Dairy

4.2.1 Background: Emissions contribution, distribution, trends and drivers

Using the National Inventory Report 2024, submitted in April 2026, total on-farm GHG emissions from the Australian dairy sector can be estimated at approximately 8.5 million tonnes of CO₂-equivalent (Mt CO₂-e), or around 1.8% of national emissions. There has been a 10% decline in subsector emissions since 2005. Attributing this decline to specific changes is difficult, however genetic selection for more efficient cows and better feed conversion ratios has reduced methane per litre of milk by 30% or more (Moate et al., 2016, Christie 2019). However, achieving absolute reductions remains constrained by:

- biological limits to methane reduction under current systems,
- expansionary pressures in dairy regions,
- limited availability of commercially scalable methane-reducing technologies suitable for pasture-based systems,
- and the persistent influence of nitrogen-related emissions from pasture management and fertiliser use,
- no clear financial incentives that overcome ROI barriers.

Nationally, dairy emissions (and livestock more generally) have trended downward more slowly than other agricultural subsectors where energy substitution or machinery electrification can achieve more immediate reductions.

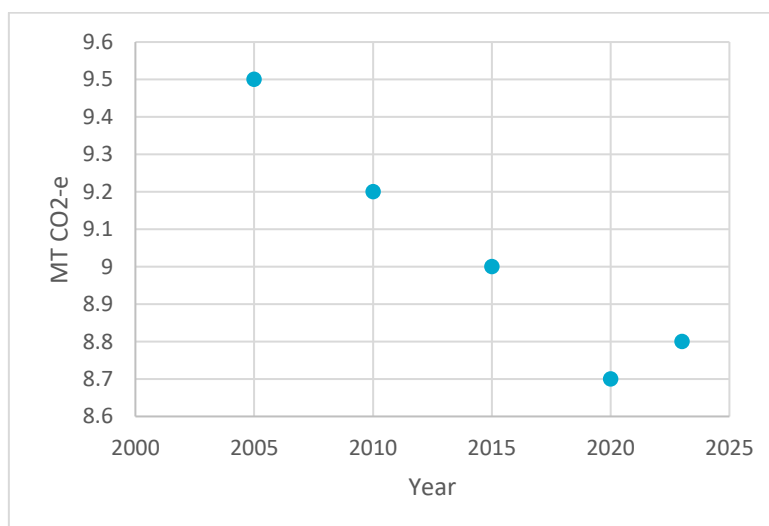


Figure 4.2-1. Dairy emissions trend from National Inventory Reports (Australian Government, 2026, 2024).

Data from Dairy Australia and Agriculture Victoria and Christie (2019) provide a typical emissions profile for Australian dairy farms (including some scope 2, 3 such as electricity and feed inputs):

2023 Dairy Farm Emissions Composition

- Enteric methane (from cow digestion): 58–70%
- Waste methane (manure management): approximately 10%
- Nitrous oxide (N₂O) from dung, urine, and fertiliser: approximately 10–11%
 - Direct N₂O from pasture: 4%
 - N₂O from manure spread: 3%
 - N₂O from fertiliser: 4%
- Energy use (electricity and diesel): approximately 8%
 - Electricity: 6% (Scope 2)
 - Diesel: 2%
- Feed production (concentrates, fodder, fertiliser): approximately 13% (Scope 2 and 3)
 - Concentrates: 8%
 - Fodder: 2%
 - Fertiliser: 3%

This distribution illustrates the structural challenge: most emissions originate from biological processes intrinsic to ruminant digestion and pasture-based systems, which cannot be wholly eliminated through simple management changes or technology substitution alone.

Dairy emissions, and the component contributions, vary regionally. Factors that drive this are:

- Feedbase quality: Enteric methane emissions intensity (g CH₄ per litre of milk) is generally lowest in the southern dairy regions and highest in subtropical regions where forage digestibility is lower and more supplemental feeding is required.
- Soil moisture and irrigation patterns: Regions with irrigation or consistently moist soils tend to exhibit higher N₂O emissions per hectare, while drier regions may have lower direct N₂O but potentially higher indirect losses (e.g., volatilisation and leaching derived emissions elsewhere).
- Effluent system design and climate: Manure emissions are generally highest (per cow) in regions using large anaerobic effluent ponds in warmer climates, and lowest where cooler temperatures or alternative effluent handling systems prevail. High-cost digesters limit adoption largely to larger southern operations, reinforcing regional disparities in achievable manure mitigation

Looking ahead the adoption environment for emissions reduction technologies may also be regionally influenced. Factors include:

- Market and processor dynamics: Milk pricing varies regionally, with southern Australia receiving some of the highest farmgate prices due to strong processor competition and export orientation. Higher prices in southern regions support investment in technology, fertiliser optimisation, and feedbase improvements that can lower emissions intensity.
- Suitability of available technologies: Current high efficacy additives (3NOP, *Asparagopsis*) require daily controlled feeding, making them more viable in southern feed supplemented herds and less so in pasture-dominant subtropical systems. Issues of efficacy beyond confined systems require evaluation and demonstration.

In addition to these regional or feedbase sources of emissions variabilities, there are some inter-annual and seasonal influences.

Pasture Seasonality: Dry seasons in western Victoria, SA, and Tasmania will reduce pasture availability and increase reliance on purchased feed, elevating emissions intensity. Wet seasons or flooding in (most notably of recent times in NSW and Qld) reduce pasture quality and increase nutrient losses, indirectly raising methane per litre of milk.

N₂O Seasonality: N₂O emissions fluctuate widely due to soil moisture. During periods of high rainfall and subsequent waterlogging, N₂O spikes. This variability complicates emissions accounting and mitigation planning, making year-to-year reductions difficult to forecast. Tracking emissions reductions (or if it came to that marketing regional differences in emissions intensity of products) is best taken over a longer integration period that averages across these strong seasonal differences.

Other regional, market and supply-chain factors influence the trajectory of emissions reduction and technology adoption, and these affect emissions beyond the scope 1 emissions considered in this report. These include:

- Major processors and retailers increasingly require greater emissions transparency due to emerging Scope 3 reporting obligations, putting pressure on producers to demonstrate progress. Without aligned price incentives or cost-sharing mechanisms, these requirements can exacerbate financial strain rather than accelerate mitigation.
- Cost-of-living pressures are driving consumer preference toward discounted dairy products, potentially limiting processor margin and willingness to pay for low-emissions milk or emissions reduction technologies.
- Feed reliance and fertiliser use: Regions that depend more heavily on purchased feed, often due to climatic constraints, tend to have higher embedded Scope 3 emissions.

4.2.2 Technology assessment

The assessment of individual technologies (Appendix C.2) is summarised in Table 4.2.1. A high-level summary is below

Table 4.2.1. High level summary of dairy emissions reduction technologies

Technology name	Archetype	Current investment	Industry abatement potential	Ag Sector abatement potential	Confidence	Key issues
Probiotic directed molecules	Unlikely	LOW	LOW	LOW	HIGH	Low/uncertain methane efficacy in vivo;
Biochar feed supplementation	Unlikely	LOW	LOW	LOW	LOW	Lack of reproducible methane reduction evidence
Ionophore antibiotic	Low abatement/High co-benefit	LOW	MEDIUM	LOW	HIGH	Regulatory constraints/withholding and market access, inconsistent results

3-NOP	A5 - Scaling Constrained	MED	HIGH	MED	LOW	Cost/ROI and processor/carbon incentive; Constrained by lack of delivery and MRV beyond controlled feeding
Phytochemicals – Pasture species	A7 - Scaling Ready	LOW	MED	LOW	LOW	Moderate abatement but requires agronomic advisory and support
Phytochemicals - diet	A7 - Scaling Ready	MED	MED	LOW	LOW	Delivery/cost/ROI barriers
Optimized N fertilizer-use on pasture	A7 - Scaling Ready	LOW	MED	LOW	LOW	Practice change and decision support (timing/rates); Production-risk perception and advisory capacity; MRV/attribution and additionality
Nitrification inhibitors	A7 - Scaling Ready	LOW	MED	LOW	LOW	Regulatory/residue constraints and market acceptance; Efficacy variability by soil/climate; Economics/ROI and application logistics
Urease inhibitors	A7 - Scaling Ready	LOW	LOW	LOW	LOW	Economics/ROI and product availability
Lipid /fat supplementation	A5 - Scaling Constrained	LOW	MED	LOW	MED	Economics/ROI and feed cost volatility; Milk yield/composition impacts at higher inclusion; Diet formulation constraints and delivery logistics
Nitrate supplementation	A5 - Scaling Constrained	LOW	LOW	LOW	LOW	High barriers (regulatory/practical); Safety management (nitrite toxicity) and protocols; Milk-market risk
Garlic and citrus extract	A5 - Scaling Constrained	LOW	MED	LOW	LOW	Cost/ROI at required dose; Evidence variability under commercial dairy conditions
On-off grazing (stand-off pads)	A5 - Scaling Constrained	LOW	LOW	LOW	LOW	Limited breadth of application; Capital/infrastructure and operational burden; Animal welfare and effluent management
Covered lagoons and digestors	A5 - Scaling Constrained	LOW	LOW	LOW	LOW	High capex/opex; viable mainly for larger farms; Fugitive emissions, monitoring and methodology/MRV
Manure slurry acidification	A5 - Scaling Constrained	LOW	MEDIUM	LOW	LOW	Chemical handling/safety and equipment needs; Economics/ROI and ongoing operating cost; Regulatory/land-application implications
Asparagopsis	A4 - Development trialling	MEDIUM	HIGH	HIGH	LOW	Supply-chain scalability & product standardisation; Stabilisation during treatment to prevent bioactive loss; Milk residues/iodine management and regulatory settings; Delivery consistency (pulse feeding impacts efficacy), systems beyond controlled feeding situations unclear
Selective breeding for low methane	A4 - Development trialling	HIGH	MED	LOW	LOW	Phenotyping/proxy measurement capacity; Time lag to realise gains
Urine patch inhibitors (spray)	A4 - Development trialling	LOW	MED	LOW	LOW	Limited breadth of application; Regulatory constraints and residue concerns; Difficulty in identifying patch and narrow application window.
Effluent solid separation	A4 - Development trialling	LOW	LOW	LOW	LOW	Cost and operational complexity (dosing/flocculants); Potential trade-offs (NH3/N2O) and approvals (as appropriate from local council and state environmental regulator, and in Tasmania the TDIA)
Synthetic haloforms	A2 - Research and Development	LOW	HIGH	HIGH	LOW	Regulatory approval pathway & residue/toxicology; Commercialisation maturity & supply reliability; Market acceptance for residues/claims
anti-methanogen vaccine	A2 - Research and Development	LOW	MED	LOW	LOW	Demonstrate durable in vivo efficacy; Regulatory pathway for biologicals; Long timelines and uncertainty

Early life rumen programming	A2 - Research and Development	LOW	LOW	LOW	LOW	Durability of effect and practical protocols; Implementation in calf-rearing systems; MRV/additionality and methodology
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The dairy technology portfolio spans several stages of development, but this should not be interpreted as a set of technologies ready for broad adoption. Some options are technically mature and scaling ready under defined conditions, while others remain constrained by economics, production-system fit, delivery, product availability, assurance or unresolved evidence requirements. Capital-intensive manure options, including covered lagoons and digesters, are generally scaling constrained (A5) because of high upfront costs, approvals, uncertain energy revenues and monitoring, reporting and verification (MRV) requirements.

For enteric methane, the critical distinction is between controlled feeding systems and pasture-dominant systems. Some inhibitors, particularly 3-NOP, are technically mature where sufficiently continuous and controlled feeding is feasible. Their wider application in Australian dairy remains limited, however, by feeding-system fit, product availability, cost, lack of a direct productivity return, and uncertainty about efficacy under intermittent or pulse-feeding regimes. Accordingly, 3-NOP should be regarded as scaling ready only within defined controlled-feeding contexts, rather than across dairy systems generally.

Other enteric options remain at development and trialling stages. *Asparagopsis*, methane-specific selective breeding, urine-patch inhibitors and some effluent-treatment technologies require further dairy-specific demonstration, delivery refinement and assurance work before broad diffusion. For *Asparagopsis*, this includes evidence on sustained efficacy under realistic feeding regimes, bioactive consistency, animal health, milk residues, product supply, cost and regulatory and market acceptance. Methane-specific breeding remains a strategically important and potentially broadly applicable pathway, but methane-trait proxies, breeding values and index integration are still under development, and reductions will accumulate gradually through breeding cycles.

Vaccines, synthetic haloforms and early-life rumen programming remain research and development options. They may ultimately provide lower-cost or more broadly applicable approaches, but their potential contribution depends on substantial improvements in technology and commercial readiness, supported by evidence on efficacy, durability, safety, delivery and system fit. These technologies should therefore be treated as preserving longer-term option value rather than contributing materially to near-term abatement.

The summary table and detailed sectoral technology assessment (Appendix C.2) reveals:

- No enteric methane technology is currently ready for broad deployment across all Australian dairy systems. Near-term opportunities are system-specific and should distinguish between selective deployment in controlled feeding systems, translational trialling in pasture-based systems, and longer-term research and development.
- Many technically mature dairy options will not pay for themselves under current milk prices and input-cost structures. Premiums, procurement arrangements, supply-shed inseting, carbon crediting, concessional finance or other forms of cost and benefit sharing

may therefore be needed where verified emissions reductions do not generate sufficient private returns.

- Technology performance and feasibility depend on feeding system, pasture contribution, soil–water–manure interactions, farm infrastructure and regional climate. Stacking and timing are important for avoiding productivity trade-offs and matching interventions to seasonal emissions windows, particularly for nitrous oxide.
- Optimised nitrogen management, appropriate use of fertiliser inhibitors, energy efficiency and some established herd-management practices can be applied relatively widely, but their efficacy, economics and relevance still vary by region and production system. Methane-specific breeding is a potentially broad and durable strategy, but the necessary breeding values, proxies and index integration are not yet ready for general deployment.
- High-TRL and high-CRL options may remain at market introduction because of weak returns, high capital costs, limited supply, approval requirements, operational complexity or MRV friction. Demand-side mechanisms and proportionate, low-cost and increasingly automated MRV are necessary complements to technical readiness.
- Grazing-compatible delivery of 3-NOP and other inhibitors, methane vaccines, synthetic haloforms and related compounds could expand pasture-system abatement over the medium to long term. Before scaling, they require dairy-specific farm-system trials, sustained-efficacy evidence, safety and residue frameworks, reliable supply, viable economics and a credible route to claimable abatement.
- For enteric technologies, reliable delivery is often a central constraint, especially in pasture-based systems. However, maturity also depends on sustained efficacy, product consistency and availability, animal and human safety, residues, economics, regulatory assurance, market acceptance and fit with dairy production systems.

Overcoming scaling constraints. The immediate task is not simply to unlock all nominally scaling-ready technologies, but to differentiate among options that can be deployed selectively now, those needing translational development before 2030, and those that may become viable after 2030. For established options, trusted advisers, effective extension, decision tools and regionally credible demonstrations can accelerate appropriate uptake. For emerging options, investment should focus on resolving the particular evidence, delivery, supply, safety and assurance constraints that prevent progression.

The remaining dairy portfolio contains two distinct bottlenecks. The first comprises technically mature but economically constrained options, including manure systems, stand-off pads and some feed and fertiliser interventions. The second comprises options such as *Asparagopsis*, methane-specific breeding, grazing-compatible inhibitor delivery and emerging compounds that require further development or validation before market activation is appropriate. Two broad levers remain important, but should be applied selectively:

1. Reduce effective cost through concessional finance, grants, shared testing infrastructure, energy-service models for methane-to-energy projects, and supply-chain standardisation where the technology has sufficient evidence and a plausible deployment pathway.

2. Create product value through processor or retailer premiums, supply-shed insetting, procurement of lower-emissions milk and, where suitable methodologies exist, carbon crediting. These mechanisms should reward verified outcomes rather than presume that particular technologies are ready for universal deployment.

Overcoming MRV challenges. Dairy requires MRV that is credible and affordable. Without MRV incentives cannot be directed, and markets will not operate efficiently to assist technology scaling. Enteric methane in pasture systems especially needs sampling-based, model-informed, herd-level methods acceptable to processors and carbon markets. For manure, methods must handle leakage, uptime and flare efficiency. Regional demonstration and modelling are priorities to achieve accuracy sufficient for payments and supply-chain claims, not high-precision modelling at individual cow level. In terms of research and development, investment priorities are herd-level MRV for enteric methane and manure project MRV that accounts for leakage and effective run-time of technologies.

Regional embedding and capability building. Adoption hinges on trusted advisers, farm systems groups, and regionally credible trials that integrate technology stacks (e.g., breeding with N optimisation with enteric inhibitor), pasture growth curves and herd management. This reduces perceived risk, clarifies ROI, and accelerates diffusion—mirroring the cropping conclusion.

4.2.3 Portfolio analysis

The dairy emissions technologies reviewed in this study present a reasonable balance across the transition phases. However, adoption is low. Many options will remain stuck with low adoption without demand-side activation and intermediating functions (e.g. incentives, MRV, finance, supply-chain alignment).

High level summary of actions:

- Scaling ready (A7): optimised N fertiliser use on pasture; nitrification inhibitors; urease inhibitors; and phytochemical-rich pasture species and phytochemical extracts in diet can scale primarily via extension, decision tools and advisory capability.
- Scaling constrained (A5): lipid supplementation; nitrates; garlic/citrus extracts; covered lagoons/digesters; stand-off pads; manure slurry acidification; and low-emissions farm machinery—require market creation (premiums/credits/procurement), concessional finance and low-friction MRV to become investable at scale. 3-NOP is classed as scaling constrained beyond the controlled feeding situations.
- Development trialling (A4) *Asparagopsis* and other high-efficacy inhibitors; selective breeding (methane trait proxies and index integration); urine patch inhibitors; and effluent solid separation—have high potential but require further demonstration, delivery refinement, assurance/regulatory co-design and means to monetise emissions reductions.
- Research/foundational (A1–A2): early-life programming, synthetic haloforms, and vaccines require longer-horizon R&D and (for dairy) early attention to delivery protocols and social licence.

- Some technologies are not effective and either deliver little abatement (“Unlikely” biochar and probiotics for methane) or deliver co-benefits with only incidental methane reductions (ionophores).

4.2.4 System interactions: risks and opportunities

Technological & infrastructure interactions. Delivery mechanism innovation (bolus/slow-release carriers for 3NOP and haloforms) and low friction MRV are pivotal to for uptake of low-emissions technology in pasture systems where most emissions occur. Renewables, on-farm biogas and electrification of equipment complement manure measures and Scope2/3 reductions. Some of these technologies may require large farms and/or shared locality-based systems to achieve sufficient economies of scale to ensure ROI.

Cross-system & cross-sector interactions. Dairy’s interaction with energy systems (e.g., biomethane from covered lagoons; electrification of milking/cooling) can shift the ROI for manure projects, especially with energy offtake and credits and the use of renewable energy certificates as the business model. Supply chain reporting (Scope3) creates an agreed market mechanism for processors to valorise on-farm abatement, creating conditions for insetting/premiums.

Socio-cultural interactions. As with cropping, imposing new expectations without equitable cost sharing risks resistance. Success depends on trusted advice, clear value propositions, and transparent communication, especially for additives subject to public scrutiny.

Cross-sectoral transformation effects. Shifts in retail/consumer preference and export market requirements may unlock premiums for low-emissions dairy. Conversely, if additives become a condition of market access, feed supply chains and delivery logistics must scale rapidly.

Dairy-specific headwinds. Dependence on imported inputs (e.g., certain inhibitors, bioactives) and limited domestic manufacturing can constrain access and raise costs of adoption; the administrative burden of climate disclosures and Scope3 reporting will create resistance to the broader introduction of low-emissions agriculture and can be reduced by simplification, automation and consistent templates through processors.

4.2.5 Investment assessment

Investment levels across dairy technologies, described in the STA (Appendix C.2), vary widely, with the overwhelmingly highest concentration in selective breeding (\$30-40M) and feed supplement (>\$20M). There is moderate investment in nitrification inhibitors and urease inhibitors (each \$2.01 M; \$1–\$5 M band). Lower investment is evident for lipid supplementation and ionophores (each \$0.84 M; \$500k–\$1 M band).

Table 4.2.2. Indicative assessment of investment in different technologies (2022-25). NB: Investments here are a limited subset of all investments focused on technologies; they may be related to technologies that span sectors and may not primarily be targeted to cropping. See Section 3.6. for details on data. “No data sourced” means there were no investment data in the dataset for this category.

Technology	Investment identified	Classification
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3-Nitrooxypropanol (3-NOP) – rumen methane inhibitor	\$8,917,056	\$5-10mill
Red seaweed (<i>Asparagopsis</i>) and extracts from seaweed as feed additive	\$7,359,712	\$5-10mill
Phytochemicals – extracts added to diet (e.g., essential oils)	\$6,054,668	\$5-10mill
Synthetic bromoform and various 2nd generation haloform anti-methanogenic feed supplements	\$3,856,970	\$1-5mill
Nitrification inhibitors	\$2,012,500	\$1-5mill
Urease inhibitors	\$2,012,500	\$1-5mill
Selective breeding for low methane	\$38,465,762	>\$30mill
Lipid / fat supplementation	\$843,755	\$500K-\$1mill
Ionophore antibiotic	\$843,755	\$500K-\$1mill
(Nil/undetected in RDC extraction) nitrates; garlic/citrus; urine patch inhibitors; stand-off pads; covered lagoons/digesters; effluent separation; slurry acidification; biochar; low-emission machinery; vaccine; early-life	no data sourced	no data sourced

Even allowing for partial coverage and imperfect tagging, the dairy-tagged RDC project set shows that activity is concentrated in SF1 knowledge generation, especially for feed additive options (*Asparagopsis*, 3-NOP, phytochemical extracts). The only technology cluster where learning (IF4) and diffusion (DF2) appear together in the dairy-tagged set is nitrogen management, reflecting program evaluation and uptake-oriented activity within broader cross-industry nitrogen programs that include dairy. Across the dairy-tagged set, IF3 (coordination/synchronisation) is absent, suggesting limited explicit project activity directed at system-level coordination, even though coordination constraints are prominent in the broader technology analysis (that is, for example, where MRV or supply of materials constrains scaling).

Overall RDC and ZNE-Ag CRC project analysis suggests funding is weighted toward knowledge generation and early validation, even for technologies that are assessed as scaling-ready or scaling-constrained. For example, the investment evidence for enteric inhibitors emphasises efficacy trials, delivery feasibility (including grazing-system delivery concepts), residue/safety assurance, and measurement foundations. This is reasonable as some of these products are scaling ready in contained animal systems but not yet for grazing, and to some extent the efficacy and safety trialling are requisites for dossier building for regulatory approval (where not eligible as feed additive or where productivity claim made) or MRV barriers. These point not so much to TRL constraints and more to broader system barriers to deployment.

Table 4.2.3. Dairy technologies, associated archetypes, and functions aligned to funded activity. This table identifies the number of investments (i.e. projects) aligned with specific technologies and functions. For example, 10 projects

had at least a partial focus on *Asparagopsis* and SF1 (Knowledge generation). NB: Projects could be classified as aligned with up to four technologies, and up to 2 functions.

Technology	Archetype	SF1: Knowledge	SF2: Networks	SF3: Resources	IF1: Direction Setting	IF2: Legitimizing	IF3: Coordination	IF4: Learning	DF1: Activation	DF2: Diffusion
<i>Asparagopsis</i>	A4 - Development trialling	10	0	1	2	1	0	0	0	0
3-NOP	A5 - Scaling Constrained	3	1	0	0	0	0	0	1	1
Precision Nitrogen Applications	A7 - Scaling Ready	2	0	0	0	0	0	1	1	1
Phytochemical extracts (diet)	A7 - Scaling Ready	2	0	0	0	0	0	0	0	1
Nitrification inhibitors	A7 - Scaling Ready	1	0	0	0	0	0	0	1	1
Urease inhibitors	A7 - Scaling Ready	1	0	0	0	0	0	0	1	1
Optimized N fertilizer-use on pasture	A7 - Scaling Ready	1	0	0	0	0	0	0	1	1
Synthetic haloforms (gen-2)	A2 – R&D	1	0	0	0	0	0	0	0	0
Lipid/fat supplementation	A5 - Scaling Constrained	1	0	0	0	0	0	0	0	0
Ionophore antibiotic (Monensin)	Low abate/High co-benefit	1	0	0	0	0	0	0	0	0
Probiotics & directed microbes	Unlikely	1	0	0	0	0	0	0	0	0
Selective breeding	A4 - Development trialling	1	0	0	0	0	0	0	0	0

4.2.6 Prioritisation analysis

The analysis flags a few key points. First, selective breeding has very high investment but is still classified as development trialling (A4) in this portfolio, reflecting that investment is being directed to building measurement/proxy capability and integration pathways rather than to simple diffusion. Investment is high proportionate with gains but may take a long time to materialise and as the technology assessment has indicated unless incentives are put in place to prevent gains being largely direct to GHG efficiency of product rather than absolute emissions reduction will be low. This suggests that in addition to continued investment in supply side R&D some investment into other innovation functions to shape system drivers and incentives should be considered. Second, the feed additive portfolio contains both scaling-ready and development-trialling items (3-NOP A7; *Asparagopsis* A4; haloforms A2), reflecting that delivery and assurance constraints continue to be a central investment target rather than broad adoption at scale. That is we have some technologies that could be deployed but we continue to enrich the available technology stack. This probably reflects longer-term concerns about safety, access, ultimate cost of goods and effectiveness of the initial tranche of feed supplement technologies.

Conversely, multiple technologies that are technically mature but scaling-constrained (A5) have nil/undetected RDC investment in the extracted classification (e.g., manure systems and several farm infrastructure options), which suggests either that investment is occurring outside the captured RDC dataset (highly likely) or that these areas remain under-served relative to their potential in suitable system.

Vaccines have a longer-term high potential for abatement at the sector and whole of agriculture level but low investment. Given centres of investment overseas (such as New Zealand and the USA) this may be appropriate, but Australia should stay engaged, ensure vaccines are suitable for our rumen biology and microbial suite, and that Australia will have access to technology when developed. This may look less like investment in supply side functions such as R&D but more networking and connecting with international research efforts.

Comparison of industry level and sector level rankings are similar reflecting the relative importance of the sector as an agricultural emissions source (i.e.. Reducing emissions within the sector is materially important to agriculture as a whole), and also that the sector has attracted a proportionate or higher level of investment to sector emission contribution.

Table 4.2.4. Industry-level assessment of adequacy of current investment coverage for Dairy comparing level of investment against whole of agriculture abatement potential (see Section 3.6 for method). Light Grey = Benign neglect; Dark Grey = overinvestment/ other investment goals?; Blue = Untapped potential; Pink = Well-supported; Purple = Missed opportunity.

	Low potential abatement	Medium potential abatement	High potential abatement
Low investment (or data not found)	Stand-off pads; covered lagoons/digesters; effluent separation; slurry acidification; low-emission machinery; probiotics; biochar	Lipids; nitrates; garlic/citrus; urine patch inhibitors	Vaccine; early-life programming
Medium investment		Phytochemical extracts (diet)	3-NOP; <i>Asparagopsis</i> ; synthetic haloforms
High investment		Selective breeding	

Table 4.2.5. Agricultural sector-level assessment of adequacy of current investment coverage (Dairy) comparing level of investment against whole of agriculture abatement potential (see Section 3.6 for method). Light Grey = Benign neglect; Dark Grey = overinvestment/ other investment goals?; Blue = Untapped potential; Pink = Well-supported; Purple = Missed opportunity.

	Low potential abatement	Medium potential abatement	High potential abatement
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Low investment (or data not found)	Lipids; nitrates; garlic/citrus; stand-off pads; covered lagoons/digesters; effluent separation; slurry acidification; low-emission machinery; probiotics; biochar	Nitrification inhibitors; urease inhibitors	Vaccine
Medium investment	Phytochemical extracts (diet)	3-NOP	<i>Asparagopsis</i> ; synthetic haloforms
High investment		Selective breeding	

4.2.7 Pathways for Dairy

Dairy differs from extensive livestock in that feed delivery, manure control, and operational data availability are more tractable, particularly in southern and irrigated systems. However, despite relatively high technical readiness for many mitigation options, adoption remains constrained by economics, delivery in grazing systems, MRV friction, and weak demand-side value capture.

The time-bound logic prioritises near-term deployment of proven options in the limited contexts where they are feasible, while building the evidence, delivery systems and assurance needed for prospective technologies after 2030. Horizon 1 therefore distinguishes between selective deployment, translational trialling and longer-horizon R&D, rather than treating the enteric portfolio as generally ready for scaling:

- Horizon 1 (now–2030) focuses on unlocking uptake of *scaling-ready* and *scaling-constrained* technologies by aligning MRV, delivery mechanisms, and early market signals. This includes targeted electrification and manure projects, nitrogen efficiency, and enteric mitigation where delivery is feasible. Critically, H1 invests in low-friction MRV, delivery systems, and advisory capability, without which later scaling is not credible.
- Horizon 2 (2030–2035) builds on these foundations to scale integrated mitigation stacks (breeding + feed + manure + energy), expand insetting and procurement mechanisms, and normalise MRV across processors and financiers. This is the main period where absolute emissions reductions accelerate.
- Horizon 3 (post-2035) consolidates low-emissions dairy as business-as-usual, with mitigation embedded in contracts, infrastructure, herd management and advisory systems, and enables uptake of breakthrough options (e.g. vaccines or long-acting enteric inhibitors) precisely because delivery, MRV and market pathways are already in place.

Table 4.2.6. Key barriers (B), enablers (E), opportunities (O) and non-investment signals (N) for dairy, synthesised from previous sections, underpinning action areas.

Item	Description
B1. Delivery constraints for enteric inhibitors in pasture systems	High-efficacy inhibitors exist, but many require consistent daily controlled feeding; delivery to grazing herds remains a central constraint for pasture-dominant systems.
B2. Weak or negative ROI for many mature options without market activation	Many technically mature options (e.g., manure systems, stand-off pads, some feed additives) are scaling-constrained because they do not pay for themselves under current milk pricing/input costs without premiums, insetting/procurement or crediting, and/or concessional finance.
B3. MRV friction (cost, complexity, poor fit) blocks incentives and finance	Without credible, affordable MRV, incentives cannot be directed and markets/finance cannot operate efficiently; because of variable action anti-methanogenic feeds for pasture fed animals needs sampling-based, model-informed herd-level approaches, and manure MRV must address leakage and effective run time.
B4. Manure mitigation is capex-heavy and operationally complex	Covered lagoons/digesters and other manure systems face high up-front costs, approvals, uncertain energy revenues and MRV requirements, limiting adoption largely to suitable larger operations and locations.
B5. Seasonality and soil moisture variability complicate N ₂ O mitigation and accounting	N ₂ O varies strongly with soil moisture and rainfall; year-to-year reductions are difficult to forecast and best assessed over longer integration periods. Dairy has one soil nitrous oxide emission factor across all soil types under irrigation versus those for dry land. To create incentive a differential emission factor would be needed that can credit action on a particular soil type and condition.
B6. Supply-chain pressure without cost-sharing can create resistance	Scope 3 transparency demands are increasing, but without aligned incentives/cost-sharing they can exacerbate strain rather than accelerate mitigation; administrative burden risks resistance.

B7. Social licence and residues/assurance risks for additives	Additives can face public scrutiny; success depends on assurance, residues frameworks and transparent communication, and missteps can trigger processor/retailer retreat and stranded investment. Farming is often resistant to legislative restrictions, and this can create backlash if risks are not managed well.
E1. Scaling-ready nitrogen management and inhibitors	Optimised N fertiliser use, nitrification inhibitors and urease inhibitors are assessed as scaling-ready with broad applicability and co-benefits, forming a near-term abatement backbone.
E2. Dairy systems can be more “tractable” for delivery and data than extensive grazing	Relative to extensive livestock, feed delivery, manure control and operational data availability are more tractable in dairy (especially southern/irrigated systems), improving feasibility of several mitigation measures.
E3. Emerging demand-side pull through Scope 3 and processors	Processor and retailer emissions transparency requirements can create demand-side pull and insetting/premiums where MRV is workable.
O1. Low-friction MRV as shared enabling infrastructure	Building proportional, automated farm-level MRV (enteric + manure) can unlock incentives, finance and claims at scale, focusing on payment/decision thresholds rather than research precision.
O2. Energy integration can improve manure project economics	Biomethane/biogas capture, renewables, energy efficiency and electrification can shift ROI for manure projects where scale and offtake/credits/renewable energy certificates exist, supporting Scope 2/3 reductions alongside methane abatement.
O3. Delivery-mechanism innovation for pasture enteric mitigation	Bolus/slow-release carriers and other delivery innovations could unlock medium-term pasture abatement, but require translational trials, residues/safety frameworks and claimable MRV pathways.
O4. Stacking rules and stack design to manage interactions and complexity	Integrated stacks (breeding + feed + N + manure + energy) offer higher impact but require evidence on additivity/neutrality and simple stacking rules embedded in advisory/MRV systems.
N1. Premature or broad scaling of additive expectations without delivery/MRV	Forcing uptake before delivery, MRV and assurance are workable risks backlash, non-compliance, greenwashing scrutiny and stranded investments.

N2. MRV that is too costly/complex will suppress uptake	MRV that is R&D-heavy, slow or expensive will deter participation, preventing incentives and market mechanisms from operating at scale.
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Table 4.2.7. Table of recommended investment pathways and prioritised actions across horizons for Dairy. Note: The order and numbering do not indicate level of importance or priority, but simply to allow cross-reference of ‘aligned action areas’ with best action in Table 4.2.8.

Action areas	Problem / Risk Addressed	Indicators of Success	Indicators of Failure	Prioritised actions aligned to horizons
1. Create targeted market signals to de-risk scaling-constrained dairy abatement investments	Many mature dairy mitigation options (especially manure systems, stand-off pads and some feed additives in limited delivery situations) are technically feasible but not investable under current pricing and input cost structures. Without premiums, inseting, procurement or crediting, adoption stalls despite technical readiness.	Targeted premiums, inseting or procurement operating for delivery-constrained options; concessional or private capital flowing into eligible projects..	Short-lived or fragmented incentives; lack of private co-investment; low uptake of capital-intensive or delivery-constrained technologies.	H1 (now–2030): Pilot premiums, procurement and inseting for manure and delivery-feasible enteric options; align concessional finance and grants. H2: Standardise market signals across processors and regions; integrate with finance. H3: Normalise incentives in contracts and procurement settings.
2. Deploy low-friction, credible MRV to unlock incentive, finance and stacking pathways	Incentives, finance and markets cannot function at scale without affordable, credible MRV. Existing approaches risk being too costly or complex for routine use, particularly for enteric methane under pasture variability and manure projects with leakage and uptime risks.	Farm-level MRV adopted by processors and financiers leading to deployment of option stacks bespoke to enterprises and geographies; clear baselines and stacking rules; incentives	MRV costs and rigidity deter participation; disputes over credibility; greenwashing scrutiny prevents use of claims; incentives fail to scale.	H1: Co-develop proportional MRV focused on payment and decision thresholds (enteric and manure) with sector and farmers focussing on feasibility that meets integrity requirements; pilot processor/aggregator embedded MRV. H2: Integrate MRV into processor data systems, inseting and finance platforms. H3: Maintain MRV as baseline sector

		operating with trusted verification.		infrastructure and update for new technologies.
3. Prioritise universally scalable nitrogen abatement technologies, application of energy efficiency into sheds and on-farm operations and manage stacking interactions	Dairy's most broadly applicable and ROI-positive abatement options (optimised N use, nitrification inhibitors, urease inhibitors, energy efficiency actions) can scale now, but benefits are diluted if stacking interactions and N ₂ O variability are not well managed or recognised in MRV.	Widespread uptake of N optimisation and inhibitors; cost-effective application of energy efficiency action; N ₂ O reductions recognised in MRV; approved stacks combining N, genetics and enteric measures performing as expected.	N ₂ O outcomes highly variable or uncredited; capital investment and hurdle barriers to implementation of energy efficiency actions; stacking reduces effectiveness; advisory burden and complexity slow uptake.	H1: Expand advisory delivery and decision tools for optimised N and inhibitors; Target incentives and concessional finance to reduce early-adopter risk of energy efficiency technologies; test stacking interactions; incorporate N pathways into MRV. H2: Standardise approved stacks through advisory and MRV systems. H3: Extend stacking frameworks to include emerging enteric options.
4. Develop and validate dairy-suitable enteric inhibitor and delivery pathways	Some enteric inhibitors have demonstrated high efficacy under controlled conditions, but broad dairy application remains constrained by feeding-system fit, reliable delivery, sustained efficacy, product availability, economics, safety and residue assurance. These constraints vary among products and should not be reduced to delivery alone.	Sustained herd-level methane reductions (e.g. 20–30%) achieved over extended periods across regions; delivery systems proven workable and safe.	Delivery failures; short persistence; residue or animal-health concerns halt deployment.	H1: Undertake dairy-specific, longer-duration translational trials of prospective inhibitors and delivery approaches across representative feeding systems. Assess sustained efficacy, dose and feeding-frequency effects, animal performance, milk residues, safety, supply feasibility, cost and herd-level MRV. Restrict deployment-oriented activity to situations where evidence and product access justify it.
5. De-risk producer economics and build coordination capacity for uptake	Adoption depends on margins, labour fit and coordination across processors, advisers and suppliers. Economic volatility and lack of intermediating	Increased participation in pilots and uptake programs; delivery models fit within farm routines;	Financial stress limits participation; fragmented delivery; low trust and low engagement in programs.	H1: Target incentives and concessional finance to reduce early-adopter risk; invest in coordination and advisory capability. Develop simple decision support and project registration to reduce cognitive load on

	functions limit uptake even where technologies are technically ready. Producers may not have 'free-board' for additional cognitive load of new markets.	coordination through processors/advisers reduces transaction costs.		producers. Develop exploration environments (virtual farms) to allow exploration of options on production and resource requirements. H2/H3: Integrate incentives with longer-term contracts and finance. Normalise farm emissions measurement in processor decision systems and commercial contracting arrangements.
6. Maintain social licence and simplify claims governance for additives and manure systems. Ensure animal welfare is prioritised	Public or regulatory pushback on additives or manure systems risks processor retreat and stranded investment. Complex or inconsistent claims frameworks raise compliance costs and reputational risk.	Stable public sentiment; accepted claims; predictable residue and environmental standards across processors and markets.	Negative media or retailer rejection; tightening standards; withdrawal of products or claims.	H1: Transparent assurance and communication; align MRV, residues and claims. Invest in safety and assurance research as a 'public good' since one product reputational misstep can poison the well for all. H2: Harmonise standards across processors and key markets. H3: Maintain adaptive governance as new technologies emerge.
7. Align international MRV and residue standards to protect exports and reduce duplication	Divergent international MRV, residue and assurance requirements fragment supply chains, increase compliance costs and threaten export access for low-emissions dairy products.	Mutual recognition or alignment across major markets; reduced duplication; portable claims.	Dual compliance obligations; rising costs; loss of market access or credibility.	H1: Engage in international alignment and co-design MRV and residue standards with export markets. H2: Secure mutual recognition where feasible. H3: Maintain alignment as standards and technologies evolve.

Best-bet actions for dairy, mapped to aligned action areas are identified and detailed in Table 4.2.8. These actions are considered to be the current sub-sectoral investment priorities to strategically advance the sub-sector's contribution to a low emissions future, and combine a variety of mechanisms and functions beyond R&D to build a foundation for speeding up low-emissions transitions for red meat and sheep post-2030, and ensuring accountability and MRV are integral to investment, market access and social licence.

Table 4.2.8. Best-bet actions for dairy, matching action area order in the table above. Note: The order of the best-bet actions in this table does not indicate their level of importance or priority. A low priority does not indicate that an action is not worth pursuing, just that it has low leverage for emissions reduction.

Best-bet actions	Aligned action areas	Rationale (why this action is needed)	Description of the action	Priority
Deploy low-friction, fit-for-purpose MRV for dairy systems (enteric methane and manure), embedded in processor and advisory workflows.	2, 6	Without credible, low-cost MRV, incentives, markets and coordination cannot function at scale. In pasture-based dairy, MRV must tolerate biological and seasonal variability and operate at herd or farm scale rather than individual animal level.	Design herd emissions measurement approaches that tolerate seasonal and regional variability and explicitly handle multiple practices used together (stacking). Focus on proportional accuracy aligned with incentives and claims to flow through supply chains to support market claims without high measurement burden or high activity/location accuracy and where possible produce enabling data and models as public good infrastructure. Embed MRV logic within processor systems and trusted advisory workflows, including clear baselines and stacking rules, to minimise producer reporting burden and transaction costs.	Priority High; Credible, low-cost MRV is a foundational requirement for directing incentives, (e.g. insetting, procurement, finance) and supporting credible claims. Without MRV that works at herd or farm scale and tolerates seasonal and biological variability, neither market signals nor coordination mechanisms can operate effectively. Investment in proportional, automated MRV therefore has the highest system leverage across all mitigation pathways.
Scale scaling-ready nitrogen abatement (optimised N use, nitrification and urease inhibitors) and energy efficiency technologies and electrification as a core, near-term pathway.	3, 2	These options are among the most broadly applicable and investable abatement measures available today for dairy, with positive or near-positive ROI and substantial co-benefits. Their impact depends on advisory delivery, stacking guidance and MRV recognition rather than further technology maturity.	Prioritise extension, decision tools and regionally credible demonstrations for optimised nitrogen management and inhibitors. Integrate nitrogen pathways explicitly into MRV and approved mitigation stacks so outcomes are recognised alongside genetics, enteric mitigation and manure options. Consideration could be given to deemed emission reduction values based on varying levels of best management practice implementation. Where initial capital investment presents barriers to adoption of energy efficient operations or electrification look to appropriate incentives and concessional finance.	Priority High: Optimised nitrogen management and fertiliser inhibitors are among the most broadly applicable and investable abatement options currently available in dairy systems. They deliver immediate emissions reductions with co-benefits and generally positive or near-positive returns. Their impact is constrained primarily by advisory delivery, stacking guidance and MRV recognition rather than technology readiness, making them a core near-term priority. Electrification and energy efficiency similarly create immediate emission reductions with cost

				savings and improved energy security for farm operations.
Create targeted market signals and concessional finance to unlock scaling-constrained manure and infrastructure options.	1, 5	Several technically mature dairy mitigation options remain non-investable due to weak ROI, high capex or delivery complexity. Market activation is a precondition for adoption, not an optional accelerator.	Pilot and scale processor premiums, supply-shed inseting, procurement and (where applicable) crediting for manure and energy-integrated projects with credible MRV. Align grants and concessional finance to these signals and support aggregation or managed-service models to reduce risk and transaction costs.	Priority High: Manure methane mitigation and related infrastructure offer material, concentrated abatement potential but are capital-intensive and rarely investable without explicit market activation. Targeted premiums, inseting, procurement and risk-sharing finance are essential preconditions for uptake. Where aligned with energy integration and credible MRV, these options can deliver durable, system-level emissions reductions and warrant high priority.
Generate controlled-system evidence and support selective deployment of validated enteric inhibitors where conditions are suitable.	1, 2, 4	Some enteric inhibitors have demonstrated efficacy under controlled feeding conditions, but this does not establish readiness for broad deployment across Australian dairy systems. Product maturity, supply, feeding frequency, sustained efficacy, animal performance, safety, residues, cost and assurance requirements differ among inhibitors. Controlled-system activity should therefore generate product-specific evidence and support selective deployment only where these requirements	Undertake targeted, product-specific trials in total mixed ration, partial mixed ration and other controlled or semi-controlled dairy systems. Assess delivery reliability, sustained efficacy, dose and feeding-frequency effects, animal performance, milk residues, safety, product availability, costs and herd-level MRV. Where the evidence, product supply and economics are sufficient, support selective deployment in clearly defined systems. Use the resulting evidence to inform regulatory and claims pathways and determine whether further development for pasture-based systems is warranted, rather than presuming progression to widespread scaling.	Priority Medium: This action can support near-term abatement in a limited set of suitable dairy systems while generating essential evidence on delivery performance, costs, residues, MRV workflows and regulatory readiness. Its value lies in distinguishing products and production contexts in which selective deployment is justified from those requiring further development, while informing any subsequent design of grazing-compatible delivery systems. Its primary impact is to de-risk future deployment rather than deliver immediate sector-wide reductions, and it should not be interpreted as establishing broad readiness across the dairy sector.

		have been adequately addressed.		
Develop grazing-compatible delivery mechanisms for enteric methane inhibitors (medium-term scale lever).	4, 2	For pasture-based dairy, the dominant barrier to enteric abatement is delivery feasibility rather than biological efficacy. Without reliable, persistent herd-level delivery, high-efficacy products remain confined to niches.	Prioritise translational R&D on bolus, block/lick, water-based and slow-release delivery systems. Define early success in terms of delivery persistence, safety and practicality, aligned with herd-level MRV, before optimising abatement performance or scale-out.	Priority: Medium: Reliable delivery to grazing herds remains a prerequisite for large-scale enteric mitigation in pasture systems. While the potential impact is substantial, delivery innovation requires further translational work and depends on upstream piloting, assurance and MRV foundations. This positions delivery mechanisms as an important medium-term priority rather than a near-term driver of emissions reduction.
Convert breeding investment into recognised, system-level abatement outcomes.	3, 6	Breeding offers durable, cumulative emissions reductions, but benefits risk being realised only as emissions-intensity gains unless genetic progress is visible and valued within MRV and market frameworks.	Strengthen methane-trait proxy validation and index integration, and ensure MRV, procurement and insetting frameworks recognise verified genetic gains. Embed breeding within approved mitigation stacks so long-term progress translates into claimable, system-level outcomes.	Priority Medium: Genetic improvement offers durable, cumulative abatement, but benefits materialise slowly and risk remaining confined to emissions-intensity gains unless recognised within MRV and market frameworks. The priority is therefore on system integration—proxy validation, index inclusion and claims recognition—rather than rapid emissions reduction, placing breeding in the medium-priority category.
Build coordination and advisory capability to reduce transaction costs and normalise uptake across dairy systems.	5, 3	The absence of intermediating and coordination functions limits translation from technical readiness to adoption. Trusted advisers and service models are decisive levers for scaling.	Invest in processor- and adviser-led delivery models, shared decision tools, standard templates and aggregation or managed-service approaches. Embed MRV logic, stacking rules and market signals within advisory practice to reduce complexity and increase participation. Harness emerging AI and virtual tools to provide in silico sandboxes for farmer experimentation and prove regionally relevant data and benchmarks to support comparative exercises.	Priority medium: Adoption of complex mitigation stacks depends on trusted advisers, coordinated delivery models and intermediating functions that reduce complexity and risk for producers. While coordination does not deliver abatement directly, it is essential for translating technical readiness and market signals into sustained practice change, giving it a medium but necessary priority.

Maintain social licence and export readiness through aligned MRV, residue and claims standards.	6, 7	Fragmented assurance frameworks and public scrutiny of additives or manure systems can trigger processor retreat, reputational risk and stranded investment. Alignment and credibility are essential system enablers.	Align MRV, residue standards and claims governance domestically and with key export markets; pursue portability and mutual recognition where feasible; and maintain adaptive assurance frameworks as new product classes and delivery options emerge. Recognised that research into safety and assurance is key least one technology destroy trust and market for a suite of similar technologies.	Priority Medium: Alignment of MRV, residue and claims standards is essential to protect market access, maintain confidence and avoid stranded investment. However, this action primarily safeguards uptake rather than driving it and delivers little direct abatement. Its importance lies in risk management and system stability, placing it at lower priority relative to MRV, nitrogen and market activation.
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4.3 Cropping

4.3.1 Background: Emissions contribution, distribution, trends and drivers

The cropping industry focus is on broad-acre, largely non-irrigated crops. Reflecting emissions and scale of each industry, the analysis predominantly focuses on extensive grains, including legumes and oilseed production, with a secondary focus on other cropping industries, predominantly sugar, rice and cotton.

Overall grain industry emissions (excluding sugar, rice and cotton from the above, and excluding LULUCF) for 2005 were 13.1 Mt CO₂-e (Burrett and Sevenster, 2025) and had increased to ~17.4 Mt CO₂-e in 2020 (Burrett and Sevenster, 2025). The scope 1 portions of these annual emissions are 7.6 Mt CO₂-e (2005) 10.4 Mt CO₂-e (2020), respectively (Sevenster and Burrett, 2024).

Variability is accounted for by seasonal differences and longer-term shifts in cropping: increased area of land under cultivation, and increasing cropping intensity accompanied by higher fertiliser use; declines in pulse production with increases in oilseed.

Total scope 1 emissions are based on estimates from recent analysis of Sevenster and Burrett, (2024). These accounts use a hybrid approach, combining bottom-up activity data (fertiliser use rates derived from surveys and benchmarks) with top-down inventory parameters (emission factors from the National Greenhouse Gas Inventory, NGGI, including updates from Grace et al. 2023). They indicate that ~60% of grains emissions were consistently from scope 1 emissions (Sevenster et al. 2022). However, the sources of these emissions varied between the baseline (2005) and 2020 (Table 4.3.1). Emissions intensity decreased from the 2005 baseline of ~317 kg CO₂-e / tonne to ~305 CO₂-e / tonne (excluding LULUCF; Burrett and Sevenster, 2024), where good seasons and higher fertiliser application led to increased grain production. Improvements in emissions intensity are linked to consistently higher rates of fertiliser application and associated closing of yield gaps. Overall, these have contributed to higher overall scope 1 emissions from grain growing, which may be at least partially offset by improved carbon cycling and land use changes, which are outside the scope of this report, but appear to both be shifting soil towards a net sink (Burrett and Sevenster, 2025).

Cotton's on-farm emissions have recently been assessed (Sevenster et al., 2025), and are now updated annually in industry sustainability reports. Their baseline scope 1 emissions from the cotton growing is estimated at approximately 0.49 Mt CO₂-e. On the basis of 5-year average data underpinning this analysis (2016-2020, Sevenster pers. comm.), contributions to these emissions from different pools are comparable to those of grains. Most of the industry's scope 1 emissions are associated with relatively high applications of nitrogen fertiliser (see Section 2.2) including 62% via direct N₂O emissions, 6% via indirect N₂O emissions (deposition), and 4% from CO₂ associated with urea usage. Diesel for farm machinery use leads to ~10% of emissions associated with irrigation, and 7% for other operations. These proportions allow for an estimate of the breakdown of cotton and other smaller cropping sub-sectors (below) into pools as a first pass (in Table 4.3.1).

Less reliable information is available on absolute emissions and their variability in sugar and rice growing. Total Scope 1 emissions from sugarcane growing are likely in a similar range as cotton. Rice cultivation in Australia is small-scale, with about 50,000 ha sown annually (Quayle et al.,

2025). The relatively high emissions intensity of rice is associated with waterlogging and anaerobic decomposition, leading to methane (CH₄) emissions estimated at 0.25-0.5 Mt CO₂ -e (Quayle et al., 2025). These three smaller industries each present significant and distinct opportunities to reduce industry emissions, despite relatively small contributions to absolute agricultural emissions. They all maintain, or have commitments to develop, world-leading practices and emissions intensity for products. For the purpose of this report their total scope 1 emissions are estimated on the basis of the above as 1.3 Mt CO₂ -e, with distributions into pools based on cotton's 5-year averages (Sevenster et al., 2025).

It is important to note that the forms and extent of emissions also vary widely among farming systems, crops and regions. Wetter areas and seasons, and irrigated crops such as cotton, create higher risks of N₂O emissions and provide potentially higher return on investment for use of nitrification inhibitors than dryland crops. Different management systems will constrain the adoption of specific technologies (e.g. precision fertiliser applications) or make them economically non-viable. For example, southern cropping zones have limited ability to use summer cover/catch-crops.

For this report, estimates of feasible emissions reductions associated with grains are based on pools associated with the higher of the grains baseline (2005) (Sevenster et al., 2022) and the update (2020) report reflecting the continued upward trend in fertiliser use (Burrett and Sevenster, 2025) (Table 4.3.1). Contributors to grain sector emissions are itemised as pools in Table 4.3.1 and describe in the Appendix C.3.

Table 4.3.1. Derivation of the total ‘pools’ used for cropping Scope 1 emissions in this report, based on 2005 (Burrett and Sevenster, 2025) and 2020 (Burrett and Sevenster, 2025) as proportions and quantities of all cropping emissions, and derived emission pools used in this report. Excludes LULUCF, as this mixes sequestration and soil related emissions/ sequestration. All totals are rounded to a single decimal point, so totals may not reflect values.

Cropping emissions categories	2005			2020			Additional emissions pool estimate (non-grains -- sugar, rice, cotton) (Mt CO ₂ e)	Emissions total used in calculation of maximum emissions for the pool (Mt CO ₂ e)
	% of total grains emissions	% scope 1 emissions	Emissions pool, grains (Mt CO ₂ e)	% of total grains emissions	% scope 1 emissions	Emissions grains (Mt CO ₂ e)		
Fertiliser (direct N ₂ O)	12%	21%	1.6	18.7%	31.4%	3.3	0.8	4.1
Fertiliser (indirect N ₂ O)	1%	2%	0.2	1.8%	3.0%	0.3	0.1	0.3
Urea application (CO ₂)	7%	12%	0.9	12.4%	20.8%	2.2	0.1	1.7
Lime (CO ₂)	12%	20%	1.5	5.9%	9.9%	1.0	(in above)	1.3
Residues	11%	19%	1.4	11.2%	18.8%	1.9	0.1	1.7
Operations	12%	21%	1.6	8.7%	14.6%	1.5	0.1	1.6
other	2%	4%	0.3	0.3%	0.6%	0.1	0.0	0.2
Irrigation and dams	1%	1%	0.1	0.6%	1.0%	0.1	0.1	0.1
TOTAL	58%	100%	7.6	60%	100%	10.4	1.3	10.7

Long-term trends in scope 1 emissions in cropping are obscured by high annual variability. Annual variability is strongly dependent on rainfall, while key longer-term trends are associated with:

- **Intensification:** as many crop/livestock farms shift to continuous cropping, they increase fertiliser and machinery usage
- **Increased mechanisation, precision and varieties:** equipment changes and increasing data intensiveness of production underpin adoption of precision and efficient farm machinery, digital tools, and new genetics. These improve efficiency and manage risk, and can help meet changing environmental and market demands, providing platforms on which to integrate MRV and GHG accounting systems.
- **Global demand:** Market demands are big drivers of production systems and their emissions intensity. Increasing demand for pulses such as legumes has the potential to shift nitrogen use and emissions profiles. Domestic interest and early-stage demand for renewable fuel feedstocks are growing, led by plans for liquid biofuels. Oilseeds — especially canola — are key to near-term pathways. Multiple projects, funding schemes and airline collaborations signal intent to scale. Market demand and domestic industrial pull remain nascent, with new government initiatives (e.g. Cleaner Fuels Program) aiming to support investment.
- **Industry focus on emissions intensity:** cropping industries focus on improving emissions intensity, rather than absolute emissions reduction. Market pressures and opportunities create pressure to intensify (global commodity and input prices, weakening wool market, demand for biofuel feedstock, high input costs, etc), which are driving agricultural intensification. As the sector increases production, emissions will grow in the absence of levers to reduce emissions. Limited supply-chain incentives in commodity markets to reduce emissions (e.g. price premiums, market access requirements, food systems governance) constrain prioritisation of improvement in emissions intensity among growers.

Industry positioning: Overall, the emissions intensity of Australian cropping industries is already low by global standards (Sevenster et al., 2022; Quayle et al., 2025). Sevenster et al (2022) suggest that a feasible GHG intensity reduction of about 15% could be accompanied by significant increases in production (30-40%). Pathways to such goals depend on farming strategies and tactics, driven by global market signals, domestic policy and available technology.

While this report focuses on scope 1 emissions, a large source of emissions for cropping industries is the scope 3 emissions from fertiliser production. Consideration of these emissions will be central to any pathway to improved emissions intensity for Australia's cropping industries, and potentially amenable to cuts via green fertiliser production. Relatedly, economy-wide emissions reduction is likely to come from the cropping industry's contribution to emerging low-carbon liquid fuels. We return to these matters in chapter 5.

4.3.2 Technology assessment

For cropping, a total of 17 technologies are assessed, largely targeting improvement in emissions intensity through improved nitrogen use efficiency, improved soil function, and improved machinery efficiency. The assessment of individual technologies (Appendix C.3) is summarised in

Table 4.3.2. Many of the ‘win-win’ (Scaling ready – A7) options (e.g. minimum till, control traffic) are already widely adopted. Mature technologies that have a high emission reduction potential are often associated with high up-front or ongoing costs, limited productivity-related returns, and significant barriers to adoption or knowledge gaps about their efficacy in specific farm systems, regional, and seasonal conditions. Another set of four technology options is ‘scaling constrained’ (high TRL and CRL with low RoI – A5). These ‘scaling constrained’ technologies require market creation and/or other incentives to support wide-scale adoption. An apparent priority to address knowledge gaps and barriers to adoption is likely only to advance scaling if accompanied by market incentives for this class of technologies.

Key emerging technologies in the early emergence phase (TRL<4) have significant potential to reduce emissions if R&D can successfully overcome technical challenges.

Table 4.3.2. Summary of scope 1 emissions reduction technology assessment for cropping, including key elements from Sector Technology Assessment, with abatement potential based on maximum feasible 10-year abatement estimates. (See paragraph above for overview of archetypes, and Chapter 3 for details of classifications). These assessments are largely based on applications in grains at a national level, and will differ for different crops, regions and farming systems.

Technology name	Archetype	Current investment	Industry abatement potential	Ag Sector abatement potential	Confidence	Key issues
Slow-/Controlled-release nitrogen fertilisers	A5 - Scaling Constrained	LOW	MEDIUM	LOW	LOW	Import costs are high due to low volumes, no premium or economy of scale to support domestic production.
Nitrification inhibitors	A5 - Scaling Constrained	LOW	HIGH	MEDIUM	MEDIUM	Regional, seasonal and farm system specific RoI, limited co-benefit
Urease inhibitors	A7 - Scaling Ready	LOW	MEDIUM	LOW	LOW	Regional, seasonal and farm system specific RoI
Reduced Tillage	A7 - Scaling Ready	no data sourced	LOW	LOW	LOW	Well-integrated, scaled and established in most regions and systems
Precision Nitrogen Applications	Low abatement/ High co-benefit	HIGH	LOW	LOW	LOW	Cost/difficulty of integration into systems, limited incentive
Controlled Traffic Farming	A7 - Scaling Ready	no data sourced	MEDIUM	LOW	MEDIUM	Upfront cost, challenges of machinery compatibility in some systems, effective in wet conditions.
Lime Application	A7 - Scaling Ready	no data sourced	LOW	LOW	LOW	Well-integrated, scaled and being refined for GHG MRV and productivity

Management						trade-offs. Improved intensity at the expense of absolute emissions.
Legume Integration	A7 - Scaling Ready	LOW	MEDIUM	LOW	LOW	Scale, and applicability. Opportunity costs of mixed systems
Cover/Catch Cropping	Low abatement/ High co-benefit	no data sourced	LOW	LOW	LOW	Limited applications, poor MRV and best practice standards
Arbuscular Mycorrhizal Fungi Inoculation	A4 - Development trialling	LOW	MEDIUM	LOW	LOW	Limited evidence base, high complexity/limited capacity, challenging fit with many systems
Biochar Application	A4 - Development trialling	no data sourced	LOW	LOW	LOW	Very high costs relative to return (more sequestration oriented)
Stubble Retention	Low abatement/ High co-benefit	LOW	LOW	LOW	LOW	Well-integrated, scaled and established in most regions and systems
Electric Farm Machinery	A5 - Scaling Constrained	no data sourced	MEDIUM	LOW	MEDIUM	Cost and duty range limiting in many systems, small vehicle potential
Alternate Fuels	A5 - Scaling Constrained	no data sourced	MEDIUM	LOW	MEDIUM	Cost, production and distribution issues
Nitrogen-Fixing Crops (non-legumes)	A2 - Research and Development	no data sourced	HIGH	HIGH	LOW	Early stage development
Biological Nitrification Inhibition Crops	A2 - Research and Development	LOW	MEDIUM	LOW	LOW	Knowledge gaps and limited platforms; high variation in field trial outcomes
Green Cane Harvesting	A7 - Scaling Ready		LOW	LOW	MEDIUM	Well-integrated, scaled and established in most regions and systems

The summary table and detailed sectoral technology assessment (Appendix C.3) reveal that:

Limited return on investment and other incentives: Many technologies are “scaling constrained” – they cannot pay for themselves under existing market conditions and will require economies of scale to reduce costs, or incentives associated with return on use to scale (see Enablers – Section 4.3.3).

Integration of technologies within farm systems, climatic situations and regional settings: Most technologies are concerned with in soil-plant-water, and farming system interactions and cannot

be advanced in isolation and need to be evaluated and applied in specific farming contexts, probably with farm systems groups and advisor guidance. The difficulty of estimating returns across these technologies reflects this wide variation in their potential implications for productivity and other co-benefit returns. Their fit within farm systems and operations is also highly site and season-specific, building capability for refining and developing integrated approaches to stacking technologies and enabling some forms of optimisation for GHG intensity will therefore mean regionally targeted participatory experiments and solutions developed with farmers.

Adoption and scaling pathways for “scaling constrained”: Some mature technologies (CRL>5) are not being adopted and scaled at least in part because they offer little to no return on investment (see Appendix C.3 for details). An exemplar technology in this category is nitrification inhibitors. High relative costs and shallow response curves around optimisation (Pannell, 2006), create price disincentives and high transaction costs for their application relative to potential financial advantages. While other challenges to adoptability are also apparent, and discussed in the Sector Technology Assessment, lack of clear ROI is a major barrier for some of the more prospective technologies (e.g. NIs, controlled-release fertilisers and electrification).

Emerging technologies have potential to dramatically improve scope 1 emissions from cropping: Biological Nitrification Inhibitors (BNI) and nitrogen-fixing non-legumes (Garba et al., 2026). While BNI presents plausible medium-term opportunities (10-15 years) to reduce N₂O emissions, it is highly contingent on uncertain research and development investment and outcomes. The potential for BNI to provide emissions reduction at low cost is due to the NI being part of the plant function and included in the cost of seed, without a high metabolic cost (and potential with yield advantage). Nitrogen-fixing non-legumes are technically a longer-term proposition but could be game-changers in avoiding costs of nitrogen production, transport and application for grains (i.e. high risk/reward research). Arbuscular Mycorrhizal Fungi (AMF) and other biostimulants appear to have significant theoretical potential, but are constrained by the same factors that have limited their adoption for productivity gain - inconsistent field performance, complex biotic and abiotic interactions, and system capacity to scale.

Overcoming scaling constraints: Existing ‘scaling ready’ technologies are, on the whole, widely adopted. ‘Scaling constrained’ technologies are failing in ‘market introduction’ phase of scaling. They do not diffuse or scale because they do not generally offer a relative advantage to users, either in operational or profitability terms, at least in the majority of situations. These include nitrification inhibitors and slow/controlled-release fertiliser. Scaling and adoption are likely to come through at least one of two pathways: reducing costs of application (e.g. reducing costs through scaling production); creating incentives for low GHG products or practices (e.g. premiums for low GHG grains, ACCU methods). Domestic premium markets and procurement policies (or programs to support private sector procurement) could be used to create protected niches to scale demand and build capacity, especially for high-value products (e.g. cotton, specialty grains). More widespread incentives (e.g. the development of ACCU and other methods) are needed to scale adoption and practice change, especially at a regional or industry level.

Overcoming MRV challenges: Robust monitoring, verification, and reporting (MRV) is needed to efficiently support standards and methods such as ACCU and SBTi methodologies or concessional finance mechanisms. The emissions reduction potential of many technologies varies significantly

by crop type, farming system, season, and region. Soil-related emissions are complex, influenced by moisture, temperature, and other climatic and management factors. For instance, emissions factors for sugarcane are more than three times higher than those for non-irrigated crops (Norton et al., 2023).

Recent improvements in understanding emission factors (e.g., Grace et al., 2023) have enabled the development of sector-specific guidance on applying mitigation measures. But evidence on the effectiveness of mature technologies, especially when combined or “stacked”, remains highly variable across farming systems, soil types, and seasonal rainfall conditions. Process-based modelling highlights that interactions between fertiliser management, rotations, residue management and climate jointly determine emissions outcomes, reinforcing the need for integrated system-level approaches (He et al., 2026).

Cropping MRV systems remain constrained by the quality of emission factors, and underpinning measurement of nitrous oxide (N₂O) fluxes at appropriate spatial and temporal scales. Simplified default emission factors (e.g. IPCC Tier 1 ~1% of N inputs) mask substantial variability driven by climate, soil, and management, leading to systematic uncertainty in emissions estimates (Hergoualc’h et al., 2021). Empirical (Hergoualc’h et al., 2021) and modelling (He et al., 2026) evidence shows that N₂O fluxes can vary markedly across regions and management conditions, with emission factors differing several-fold across climate zones and fertiliser types, and high spatial and temporal variability observed even within fields. Australian meta-analysis confirms this heterogeneity, with cropping emission factors ranging widely and a revised grains-specific factor of ~0.41% recommended alongside geographically differentiated estimates (Grace et al., 2023). For operational MRV, sustained field- and landscape-scale N₂O measurement (e.g. chamber and micrometeorological approaches) and improvement in technologies to make this efficient, will be needed to generate regionally calibrated emission factors that are representative and defensible. Without these, coarse assumptions could undermine the credibility and portability of proportional, stack-aware accounting and market integration

Developing high-quality MRV systems should also prioritise trialling, demonstration, and application within and across regions, supported by robust modelling. Initial MRV investment should focus on generating regionally informed evidence about how practices and technology stacks affect emissions intensity. This avoids placing the primary burden on individual farms to produce precise farm-scale accounts. This implies incentive systems based on well-validated regional ‘best-practice methods’ or similar.

Regional embedding and capability building: Addressing the trade-offs associated with the application of technologies and practices requires regional-scale investment in trialling, demonstration and modelling to support assessment across diverse regions, farming systems and soil/climate contexts.

For improved emissions intensity in cropping, technology change will be more about adopting and adapting portfolios of technologies than individual technology replacements or single technology adoption. For example, in some areas leguminous cover crops and catch crops may provide a useful tool for reducing emissions intensity. In others, more emphasis on precision applications or nitrogen, or strategic and tactical use of nitrification inhibitors will be the most advantageous pathway. Refining and targeting region, season and farm system strategies require consolidated

focus across research, development, advisory and farming capability around stacks of technologies that are likely to work well together in a given region.

An overarching principle here is that Australian cropping industries are already efficient in economic and GHG terms by world standards. A central strategy is to enhance continuous improvement through approaches that link currently available technologies with regional capacity to trial and evaluate their value. This creates the capability to fast-track the scaling of emerging technologies in later time horizons.

Emerging technologies: Three emerging agricultural technologies have been identified here as potential areas for R&D investment and to ensure Australian research remains part of, and receptive to, inbound innovation from international R&D efforts. These are (1) biological nitrification inhibitors, (2) nitrogen-fixing crops (non-legumes), and (3) arbuscular mycorrhizal fungi (AMF) and other biostimulants. All three are at relatively low readiness levels (low TRLs and CRLs), but they differ in how knowledge is applied for adoption. The BNI and nitrogen-fixing non-legumes are knowledge-embedded – the innovation is built into plant varieties or products, making them easier to scale once developed, although development, and trialling to fit within farming systems can be difficult, expensive and time-consuming. AMF is knowledge-intensive, requiring significant changes in farm management and systems, standards, advisory systems, and machinery use for implementation.

The two emerging, knowledge-embedded technologies could be advanced by crowding in investment, fostering international and long-term partnerships, backed by industry. The knowledge-intensive work on biostimulants requires early investment in some basic standards and targeted R&D to improve understanding of microbial action on N pathways. If scalable approaches can be developed, the knowledge-intensiveness of this pathway is likely to require strong regional innovation networks to share learning on application. That is, this pathway would require both significant R&D investment *and* capability building in extension and learning to support scaling.

4.3.3 Portfolio analysis

Across the cropping technologies analysed, the distribution of technology types is relatively balanced across transition phases. Most scaling-ready (A7) technologies are already widely adopted, with some exceptions (e.g. minimum till, and CTF in certain regions). There is a bottleneck in the late emergence phase for scaling-constrained (A5) technologies. Accelerating adoption will require stronger demand-side measures and intermediating functions over a 5–10-year horizon to enable rapid scaling thereafter. This provides a window to define demand-side activation pathways (DF1, see Section 3.4.3). Key lines of action could be tackled in this period:

- 1) Because many technologies will be applied in stacked combinations on farms, MRV systems will need to adapt to regions, farm types, seasons, and soil conditions. Developing the necessary knowledge infrastructure and data will take time. An early priority is to establish medium- to long-term partnerships and networks to test and develop technologies and MRV approaches relevant to them. This will enhance the adoptability of technologies and the willingness of producers to trial appropriate technology packages.
- 2) In parallel, incentives for scaling-constrained technologies should be developed. These require costs and benefits to be shared across supply chains. For example, procurement

and demand management could support premium markets in high-value crops (and horticulture) to build economies of scale for domestic production of inputs where this can reduce costs (e.g. nitrification inhibitors, controlled-release fertilisers, and green urea).

4.3.4 System interactions: risks and opportunities

Technological and infrastructure interactions: AI, computing power and big datasets are likely to simplify farm-level accounting over the coming years and make estimation of scope 1 emissions and sources a normal part of these activities. Underpinning science and effective proportional MRV will be needed to underpin credibility.

Cheap renewable power and green urea production could reduce costs of nitrogen fertiliser, potentially changing the incentive structures around both farm productivity and emissions and leading other inputs to become limiting (e.g. lime).

Cross-system and cross-sector interactions: Interaction with the energy sector and especially the emerging low-carbon liquid fuel sector is likely to create numerous opportunities and risks as new markets emerge. For example:

- 1) Marginal land being brought into production of ligno-cellulose as bioenergy feedstocks, and the introduction of woody row crops could shift the hydrological balance, reducing production losses due to salinisation. This could be combined with changing ground cover for pollination services. These shifts may improve business-level GHG efficiency.
- 2) New market opportunities associated with emerging liquid biofuels industries could shift rotational cropping (canola, *Carinata* etc) and potentially reduce inputs. Integrating system opportunities may require a broader mechanism to assess opportunities and risk across industry and government portfolios.
- 3) Modular, plug-and-play mechanisms to assess regional, business and commodity GHG efficiency would be in greater demand.

Continued development of low-emissions vehicles in the mining sector may create opportunities for modification and adoption into agriculture.

Socio-cultural interactions: The speed of imposition and forms of new standards, market structures, and other expectations will influence social, cultural and political resistance to change. The distribution of the burdens and rewards of transition and the phasing of these are critical risks to consider in ensuring policies, systems of use and technologies have progressive and enduring legacy.

Cross-sectoral transformation effects: Shifting diet preferences alongside technological change may create changing markets for products, with potentially higher demand for plant-based protein or synthetic meat. Conversely, if low-emissions meat production becomes more dependent on additives, demand for animal feed may grow substantially over the coming decades if delivery mechanisms and practices to support extensive grass-fed meat production fail. These shifts could significantly affect grain demand and prices and thus the economics of both grain production and emissions intensity changes. The materiality of these shifts will depend on the composition and value of markets, and may be low given high export demand for Australian meat.

Growing interest in circularity also provides opportunities for cropping industries to benefit from waste streams from other industries, which has some potential to reduce emissions – see STA discussion on biochar (Appendix C.3).

Cropping specific headwinds

- Dependence on foreign suppliers for inhibitors and green fertiliser technology can limit the supply of products and restrict access.
- Inherent industry tensions between moves towards low-input, or regenerative systems and shorter-term production goals. Apparent tension among growers with the cost-price squeeze of finding low-input pathways to profitability at the expense of wider national productivity, or optimising profitability through relatively high-input, high output systems.
- Pressure through supply chains to reduce fertiliser rates could have both production risks and risks for declining natural capital through mining of the soil as a natural resource.
- The complexity of climate-related financial disclosure and Scope 3 reporting frameworks makes them difficult to implement in some cropping situations

4.3.5 Investment assessment

Investment levels across cropping technologies, described in the STA (Appendix C.3) vary widely, with the highest concentration of funding directed toward precision nitrogen application, enhanced efficiency fertilisers (EEFs)—including controlled-release products, nitrification inhibitors, and urease inhibitors. Key investments include \$17.33 M in the national GRDCs LEIFs program (2024–28) and the \$5 M ARC Smart Fertilisers Hub. These investments are often targeted to regional and farm system-specific applications, and strongly aligned with knowledge generation (SF1) with complementary support for learning (IF4) through multi-site trials, modelling and economic analysis. Medium-level investment is evident for legumes, reduced tillage, CTF, biochar, and electric machinery, typically in the \$1–10 M range, reflecting mixed emphases on research, with some coordination and pathway activation through trials, equipment R&D and early-stage commercial pilots. The lowest investment occurs for emerging biological and genetic technologies—BNI crops, AMF inoculants, nitrogen-fixing crops—with Australian commitments generally \$0.1–5 M, far below global programs (> \$100 M for synthetic biology N-fixation). These focus heavily on foundational research with minimal commercial-scale mobilisation (SF3/DF2) due to low TRLs.

Across all technologies, investment estimates are uncertain. Published figures typically exclude private-sector contributions, costs of internal government programs, policy and strategy development, in-kind support, global R&D pipelines, supply-chain capital expenditure, farm systems group investments and more. Many programs also report aggregated funding that spans multiple technology classes, limiting disaggregation. This leaves considerable uncertainty about how much investment is targeted at which technologies, mechanisms and innovation functions. Despite these challenges, the above trend of focusing on R&D (SF1) in relatively mature technologies is clear.

Investment analysis based on data obtained from the Council of RDCs (see section 3.6) and ZNE-Ag CRC (from public website) suggests funding is weighted toward key focal areas. Many agricultural

technologies identified in this report are not covered, or their coverage was not identified through reading of project descriptions (Table 4.3.3). Our analysis points to high levels of investment in nitrogen management through precision and targeted application, and relatively high investment in controlled release products, nitrification inhibitors, legume integration and stubble retention.

Table 4.3.3. Indicative assessment of investment in different technologies as classified through project descriptions.
NB: Investments here are a limited subset of all investments focused on technologies; they may be related to technologies that span sectors and may not primarily be targeted to cropping. See Section 3.6. for details on data.
 “No data sourced” means there were no investment data in the dataset for this category.

Technology	Investment source	Investment identified	Classification
Slow/controlled-release nitrogen fertilisers	RDCs	\$2,123,500	\$1-5mill
Nitrification inhibitors	RDCs	\$2,012,500	\$1-5mill
Urease inhibitors	RDCs	\$2,012,500	\$1-5mill
Precision Nitrogen Applications	RDCs	\$23,051,449	\$20-\$30mill
Legume Integration	RDCs	\$2,750,000	\$1-5mill
Controlled Traffic Farming	RDCs	\$0	no data sourced
Stubble Retention	RDCs	\$4,200,000	\$1-5mill
Reduced Tillage	RDCs	\$0	no data sourced
Biochar Application	RDCs	\$0	no data sourced
Lime Application Management	RDCs	\$0	no data sourced
Cover/Catch Cropping	RDCs	\$0	no data sourced
Biostimulants / arbuscular mycorrhizal fungi (AMF) inoculation	RDCs	\$61,500	less than \$100K
Biological Nitrification Inhibition Crops	RDCs	\$270,000	\$100K-\$500K
Green Cane Harvesting	RDCs	\$0	no data sourced
Electric Farm Machinery	RDCs	\$0	no data sourced
Alternate Fuels	RDCs	\$0	no data sourced
Nitrogen-Fixing Crops	RDCs	\$0	no data sourced
Legume Integration	ZNE-Ag CRC	\$2,750,000	\$1-5mill
Precision Nitrogen Applications	ZNE-Ag CRC	\$1,800,000	\$1-5mill

Further analysis, summarised in Table 4.3.4, was based on classification of projects into archetypes (see Technology Assessment in this section) and classification of projects-aligned innovation functions (see Section 3.4.3) on the basis of project descriptions (up to 3 per project). Based on the

limited sample, this suggests that most RDC-funded projects were focused on knowledge generation (SF1), even for technologies that are classified as scaling ready or scaling constrained. The activation pathways function (DF1) was apparent across 5 projects, and learning and improvement (IF4) and coordination and synchronisation (IF3) across 3 and 2 projects, respectively. Other functions are minimally represented. This analysis could usefully be updated for more recent investment.

Table 4.3.4. Cropping technologies, associated archetypes, and functions aligned to funded activity. This table identifies the number of investments (i.e. projects) aligned with specific technologies and functions. For example, 12 projects have at least a partial focus on precision nitrogen applications and SF1 (Knowledge generation). NB: Projects could be classified as aligned with up to four technologies and up to 2 functions. Note: other technologies assessed in this report that are not listed here had no identifiable projects coded to them.

Technology	Archetype	SF1: Knowledge	SF2: Networks	SF3: Resources	IF1: Direction Setting	IF2: Legitimizing	IF3: Coordination	IF4: Learning	DF1: Activation	DF2: Diffusion
Biological nitrification inhibition crops	A2 - Research and Development	1	0	0	0	0	0	0	0	0
Precision nitrogen applications	Low abatement/High co-benefit	12	0	1	1	0	1	2	2	1
Slow/controlled-release nitrogen fertilisers	A5 - Scaling Constrained	2	0	0	0	0	0	0	1	0
Electric Farm Machinery	A5 - Scaling Constrained	0	0	0	0	0	0	1	0	0
Legume integration	A7 - Scaling Ready	1	0	0	0	0	0	0	0	0
Urease inhibitors	A7 - Scaling Ready	1	0	0	0	0	0	0	1	0
Nitrification inhibitors	A5 - Scaling Ready	1	0	0	0	0	0	0	1	0
Stubble retention	Low abatement/High co-benefit	1	0	0	0	0	1	0	0	0

Although these data are partial and limited, they clearly point to an emphasis on knowledge generation as the primary area of investment for RDCs. It is also possible that extension and participatory work within more technically described projects have led to mis-weighting of the functions being invested in. Also, the scope of this project did not enable us to survey wider investment in innovation functions across other public, private and third sector entities. However, in this limited analysis of investment and its targets, there is a strong focus on knowledge generation through R&D. This may be the case for some technologies, where scaling requires overcoming technical hurdles to reduce input costs, or making implementation more efficient and less risky through experimentation and testing. Across multiple projects, this emphasis diverges significantly from the enablers of scaling in transition settings predicted through international experience and theory (Section 3.4.3), which emphasise a greater need for investment in demand and intermediation functions as TRL and CRL increase.

4.3.6 Prioritisation analysis

Based on the assessments in previous sections, the summary prioritisation analysis provides a high-level perspective on which technologies are receiving differing levels of investment from

RDCs (high >\$10mill, medium \$5-\$10mill, or low <\$5mill), relative to their abatement potential. There is high uncertainty in estimates of abatement potential, and the low confidence intervals for assessing it in most of the technologies (see Section 4.3.2). Also, abatement potential is one outcome among many considered in making investment decisions. For example, classification of investment in precision nitrogen application as ‘over-investment’ (see Section 3.6 for method) reflects the high relative investment in this area targeted to improve farm profitability, with GHG intensity a secondary consideration. In general, technologies classified as ‘over-investment’ should have high co-benefits or be seriously reconsidered.

The tables below, respectively, assess the adequacy of investment to scale feasible abatement at an industry level (i.e. as abatement options for cropping industries, Table 4.3.5) and across all of agriculture (Table 4.3.6). They do so in very high-level terms and should be considered as the basis for opening up and informing discussions about decisions and direction-setting, rather than providing definitive actions, which are in the following section. For example, the high-potential options (nitrification inhibitors and nitrogen-fixing non-legume crops) have very different constraints and barriers. Current Australian capabilities, resourcing or strategic intent may not be aligned to addressing these barriers. In this case, maintaining a relatively low investment and a watching brief may be sufficient.

Most of the technologies assessed have low potential for abatement relative to all of agriculture. Table 4.3.6 suggests that nitrification inhibitors and the blue sky and high-risk potential of nitrogen-fixing non-legume crops have the highest abatement potential in cropping industries and across all of agriculture.

Table 4.3.5. Industry-level assessment of adequacy of current investment coverage for cropping, comparing level of investment against the whole of agriculture abatement potential (see Section 3.6 for method). Light Grey = Benign neglect; Dark Grey = overinvestment/ other investment goals?; Blue = Untapped potential; Pink = Well-supported; Purple = Missed opportunity.

	Low potential abatement	Medium potential abatement	High potential abatement
Low investment (or data not found)	Reduced Tillage Precision Nitrogen Applications Lime Application Management Catch Cropping Biochar Application Stubble Retention Green Cane Harvesting	Slow-/Controlled-release nitrogen fertilisers Urease inhibitors Controlled Traffic Farming Legume Integration Arbuscular Mycorrhizal Fungi Inoculation Electric Farm Machinery Alternate Fuels Biological Nitrification Inhibition Crops	Nitrification inhibitors Nitrogen-Fixing Non-legume Crops
Medium investment			
High investment	Precision Nitrogen Applications		

Table 4.3.6. Agricultural sector-level assessment of adequacy of current investment coverage (see Section 3.6 for method). Light Grey = Benign neglect; Dark Grey = overinvestment/ other investment goals?; Blue = Untapped potential; Pink = Well-supported; Purple = Missed opportunity.

	Low potential abatement	Medium potential abatement	High potential abatement
Low investment (or data not found)	Reduced Tillage Lime Application Management Green Cane Harvesting Biochar Application Stubble Retention Catch Cropping Arbuscular Mycorrhizal Fungi Inoculation Controlled Traffic Farming Alternate Fuels Biological Nitrification Inhibition Crops Urease inhibitors Legume Integration Electric Farm Machinery Slow-/Controlled-release nitrogen fertilisers	Nitrification inhibitors	Nitrogen-Fixing Crops
Medium investment			
High investment	Precision Nitrogen Applications		

4.3.7 Pathways for Cropping

Emissions reduction in cropping is fundamentally a systems-integration and incentives challenge, not a technology-availability challenge. Most technically mature options (precision nitrogen, inhibitors, controlled-release fertilisers, electrification of machinery) are already well understood, but have significant barriers to scaling, while the few high-impact options (e.g. biological nitrification inhibition and nitrogen-fixing crops) remain long-term as global R&D efforts.

The defining features of cropping abatement pathways are:

- Wide diversity of pathways defined by region, crop, soil, season and enterprise structures;
- Predominant emphasis on emissions intensity rather than absolute reduction, with risks of rebound through intensification;
- Low private ROI for many abatement-effective practices under current commodity pricing; and
- High dependence on MRV, advisory capacity, and demand-side activation to translate capability into uptake.

The sequencing logic prioritises building regional capability, evidence and MRV in Horizon 1 with early demand side interventions to create some demand in areas where opportunities exist, but is more focussed on readiness and optionality for growers, so that scaling-constrained technologies can be rationally supported in Horizon 2, and genuinely transformative technologies can be absorbed rapidly in Horizon 3.

- Horizon 1 (now–2030) focuses on regional grounding and learning to underpin value capture for growers: trialling and demonstration to prove up regionally relevant mixes of EEFs, precision N applications, stubble retention, reduced tillage, legume integration, and controlled traffic farming (CTF) for wetter soil conditions. These efforts should develop proportional MRV (see Section 5.5.1) that focuses on benchmarking emissions intensity, targeted measurement, and developing proxies and surrogates that are robust across seasonal variability, representative and easily interpretable for farmers. This will require early investment in N₂O flux measurement to develop credible emissions factors as a basis of MRV, and work to establish the sufficiency of these for different incentive mechanisms. Building advisory capacity and targeted demand signals (e.g. protected niches) will be needed, while continuing investment in emerging knowledge-embedded technologies (e.g. BNI), and validation and standard development and targeted science for knowledge-intensive technologies (e.g. biostimulants).
- Horizon 2 (2030–2035) sees MRV translation from regional benchmarking to interoperable MRV systems that operate effectively along supply chains, investment pathways and are supported by advisory systems. Deployment of mature but previously ROI-constrained technologies accelerates. This horizon focuses on governing and standardising proxy-based MRV through agreed proxy/surrogate definitions, referencing

groups and rule-setting, linking Tier-2 and Tier-3 insights and assessments. These developments enable wider adoption of technology stacks in regionally targeted ways, based on clear value propositions and ROI linked to value chains and finance incentives.

- Horizon 3 (post-2035) consolidates low-emissions cropping as business-as-usual and enables rapid uptake of breakthrough options (BNi, non-legume nitrogen-fixing crops) because the system already has absorptive capacity. MRV escalates to higher assurance reporting, with clearer rules for stacking and defining system boundaries. Higher resolution methods are developed and applied, where these create value for growers and along value chains.

In cropping, Horizon 1 is about learning and alignment, Horizon 2 is about selective scaling through valorisation, and Horizon 3 is about consolidation of low-emissions cropping systems. Across horizons, proportional MRV must deliberately balance bottom-up decision needs with top-down comparability requirements. In early phases, systems are designed bottom-up —prioritising interpretability, benchmarking and low burden—while remaining consistent with top-down frameworks. Participation of farmers and regional groups in Horizon 1 requires appropriate incentives and development of infrastructure and capability to return benefits in later phases. Similarly, attention to benefit-sharing from market regulation and incentives needs careful attention across phases to maintain participation and legitimacy (see Sections 5.3.4 and 5.6.3). Over time, governance, standardisation and method ladders should allow MRV used for benchmarking to be repurposed to create support supply-chain and finance incentives without re-instrumenting farms or increasing cost-burdens and friction.

Table 4.3.7. Key barriers (B), enablers (E), opportunities (O) and non-investment signals (N) for cropping, synthesised from previous sections, underpinning action areas

Item	Description
B1. Weak or variable private ROI	Many abatement-effective practices (e.g. enhanced-efficiency fertilisers, precision nitrogen management) are technically mature but deliver inconsistent or marginal private returns under current input costs and commodity prices, limiting voluntary uptake.
B2. Strong biophysical and system heterogeneity	Emissions outcomes and productivity impacts vary substantially by soil type, climate, crop choice and seasonal conditions, reducing confidence in generic recommendations or uniform incentive settings.
B3. MRV complexity and cost	High spatial and temporal variability in soil N ₂ O emissions makes accurate, scalable and low-cost MRV difficult, constraining access to incentives, credible claims and market mechanisms where these exist. N ₂ O flux measurement and analysis that can inform MRV is currently expensive.
B4. Weak demand-side signals	There are limited procurement, insetting or premium market signals that directly reward lower-emissions crop production, meaning adoption relies largely on private productivity benefits alone.
B5. Thin input and service markets	Domestic supply chains and advisory capacity for key inputs (e.g. inhibitors, emerging bio-inputs) remain limited, increasing costs and slowing adoption even where practices are technically viable.
E1. Strong regional advisory and trial networks	Existing farm systems groups, grower networks and extension services provide a solid platform for regionally tailored trialling, learning and adoption of emissions-reducing practices.

E2. High baseline efficiency	Australian cropping systems are already relatively emissions-efficient, enabling incremental improvements to deliver measurable emissions reductions if adoption barriers are addressed.
E3. Growing digital and data capability	Increasing uptake of precision agriculture, digital records and farm-level data systems provides a foundation for benchmarking, MRV integration and decision support.
O1. Protected market niches	Higher-value crops, differentiated supply chains and targeted domestic procurement offer opportunities to create early demand for low-emissions production and support learning-by-doing.
O2. International technology pipelines	Advances such as biological nitrification inhibition traits, self-fertilising crops and novel nitrogen technologies are progressing globally, offering future step-change potential if local absorptive capacity exists.
O3. Stacking and systems integration	Combining multiple management practices (e.g. EEFs, precision N, rotations) can deliver greater and more resilient abatement outcomes than single interventions deployed in isolation.
N1. Diminishing marginal gains from further intensification	Further intensification without system redesign may yield diminishing emissions returns and introduce rebound risks that erode net abatement outcomes at a national level.
N2. High uncertainty in some emerging inputs	Evidence for the abatement effectiveness of some bio-inputs and microbial products remains limited, suggesting a need for staged, evidence-led investment rather than premature scaling.

Action areas (Table 4.3.8) address constraints and preconditions for scale, then enable selective uptake, and later position the system to absorb breakthrough options, developed through ongoing Australian participation in international R&D efforts. The action areas below translate identified barriers, enablers, and opportunities (Table 4.3.7) into an investment pathway that aims to catalyse long-term impact. Some elements of the above table (e.g. B1, B5) are best addressed through cross-sector/systems-level interventions (detailed in Chapter 5).

Table 4.3.8. Pathways for investment defined by action areas and associated problems (with links to barriers and enablers from the previous table) for cropping. Note: The order and numbering do not indicate level of importance or priority, but simply to allow cross-reference of ‘aligned action areas’ with best action in Table 4.3.9.

Action Areas	Problem/Risk Addressed	Indicators of Success	Indicators of Failure	Prioritised Actions
1. Activate market signals to provide incentives to scale “scaling-constrained” technologies (NI, controlled/slow-release fertilisers)	Weak private ROI and uptake despite technical maturity (B1, B4), thin supplier markets (B5) and strong dependence on favourable niches (O1)	Premium/procurement or risk-reducing demand signals (e.g. procurement commitments, concessional finance) operating; uptake of NI/controlled-release/precision N rises; progress toward ~15% GHG-intensity reduction alongside 30–40% output growth where feasible.	No premium or crediting maintains a limited incentive structure; low adoption despite maturity; supply chains remain indifferent to emissions intensity.	H1: Investigate and develop targeted market incentives or protected niches where sets of mature technologies could scale or be further developed (e.g. in cotton, specialty grains, etc.), through specific instruments such as procurement, concessional finance, and standards (see Box 3.1). H2: Roll-out of broader procurement and insetting opportunities aligned to intensity outcomes. Transition from practice-based incentives towards outcome-based incentives linked to verified emissions performance. H3: Mainstream incentives integrated into supply chains.
2. Deploy regionally-adapted, proportional MRV to unlock incentives as practices/technologies are validated	High MRV cost and complexity (B3) interacting with strong biophysical heterogeneity (B2), despite growing digital capability (E3)	Region-appropriate MRV frameworks in place; trials + modelling inform region/season/farm- type guidance; schemes interoperable for domestic/export claims. These start to create farm-level revenue associated with the adoption of technologies.	MRV too expensive/complex; credibility disputes; low participation; inability to stack technologies in accounting.	H1: Define and invest in proportional regional MRV (GAF tools, ACCU Methods, etc) explicitly designed for benchmarking, targeting N ₂ O measures and robust proxies and surrogate methods informed by trials and modelling. This provides a foundation for farm systems, geographic comparability and stacking rules, enabling later market and finance integration. H2/3: MRV evolves with new on-farm and enabling technologies. Integrate MRV outputs into grain marketing, procurement and contracting systems as well as finance to reward verified low-emissions production.
3. Build/ extend regional trial/ demonstration networks to benchmark and /or manage context and stacking	High context dependence (B2) and need for credible stacking and interaction effects (O3), leveraging advisory networks (E1)	Multi-region trials running; clear “what works where/when” playbooks; advisors deliver lean 1–2 technology packages suited to local systems. Regional champions benefit from early adoption, on average.	Lower-than-expected abatement in practice; advisors revert to single measures; confusion about compatible combinations. Disadoption high.	H1: Examine the current network of demonstrators and assess options by enterprise type adequacy and representation of practices. Using benchmarking to establish consistency of metadata and data protocols, and connect through an accessible data ecosystem that supports learning, and advisory products. Develop locally credible playbooks, use of virtual farm systems, and build advisory capability to extend novel technologies and stacking methods, alongside MRV and market opportunities.

				H2/3: Networks scaled and connected nationally Platforms assimilate emerging technologies and facilitate rapid scaling (e.g. BNI, biostimulants).
4. Strengthen extension/advisory and producer capability for tailored adoptability	Fragmented delivery and advisory capacity (B5) despite strong regional networks (E1)	Active regional advisory networks; producer confidence in tailored packages; higher participation in trials; improved emissions-intensity outcomes in priority regions.	Low trial participation; technology “churn” without persistence; limited translation from trials to practice.	H1: National curricula and regional networks developed to respectively build capacity of future advisors around low-emissions cropping and build additional interest and capacity in the existing advisor network (see 5.6.4) H2/3: Abatement advice is made relevant to stacks or packages and integrated across agronomic, MRV, and markets / finance.
5. Coordinate RD&E pipeline for emerging knowledge-embedded technologies (BNI, nitrogen fixing (non-legume) crops) and standards/capability for biostimulants (AMF)	High uncertainty for novel options (N2) but significant future potential from global pipelines (O2)	International partnerships and long-horizon projects stood up; BNI traits advancing; credible practice standards for AMF; clear go/no-go milestones for nitrogen fixing crop development.	Fragmented R&D; weak standards → variable performance for AMF; missed international innovation waves.	H1: Develop medium to long-term programs and international partnerships around prospective technologies and agreed critical pathways / KPIs that help manage these H2/H3: Maintain and redirect R&D effort and partnerships through watching brief capability build to evaluate changing opportunity-space. Translation through commercialisation and scaling as possible.
6. Secure inputs and absorptive capacity (domestic supply + international linkages)	Supply bottlenecks and cost pressures (B5) limiting adoption of mature and emerging options (EEFs generally)	Domestic manufacturing of EEFs/assured supply pathways for key inputs; active technology-scouting and rapid integration into local systems.	Input shortages; price spikes; late or poor adoption of globally advancing tools.	H1: Coordinated investment/ intervention in demand-side measures and Australian input production facilities (e.g. through concessional finance) where appropriate; catalyse economies of scale and readiness to support domestic supply chain for EEFs in specific geographical/agroecological zones. H2/3: Extend production and distribution networks of inputs to create sovereign capability to produce green and low-emissions fertilisers. Advisory and trialling/development networks are scaled and connected nationally (see Section 5.6.2) and able to absorb emerging technologies (BNI, N-fixation) and inputs.

7. Anticipate cross-sector shifts (AI/MRV data, energy, biofuels, low-emission machinery)	Exposure to external system shifts (energy, fertiliser, data) interacting with existing enablers (E3, O3)	Farm-level emissions estimation becomes routine via digital tools; declining N costs with green urea; new rotations/value chains aligned with low-carbon fuels.	Policy/market mis-alignment; stranded investments; missed opportunities from infrastructure and energy transitions.	H1: Cropping, and especially grains industry, takes key leadership role in energy-agriculture nexus, to support orderly shifts that benefit cropping industries (see Section 5.6.2) . H2/3: Broader procurement and insetting aligned to intensity outcomes, and ultimately become integrated into supply chains.
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Best-bet actions for cropping, mapped to aligned action areas, are identified and detailed in Table 4.3.9. These actions are considered to be the sub-sectoral investment priorities to strategically advance the sub-sector's contribution to a low-emissions future, and combine a variety of mechanisms and functions beyond R&D to build a foundation for speeding up low-emissions transitions for cropping post-2030, and ensuring accountability and MRV are integral to investment, market access and social licence. Substantial advantage across many actions could come from cross-commodity collaboration (e.g. GRDC, CRDC, Sugar Australia) along with coordination across state and federal investment.

Table 4.3.9. Best-bet actions for cropping, aligned to action areas in the above table. Note: The order of the best-bet actions in this table does not indicate their level of importance or priority. A low priority does not indicate that an action is not worth pursuing, just that it has low leverage for emissions reduction.

Best-bet action	Linked pathways	Why this matters	What it involves in practice	Priority
Regionally validate and selectively scale underutilised technologies such as enhanced-efficiency fertilisers, precision technologies and machinery efficiency, through regional trials, capability building and targeted incentives. Build supply chains that are robust in the face of market volatility.	1, 3, 5	These inputs can deliver near-term abatement where agronomic, economic and emissions outcomes have been demonstrated but are constrained by weak private ROI, partially driven by high import costs.	The use of different products under the banner of enhanced efficiency fertilisers (EEFs) presents a near-term opportunity to reduce emissions intensity, which can best be advanced through a combination of incentives (e.g. new ACCU methods for effective EEF applications, concessional loans on precision equipment, and other incentives), regionally relevant advice and underpinning advisory capability, linked to regional trials and demonstrations. This recommendation aligns with other proposals (Cowie et al., 2025) to coordinate such action via a national strategy for EEFs. This should include the use of EEFs with wider sets of inputs and equipment and be linked to the MRV and benchmarking activity above.	Priority: High, varied. This action can be regionally targeted to systems where the scale of benefits and potential to move rapidly from demonstration to scaling via adoption is high. Incentives can be used early and strategically in these areas to scale demand and underpin efficient domestic production.
Deploy regionally adapted, proportional MRV and benchmarking based on credible measures and proxies, and linked to incentives	2, 3, 7	MRV is the foundational infrastructure for incentives, markets and credible claims, but also provides a foundation for learning, design of proxies and surrogates, and mechanisms for adoption and scaling. As such, it is	Implement proportional regional MRV linked to real farm systems and decision contexts. Build off LEIFS, work on improved emissions factors, and other commodity-focused investments to develop regionally-targeted MRV systems, rules and incentives that reduce participation barriers and provide market-ready measures that can support adoption and be regularly and easily upgraded. MRV can relate to input or	Priority: Very high. Continued and systematic work to build the foundational MRV and incentive mechanism is critical to participation, valorisation, adoption and scaling. The regional focus is integral to capturing the heterogeneity of systems and

		a likely early investment priority, alongside incentives that transition from pilots to practice, to performance measures over time.	output/outcome measures but will ideally be very low or zero cost. While regional applications will be necessary for validity and credibility, a networked approach should be designed to ensure innovation, learning, standard setting and accountability across regions and within market and other incentive systems. Developing, piloting and scaling wider demand-side mechanisms will be critical to scaling (see Section 5.6.3). This program of work could commence with regions that have demonstrable abatement potential in cropping industries and regional capacity to support goals, and extend from these.	differing GHG and co-benefits of stacking technologies and practices in season, systems, and regionally appropriate ways. This will include improvement in measurement and measurement technologies, alongside development, trialling, alignment and demonstration of technology stacks.
Expand regional demonstration and learning networks	3, 5	Cropping outcomes are highly context-specific and regional learning and capability development will be integral to the development of feasible and scalable options in regions.	Support region-specific trials and peer-learning networks that build advisory and farmer capacity to evaluate, trial and adopt relevant and effective technologies and technology stacks, including soil management. Existing groups (e.g. Farm Systems Groups, Drought Hubs and NRM Organisations) provide the foundation for extending regional capability, linking research, policy and practice and ensuring technologies can fit regional needs. There is growing promise to use virtual tools and <i>in silico</i> sandboxing to trial options and ensure early learning is low-cost and effective. Calculators and advice will often need to be calibrated to regional conditions. While regional networks should primarily build farmer and advisory system capacity relevant to a region, networks among regions should be an investment priority to ensure cross-regional learning and to test and refine policy options.	Priority: High. There is potential to target specific early-scaling regions where abatement opportunities and existing capacity align, and to build from other initiatives (CFOP, Drought Hubs, Farm Systems Group projects) , especially through cross-commodity grant programs with regional focus and linked capacity building and demonstration objectives. This is a two-way capability build that links to advisory capability (below).
Strengthen advisory capability	5, 6	Adoption stalls without advisory systems that underpin wider agricultural capacity, but understand which options are at what stage of maturity, relevance, and efficacy for specific farms.	For cropping, regional advisory capacity could be strengthened through ongoing learning and continuous improvement, ranging from learning from regional trials and demonstrations (see above) to micro-credentialing and short courses through tertiary institutions. Generally, the capacity to support low-emissions agriculture in the cropping industries requires a shift from advisory networks that focus on agronomic and/or financial advice to integrative approaches that include management of emissions intensity and associated cost risks and benefits as a normal part of farm businesses. This action applies across sectors and is detailed in section 5.6.4.	Priority: Medium. Advice networks, especially independent agronomists and advisors, have a critical role in mediating the pace and participation in low-emissions agriculture and will be key actors and partners in ensuring the infrastructure and technologies that underpin transitions are fit-for-purpose, especially at local and regional scales. This is a two-way capability build that links to regional demonstrations (above).
Collaborate internationally and build readiness for breakthrough nitrogen innovations	4, 6	Global advances could shift the abatement frontier	Invest in international R&D partnerships, absorptive capacity, and testing of novel approaches in appropriate settings/systems, particularly around BNI and nitrogen-fixing non-legume crops. Maintaining and attracting talent in areas of	Priority: Medium. Maintaining and building scientific expertise and networks will be integral to ensuring Australian agriculture remains among

			opportunity and building the capacity to develop and extend commercially viable germplasm suited to Australian farming systems will require early patient capital for high-risk/return research investment that the Australian agricultural RD&E system is not geared to support consistently over the required timeframes (e.g. 5-15 years)	global leaders in low-emissions agriculture. Participation (and in some instances leadership) in global programs will ensure access to scalable and feasible technologies as they emerge.
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4.4 Horticulture

4.4.1 Sub-sector summary

The horticulture sector as covered in this report is extremely diverse, spanning fruit, viticulture, vegetables, nuts, flowers, turf and nursery products across open-field, irrigated, protected cropping and controlled-environment systems. This diversity drives large variation in emissions sources, emissions intensity, and abatement pathways across regions and enterprise types. Heterogeneity creates uncertainty in sector-wide generalisations. Also, as horticulture growers often span supply chains, they often manage emissions beyond the farm gate.

Partly because of the diversity and complexity of operations, there is insufficient national data to provide a robust assessment of horticulture scope 1 GHG emissions, and existing estimates are best treated as indicative. In the Sub-sector Technology Assessment for horticulture (Appendix C.4), combined scope 1 emissions are estimated to be ~1–2% of related agricultural emissions, indicatively at 0.8–1.6 Mt CO₂-e per annum, based on figures from the 2024 National Greenhouse Gas Inventory Report (Australian Government, 2024). Despite uncertainty in sector totals, there is higher confidence in the major on-farm emissions sources that shape mitigation options. For preliminary estimates in this report, pools of emissions for potential and feasible abatement through technological change are included in Table 4.4.1.

Table 4.4.1. Scope 1 horticulture emissions pools used in technology assessment for this report (see Appendix C.4).

Emissions pool (horticulture scope 1)	% of horticulture scope 1 emissions (range)	Et used in feasible abatement assessments (Mt CO₂-e/yr)
Diesel combustion (fuel use in farming operations: vehicles, pumps, machinery) – CO ₂	26.3% (DPIRD, 2024)	0.21–0.42
Nitrous oxide (N ₂ O) – overall horticulture scope 1 N ₂ O component	36.8% (DPIRD, 2024)	0.29–0.59
Nitrous oxide (N ₂ O) – residual after precision nitrogen application (used for precision irrigation calculation)	Derived from N ₂ O pool after factoring reduction from precision N	0.28–0.54
Fertiliser-derived N ₂ O (inorganic/mineral fertilisers) – horticulture proxy based on fertiliser N-use share	Assumes horticulture uses ~3% of national fertiliser N (implies ~4.6–9.3% of 0.8–1.6 Mt)	0.074

Emissions intensity and mitigation potential differ materially between production systems. Deciduous orchards and vineyards generally have low N₂O emissions, associated with lower nitrogen inputs, cooler temperate conditions, and often efficient drip irrigation (Swarts et al.,

2016). Conversely, intensive vegetable production can be among the most emissions-intensive farming systems across cropping and horticulture due to frequent cultivation and relatively high inputs of nitrogen and water (Tongwane et al., 2016). Emissions intensities in per kilo of product, and in relation to human nutrition, are low across horticulture (Jarmul et al., 2020). Even within vegetables, there is wide variability in emissions among crops. Within horticulture, viticulture is estimated to contribute ~0.1 Mt CO₂-e per annum scope 1 emissions, with most emissions from fuel combustion and irrigation pumping and relatively low N₂O compared with irrigated annual systems.

Although a comprehensive time series of horticulture-specific scope 1 emissions is not available, plausible trends can be inferred from sector structure and technology uptake. Energy efficiency improvements, electrification of pumping in some regions, and digitisation in larger enterprises are likely to reduce emissions intensity, while absolute emissions could rise if sector output continues to increase and if expansion occurs in input-intensive production systems. The absence of a longitudinal dataset is a key constraint on confidence in trends and projections.

From a transition and scaling perspective, horticulture is characterised by: (i) high heterogeneity in enterprise size and capability, (ii) labour constraints shaping technology choices, and (iii) strong dependence on reliable irrigation energy and logistics in many production regions. These factors condition the “systems of use” and create distinct bottlenecks and barriers for technology diffusion and reconfiguration across the sector.

4.4.2 Technology assessment

The assessed portfolio is dominated by technologies that are mature in technical terms (high TRL), but for which diffusion is constrained by economics, fit with enterprise systems, or enabling infrastructure, consistent with late-emergence/diffusion phase bottlenecks. Notably, other technologies may be available in sub-sectors of horticulture that are not considered here. For example, some horticultural businesses rely extensively on refrigerated storage, from which fugitive refrigerant emissions can represent a material component of Scope 1 emissions. For some businesses, these may be comparable to or exceed other operational emissions sources. Stakeholders also noted that opportunities may exist to further reduce emissions through optimisation of nitrogen forms, fertiliser formulation and fertigation practices. Further assessment of these effects was beyond the scope of the current analysis.

Table 4.4.2. Summary of scope 1 abatement technology assessment for horticulture, including key elements from Sector Technology assessment.

Technology Name	Archetype	Current Investment	Industry Abatement Potential	Agriculture Sector Abatement Potential	Confidence	Key Issues
Electrification of Farm Machinery	A4 - Development trialling	LOW	MEDIUM	LOW	MEDIUM	High capex and ROI uncertainty; grid capacity and upgrade costs; limited equipment availability,

						servicing and charging infrastructure
Precision Agriculture	A5 - Scaling Constrained	LOW	MEDIUM	LOW	LOW	Upfront costs and skills requirements; connectivity and service gaps; complex integration with mixed equipment and enterprise systems
Nitrification inhibitors	A5 - Scaling Constrained	LOW	LOW	LOW	MEDIUM	Variable efficacy by soil, climate and crop; price premium; management complexity and postharvest N ₂ O and NH ₃ trade-offs
Controlled and slow-release fertilisers	A7 - Scaling Ready	NO DATA SOURCED	LOW	LOW	LOW	Cost premiums and uncertain ROI; limited suitability in fertigation systems; uneven supply chains and advisory support
Urease inhibitors	A6 - Scaling Limited	LOW	LOW	LOW	LOW	Context-specific benefits; limited domain where surface urea is used; weak horticulture-specific evidence and ROI signals
Cover Cropping (Non-legume Covers)	A7 - Scaling Ready	NO DATA SOURCED	LOW	LOW	LOW	Opportunity costs of land, water and labour; timing conflicts in short rotations; pest, disease and event-driven N ₂ O risks
Soil Microbial Inoculants	A5 - Scaling Constrained	NO DATA SOURCED	LOW	LOW	LOW	Highly variable field performance; suppression under high P and fungicide regimes; product quality assurance and ROI uncertainty
Biological Nitrification Inhibition Crops	A2 - Research and Development	LOW	LOW	LOW	LOW	No commercial horticulture cultivars; long breeding timelines; uncertain efficacy and lack of MRV or inventory methods

Interpreting the summary table reveals three broad patterns:

1. Electrification/alternative fuels encompasses a diverse set of technologies, but largely these are in development/trialling (A4). While some components are mature (e.g. pump electrification), enterprise-wide electrification and especially heavy-duty applications, that could significantly reduce emissions, face constraints linked to capital costs, grid capacity, servicing capability, and supply-chain maturity. Electrification and associated automation and roboticization have significant win-win potential for many horticultural enterprises in that they reduce costs and risks of labour, fuel, and create co-benefits associated with improved data integration and resilience in the face of shocks and policy change.

2. Several technologies sit in the “scaling constrained” class (A5)—notably precision agriculture, nitrification inhibitors, and soil microbial inoculants—signalling that barriers are less about “whether the technology works” and more about ROI, operational integration, and demand-side pull. This pattern mirrors the Methods’ expectation that as TRL/CRL rise, the innovation system needs to shift toward intermediating and demand-side functions rather than continued emphasis on knowledge generation alone.
3. Scaling-ready technologies (A7) in the portfolio (e.g., cover cropping (non-legume covers) and controlled/slow-release fertilisers), generally exhibit low potential abatement and low confidence for some entries. While these options may be increasingly adopted, they are unlikely to make major inroads into sub-sectoral emissions.

Horticulture’s abatement opportunities are shaped strongly by (i) nitrogen management in high-input annual systems, and (ii) energy transitions for pumping and on-farm operations, with supporting roles for platform technologies (precision agriculture) that enable stacking and performance optimisation.

4.4.3 Portfolio analysis

Because horticulture technologies cluster in development, trialling, scaling limited, scaling constrained, scaling ready (A4–A7) archetypes (Table 4.4.2), the primary enabling challenge is not invention but scaling through diffusion and system integration. That is, technologies generally require improved relative advantage, reduced adoption risk, strengthened legitimacy, and building demand and/or coordination capacity. Across the horticulture portfolio, three enabling themes stand out:

1) Overcoming scaling constraints (A5) through ROI improvement and demand activation

The scaling constrained technologies (e.g. precision agriculture, nitrification inhibitors, soil microbial inoculants) suggest potential value in market creation, risk reduction, and targeted incentives. In horticulture, these constraints often manifest as:

- high up-front capital or operating costs;
- fragmented adoption populations (many smaller producers);
- uncertainty about performance in specific crop/region contexts; and
- limited ability to capture value from emissions reductions without credible claims pathways.

As horticultural products are of high value and for domestic markets, there may be relatively greater opportunity for differentiated supply chains, procurement programs, branding initiatives and premium market segments within horticulture to recognise and reward verified emissions performance, compared with many bulk commodity sectors. However, it needs to be recognised that almost all horticulture businesses are price takers and are unlikely to be able to achieve premiums without targeted market interventions. Targeted rebates and concessional finance for high-upfront costs of electrification and precision upgrades may be warranted where underpinned by credible MRV/claims to emissions reduction.

2) Proportional MRV and data infrastructure to enable stacking and credible claims

The high variability across crops and farm systems and the lack of robust sector-wide emissions data are constraints on both confidence and scaling. For horticulture, this implies prioritising MRV approaches that:

1. Capture major controllable drivers (nitrogen inputs, irrigation energy, fuel);
2. Enable comparison of practices and technology “stacks” (e.g., precision irrigation + inhibitors + N rate optimisation); and
3. Reduce transaction costs for participation (especially for smaller enterprises).

3) Regional embedding, cross-sector capability and “systems-of-use” integration

Because adoption is shaped by labour constraints, enterprise fragmentation and trusted local networks, scaling strategies should prioritise service delivery models, regionally credible demonstrations, and low-burden MRV that reduces transaction costs for smaller enterprises.

Emission-reducing technologies for horticulture will often be evaluated as bundled packages, and in terms of their fit with complex enterprise contexts. Adoption will rely on trusted local advisory networks and service capability. This is particularly relevant where technology performance depends on place-based factors (e.g. soil moisture regimes, fertigation infrastructure, contractor arrangements and capability to service complex equipment, grid capacity). For emerging electrification and automation equipment, enabling pathways include coordinated demonstration programs, aggregator models for grid upgrades, and regional investment in service and maintenance capability. For nitrogen-related options, pathways include practical decision-support tools, regionally validated guidance on N rate reductions without yield penalties, and simple stacking rules for avoiding pollution swapping (e.g. managing NH₃ vs N₂O trade-offs).

Based on the summary table, the portfolio includes a small early-stage ‘watch and shape’ set (A2), alongside a larger scaling limited and constrained (A4–A5) middle, where intermediating and demand-side functions (direction-setting, legitimating, coordination, learning and pathway activation) are critical for adoption. A7 options are largely practice-based and can scale where they fit, provided regional advisory support and operational integration are strong.

This distribution implies:

- A small but important early-stage “watch and shape” set (A2) where maintaining absorptive capacity and strategic linkage to global programs and developments in larger cropping sector will matter more than domestic and sectoral investment in the near-term;
- A meaningful A4–A5 middle where intermediating and demand-side functions (direction-setting, legitimating, coordination, learning, pathway activation) become critical to translate technical readiness into uptake; and
- A7 options that are largely practice-based and can potentially scale where they fit, provided regional advisory support and operational integration is strong.

A notable portfolio feature is that technologies with plausible enterprise-level productivity or risk-management co-benefits (e.g. precision irrigation and precision operations; electrification with VSD pumping; some nitrogen efficiency tools) can scale faster than “pure abatement” options, but only if costs, service support, and credible claims pathways align.

4.4.4 System interactions: risks and opportunities

Technological and infrastructure interactions:

Horticulture is highly exposed to energy-system change due to the importance of irrigation, pumping, cold-chain and processing interfaces. Electrification pathways depend on grid capacity, connection costs, regional reliability, and the economics of on-farm solar and storage. As these factors improve, emissions accounting becomes simpler for enterprises that remove scope 1 diesel combustion from operations, and electrification can enable automation and digitised operations. In many regions, the limiting constraint is not the technology itself but the capacity of local distribution networks and the cost and timing of upgrades. Aggregator or precinct approaches (e.g. coordinated upgrades for irrigation districts, shared connection works, and regional service hubs) can reduce these barriers and improve the investability of electrification bundles.

Cross-system and cross-sector interactions:

The feasibility of electrification and alternative fuels for horticulture applications depends on wider transport and industrial decarbonisation dynamics, including feedstock competition and energy distribution infrastructure. Horticulture may benefit from spillovers from freight/mining electrification and hydrogen infrastructure development but may also face rising costs if low-carbon fuels remain scarce and premium-priced. There is potential for supporting appropriately scaled experimentation, demonstration and innovation in electrification and automation in horticultural industries that create spill-in benefits for broadacre cropping. This is already a clear focus on the sector and likely to continue across the horizons in this report. This is already occurring in parts of the sector through mechanisation, digital monitoring and energy-saving upgrades that improve labour efficiency and operational resilience while also reducing emissions intensity.

Socio-cultural interactions:

The scaling of low-emissions technologies in horticulture and viticulture is shaped as much by socio-cultural conditions as by technical readiness or cost. Enterprise diversity, labour markets, regional identity and trust networks influence which options are perceived as viable, legitimate and worth the effort of adoption, and help explain why many technically mature options remain diffusion constrained.

A defining feature of horticulture is its dependence on labour-intensive production systems and seasonal workforces. In practice, labour availability and skills constraints strongly shape the 'systems of use' into which technologies must fit. As a result, electrification, automation and digitally enabled monitoring often gain traction primarily for productivity and risk-management benefits (e.g. labour saving, reliability and operational resilience), with emissions reduction a secondary benefit. Technologies that increase management burden without clear labour or cost advantages are more likely to face resistance.

Enterprise structure reinforces these dynamics. Horticulture includes many small and mid-scale businesses across diverse crops and production systems, which raises transaction costs and reduces capacity to absorb integration complexity. For smaller enterprises, adoption of precision tools, nitrogen decision support and MRV is more likely when packaged as simple starter bundles, delivered through contractors or service providers, and supported by audit-lite data capture rather than bespoke optimisation.

Regional identity and place-based norms also matter. Technologies are judged against ‘what works here’, shaped by local irrigation infrastructure, contractor ecosystems, service availability and grid capacity. Regionally credible demonstrations and peer-to-peer learning play an outsized role in building legitimacy and reducing perceived risk, particularly where performance depends on soil–water regimes and operational timing.

Viticulture adds an additional layer of regional identity linked to brand, tourism and reputation, which can create demand-side pull for credible sustainability practice in premium regions. Conversely, regions experiencing sustained margin pressure and market volatility may exhibit heightened risk aversion, making cost-reducing measures and de-risking finance more influential than aspirational sustainability narratives.

Finally, trust and legitimacy are central to diffusion. Growers rely on locally validated evidence and adviser credibility, and negative experiences with variable-performance products can spread quickly through local networks. Scaling strategies should therefore prioritise transparent evidence, regionally embedded trials, and proportional MRV that supports credible claims without shifting excessive compliance burden onto producers.

Cross-sectoral transformation effects:

Changes in labour availability, automation, and digital infrastructure may be as influential for horticulture emissions as direct mitigation technologies. As horticulture often operates under labour constraints and high product value, productivity-enhancing technology bundles can become key “transition carriers” that also reduce emissions intensity.

4.4.5 Investment assessment

Investment signals from the investment sample indicate horticulture-related funding is concentrated on electrification and precision agriculture, with additional spill-in from cross-sector nitrogen investments. Identified horticulture-tagged investment totals include electrification of farm machinery and alternative fuels (~\$3.22m), precision agriculture (~\$0.59m), nitrification inhibitors (~\$2.01m) and urease inhibitors (~\$2.01m). Biological nitrification inhibition crops attract small early-stage investment (~\$0.27m), while controlled/slow-release fertilisers, cover cropping and soil microbial inoculants show nil/undetected investment in the extracted dataset. Overall, the pattern suggests funding is weighted toward knowledge generation and technical validation, with comparatively limited explicit investment in coordination, learning and diffusion functions needed to translate technical readiness into uptake.

Table 4.4.3. Indicative RDC investment in different technologies as classified through project descriptions. NB: investments may be related to technologies that span sectors and may not primarily be targeted to horticulture. Investments here are a limited subset of all investments focused on technologies; they may be related to technologies that span sectors and may not primarily be targeted to cropping. See Section 3.6. for details on data. “No data sourced” means there were no investment data in the dataset for this category.

Technology	Investment source	Investment identified	Classification
Electrification of Farm Machinery (and Alternative Fuels)	RDCs	\$3,220,000	\$1-\$5m
Precision Agriculture	RDCs	\$589,389	\$500K-\$1m

Nitrification Inhibitors	RDCs	\$2,012,500	\$1-\$5m
Controlled and Slow-release Fertilisers	RDCs	\$0	no data sourced
Urease Inhibitors	RDCs	\$2,012,500	\$1-\$5m
Cover Cropping (Non-Legume Covers)	RDCs	\$0	no data sourced
Soil Microbial Inoculants	RDCs	\$0	no data sourced
Biological Nitrification Inhibition Crops	RDCs	\$270,000	\$100K-\$500K

The innovation system function alignment table (Table 4.4.4) suggests that the documented activity is heavily weighted toward SF1 (knowledge generation) across multiple technologies, with limited evidence of systematic investment in coordination (IF3), learning and improvement (IF4), or demand-side diffusion functions (DF1/DF2), except for a small number of pathway activation counts for nitrification inhibitors and urease inhibitors.

Table 4.4.4. Horticulture-associated technology archetypes and innovation system functions aligned to funded activity. This table identifies the number of investments (i.e. projects) aligned with specific technologies and functions. For example, two projects had at least a partial focus on slow/controlled release fertilisers and SF1 (Knowledge generation). NB: Projects could be classified as aligned with up to four technologies, and up to 2 functions.

Technology	Archetype	SF1: Knowledge	SF2: Networks	SF3: Resources	IF1: Direction Setting	IF2: Legitimizing	IF3: Coordination	IF4: Learning	DF1: Activation	DF2: Diffusion
Electrification of Farm Machinery (and Alternative Fuels)	A4 - Development trialling	1	0	0	0	2	0	0	0	0
Precision agriculture	A5 - Scaling Constrained	0	0	0	0	1	0	0	0	0
Nitrification inhibitors	A5 - Scaling Constrained	1	0	0	0	0	0	0	1	0
Slow/controlled-release nitrogen fertilisers	A7 - Scaling Ready	2	0	0	0	0	0	0	1	0
Urease inhibitors	A6 - Scaling Limited	1	0	0	0	0	0	0	1	0
Biological nitrification inhibition crops	A2 - Research and Development	1	0	0	0	0	0	0	0	0
Cover Cropping (Non-legume Covers)	A7 - Scaling Ready	0	0	0	0	0	0	0	0	0
Soil Microbial Inoculants	A5 - Scaling Constrained	0	0	0	0	0	0	0	0	0

While the RDC data and investment analysis are very limited, the pattern raises questions about the realism of scaling pathways for electrification, automation and precision. Pathways will likely

rely on cross-sector coordination and targeted work to build out regional demonstrators and learn across them. For instance, demonstrating the capacity to utilise long-duty electric vehicles for specific industry applications and generate returns on these as grid-connected batteries while not in service, will also require grid configurations and feed-in tariffs, financing options, and other institutional design features that complement the technical alignments of technologies to farm needs.

4.4.6 Prioritisation analysis

As a relatively small and low-emissions sector, horticultural emissions reduction has consistently low-rated RDC investment across the technology portfolio, with only two technology classes (Electrification and Precision Agriculture) rated as able to feasibly advance medium abatement at an industry level (Table 4.4.5).

Table 4.4.5. Industry-level assessment of adequacy of current investment coverage, comparing level of investment against industry abatement potential (see Section 3.6 for method). Light Grey = Benign neglect; Dark Grey = Possible over investment; Blue = Untapped potential; Pink = Well-supported; Purple = Missed opportunity.

	Low potential abatement	Medium potential abatement	High potential abatement
Low investment (or data not found)	Nitrification inhibitors Controlled and slow release fertilisers Urease inhibitors Cover Cropping (Non-legume Covers) Soil Microbial Inoculants Biological Nitrification Inhibition Crops	Electrification of Farm Machinery (and Alternative Fuels) Precision Agriculture	
Medium investment			
High investment			

Interpreting these prioritisation results requires caution, given horticulture's sector-wide abatement potential is limited by its modest scope 1 share and by the diversity of production systems. However, the matrix still provides useful directional insight: near-term abatement in horticulture is likely to be driven by a combination of energy transitions in irrigation pumping and on-farm vehicles, and precision-enabled nitrogen and water management, supported by improved MRV and claims pathways. A second caution relates to technologies whose primary value is to increase efficiency and productivity (e.g. precision agriculture): their role can be underrepresented if prioritisation is based solely on direct abatement estimates rather than system-level enabling potential.

4.4.7 Pathways for Horticulture

Horticulture emissions reduction is best understood as a diffusion and system-integration challenge, rather than an invention challenge. The priority technologies identified in the sector assessment—electrification of irrigation and on-farm operations, precision water and nutrient management, nitrification inhibitors—are largely technically mature or near-mature. Yet uptake remains constrained by economics, fit with diverse enterprise systems, service and infrastructure capability, fragmented adoption populations, and weak or uneven demand signals.

Accordingly, the pathways for horticulture identified in Table 4.4.7 emphasise sequencing of enablement and address the synthesised barriers and challenges in Table 4.4.6. The overarching logic is to focus first on actions that reduce adoption risk, transaction costs and complexity, and that deliver clear productivity or resilience co-benefits, thereby creating the conditions under which more complex or lower-ROI options can scale in later horizons:

- **Horizon 1 (now–2030)** focuses on unlocking adoption. The emphasis is on scaling low-risk, “win-win” actions where private returns are already plausible—particularly electrification and automation of irrigation pumping (including VSDs), energy-efficient packhouse operations, and precision fertigation—while simultaneously building the foundations required for broader diffusion. These foundations include credible, but low-burden MRV focused on major controllable drivers (nitrogen, irrigation energy, fuel), regionally embedded advisory and service capability, coordinated demonstration of “what works where”, grid and servicing readiness for electrification, and practical decision rules for nitrogen and irrigation management. Horizon 1 investments are designed to reduce risk and effort for enterprises, especially smaller producers, and to translate technical readiness into investable practice.
- **Horizon 2 (2030–2035)** builds on these foundations to scale integrated systems. This period sees wider uptake of bundled technology stacks (e.g. precision irrigation combined with nitrogen optimisation and electrification), expansion of demand-side pull-through, procurement, branding or insetting arrangements in suitable supply chains, and extension of MRV and advisory networks to support stacking and credible claims at scale. Coordination and service delivery models become increasingly important, enabling aggregation of participation across heterogeneous enterprises and regions and reducing per-unit transaction costs.
- **Horizon 3 (post-2035)** consolidates low-emissions horticulture as business-as-usual. In this horizon, electrification and automation are mainstreamed where appropriate, MRV is embedded as routine sector infrastructure, and emerging options—such as next-generation biological products or biological nitrification inhibition cultivars—can be incorporated as evidence and assurance mature. Crucially, Horizon 3 uptake is enabled by the institutional, advisory, infrastructure, and assurance arrangements established in earlier horizons, rather than by continued reliance on stand-alone incentives.

Across all horizons, technology performance and adoption in horticulture are shaped by place-based conditions, labour constraints, and enterprise diversity. Without sensible sequencing, later-horizon options remain technically feasible but economically and institutionally stalled, whereas with it, horticulture can contribute proportionately and credibly to a low-emissions

agricultural transition. Accordingly, current best-bet actions that (Table 4.4.8) prioritise enabling infrastructure, advisory capacity, proportional MRV and demand activation alongside targeted technology uptake.

Table 4.4.6. Key barriers (B), enablers (E), opportunities (O) and non-investment signals (N) for horticulture, synthesised from previous sections, underpinning action areas

Item	Description
B1. Enterprise heterogeneity and fragmentation	Wide variation in crops, systems, regions and enterprise size limits the effectiveness of one-size-fits-all mitigation approaches and raises transaction costs for adoption and coordination.
B2. Upfront cost and ROI uncertainty for electrification and precision systems	Electrification, automation and precision technologies are technically mature, but adoption is constrained by capital costs, grid connection uncertainty, servicing capability and unclear payback, particularly for smaller enterprises.
B3. MRV cost, complexity and weak baseline data	Lack of robust emissions data and high variability across systems make MRV expensive and uncertain; without proportional MRV, incentives, stacking and claims pathways cannot operate at scale.
B4. Labour constraints shaping systems of use	Labour availability and skills shortages strongly influence technology choices, favouring low-risk productivity bundles over mitigation options that add management burden.
B5. Variable efficacy and legitimacy risks for nitrogen and biological options	Performance of nitrification inhibitors and biologicals varies by soil, climate and management; inconsistent outcomes and weak QA risk reputational damage and adoption retreat.
E1. Win-win productivity and resilience benefits	Electrification, VSD pumping, automation and precision water/nutrient management deliver labour savings, energy efficiency and operational resilience alongside emissions reduction.
E2. Presence of scaling-ready nitrogen and practice-based options	Precision N management, some fertiliser technologies and non-legume cover crops are technically ready and can scale where they fit, given advisory support and operational integration.
E3. Existing spill-ins from cropping and nitrogen programs	Cross-sector investment in nitrogen efficiency, precision irrigation and digital tools creates spill-in opportunities that horticulture can leverage.
O1. Proportional MRV as shared enabling infrastructure	Proportional MRV focused on major drivers (N, irrigation energy, fuel) to unlock incentives, stacking and claims while reducing SME transaction costs.
O2. Regionally embedded demonstration and service models	Place-based demonstrations, trusted advisers and contractor-led service delivery can translate technical readiness into sustained uptake across diverse systems.
O3. Demand-side pull through branding, procurement and domestic markets	High-value horticultural products and domestic supply chains offer scope to activate demand-side signals where credible MRV and claims pathways exist.
O4. System-level productivity transitions as “transition carriers”	Automation, digitisation and electrification driven by labour and resilience pressures can simultaneously reduce emissions intensity, even where abatement is not the primary motivation.
N1. Premature expectations for mitigation without ROI or service readiness	Pushing uptake without addressing cost, service capability and grid readiness risks stalled pilots, fragmented adoption and loss of confidence.
N2. MRV designs that are too complex or compliance-heavy	High-precision, research-grade MRV approaches risk excluding smaller growers and suppressing participation, preventing incentives from functioning.
N3. Broad promotion of biologicals without standards or evidence	Scaling biological products without minimum QA and domain-of-use guidance risks “snake-oil” perceptions and reputational spill-over across the category.

Table 4.4.7. Summary of investment pathways for technology scaling for the Horticulture Sector. Note: The order and numbering do not indicate level of importance or priority, but simply to allow cross-reference of ‘aligned action areas’ with best action in Table 4.4.8.

Investment pathway	Problem / Risk Addressed	Indicators of Success	Indicators of Failure	Prioritised Actions
1. Accelerate electrification + automation bundles (pumps, variable speed drives, precision equipment, traction)	Electrification is technically attractive, but adoption is constrained by upfront capital cost, ROI uncertainty, grid constraints, servicing/charging capability, and limited availability of fit-for-purpose machinery. Without coordinated enabling, uptake remains uneven and pilot-heavy.	Saturation of electrified irrigation pumping and early machinery segments; regionally coordinated grid upgrades and service networks; measurable reduction in diesel use with co-benefits for labour efficiency and operational resilience.	High interest but low conversion; projects stall at pilot stage; grid connection delays and upgrade costs dominate decisions; limited dealer and service coverage sustains perceived risk.	H1 (now–2030): Incentives and concessional finance for pumps, VSDs and small electric machinery; aggregator or precinct models for grid upgrades; integrate electrification with digital MRV, regional skills and servicing programs; regionally coordinated demonstrations bundling electrification, automation and on-farm solar/storage. Region-specific adoption pathways and infrastructure/capacity building based on regional advantages and current state. H2/H3 (beyond 2030): Scale electrification to larger machinery and integrated automation; expand grid upgrades and regional service networks; establish regional electrification/robotics hubs.
2. Activate demand-side pull for ‘scaling-constrained’ options (precision agriculture, nitrification)	Several options are technically mature but scaling-constrained: economics, integration burden and perceived performance variability limit uptake; without demand signals or risk-sharing, A5 options plateau.	Buyer, procurement and brand programs reward verified lower-emissions production, starting with high-value products; adoption increases for precision tools and selected nitrogen options; growers report clearer ROI and reduced downside risk.	No credible claiming or procurement pathway; adoption remains fragmented and concentrated among large enterprises; technology churn without sustained practice change.	H1: Establish demand mechanisms (procurement specifications, price premiums, finance linked to verified outcomes); de-risk early adoption through warranties, insurance-like mechanisms and demonstration-backed guidance; prioritise high-value irrigated supply chains. H2/H3: Support claims for advanced, integrated technology stacks as standard practice. Expand marketing and product differentiation programs supported by credible emissions claims.
3. Build proportional, practical MRV and data infrastructure for horticulture	Sector heterogeneity and weak baseline data make MRV expensive and uncertain; without proportional MRV, incentives, stacking and credible claims remain difficult to operationalise, particularly for smaller enterprises.	A simple MRV spine is adopted: consistent capture of nitrogen rates/forms/timing, irrigation energy and fuel; lower transaction costs for participation; interoperability with domestic and export reporting; stacking rules become implementable.	MRV perceived as burdensome or compliance-driven; low SME participation; disputes over credibility; inability to compare technology bundles or quantify improvement across regions and crops.	H1: Prioritise MRV on major controllable drivers (nitrogen, irrigation energy, fuel); harmonise audit-lite data rules; embed MRV in existing farm software and irrigation telemetry; design basic stacking logic. Expand MRV to support multi-technology stacking and regional benchmarking; integrate MRV with supply-chain, finance and procurement platforms. H2/H3: Extend MRV to emerging technologies and evolving claims requirements.
4. Establish advisory networks delivering ‘what works where’ packages	Performance and practicality are highly context dependent (soil–water regimes, fertigation infrastructure, contractor arrangements, grid capacity).	Multi-region demonstrations produce crop- and region-specific playbooks; advisors translate these into 1–2 starter bundles per system; sustained adoption	Demonstrations remain isolated; results fail to translate into practice; advisors revert to generic advice; poor guidance on interactions (e.g. NH ₃ vs	H1: Build regionally embedded demonstration clusters focused on clear productivity–emissions win-wins; co-design packages with growers, advisers and contractors; publish stacking windows and practical decision rules.

	Without trusted, place-based evidence and advisory capability, adoption is slow and uneven.	increases; clearer guidance on compatible combinations and trade-offs.	N ₂ O, residue phases) undermines outcomes.	H2/H3: Scale and connect demonstration networks nationally; develop advanced advisory and decision-support tools for integrated systems.
5. Optimise nitrogen management in high-input systems	Nitrogen is important for mitigation opportunities in intensive systems, but scaling is constrained by yield-risk concerns, variable efficacy, post-harvest emissions risks and weak cost–benefit clarity for NIs, CRFs and UIs.	Wider use of decision support reduces over-application; regionally validated guidance on safe rate reductions; EEFs deployed where they pay; fewer unintended trade-offs (post-harvest N ₂ O, NH ₃ losses).	Continued “insurance” nitrogen use; inconsistent or abandoned EEFs adoption; post-harvest emissions erode net abatement; no clear economic advantage perceived by growers.	H1: Develop practical decision tools (rate-reduction thresholds, timing rules, residue-phase guidance); fund trials measuring net seasonal outcomes; publish simple stacking guidance (precision + NI/UI + irrigation scheduling). Integrate decision tools into digital MRV and advisory platforms; expand guidance across crops and regions; pilot next-generation stabilisers. H2/3: Mainstream precision nitrogen management as standard practice; support uptake of emerging biological inhibition options as evidence matures. Support regionally coordinated deployment programs for bundled technology packages.
6. Set quality, standards and evidence pathways for biologicals	Biologicals face a classic A5 barrier: variable field performance, QA uncertainty, limited replicated commercial-scale evidence, and inconsistent fit across crops and management systems (e.g. high-P suppression).	Minimum QA, labelling and reporting standards adopted; replicated multi-site trials in relevant horticultural systems; clear guidance on where biologicals are likely to work; reduced reputational risk and improved buyer confidence.	“Snake-oil” perception persists; growers disengage after mixed results; fragmented market with weak standards; no credible emissions claim pathway.	H1: Establish minimum QA/QC and labelling standards; create independent evaluation and reporting networks; frame adoption primarily around agronomic co-benefits rather than emissions claims. Expand trials and standards across crops and regions; link validated products to MRV and claims where appropriate.

Table 4.4.8. Best-bet actions for horticulture, aligned to investment pathways. Note: The order of the best-bet actions in this table does not indicate their level of importance or priority. A low priority does not indicate that an action is not worth pursuing, just that it has low leverage for emissions reduction.

Best-bet actions	Aligned action areas	Rationale (why this action is needed)	Description of the action	Priority
Deploy low-burden, input-focused MRV for horticulture (N, irrigation energy, fuel), embedded in existing tools	3, 2	Incentives, claims and coordination fail without MRV that producers can use routinely; horticulture’s heterogeneity makes “research-grade” MRV unrealistic.	Build horticulture-specific, audit-lite MRV modules focused on nitrogen inputs, irrigation energy and fuel use, drawing on tools such as HortCarbon Info and Wine Australia calculators. Embed MRV in advisory platforms and farm software used in Victoria, Tasmania and NSW, with simple stacking logic for bundled actions.	High: Foundational enabler for incentives, procurement, claims and coordination across all pathways.
Accelerate electrification and energy-efficiency bundles for irrigation, packhouses and light machinery	1	Evidence shows irrigation pumping and cooling offer the fastest, lowest-risk emissions reductions with strong productivity co-benefits; barriers are	Scale targeted rebates and/or concessional finance for pumps, VSDs, electric UTVs and refrigeration upgrades, aligned with relevant state government initiatives (e.g. Victorian energy audit programs, Tasmanian irrigation schemes and NSW renewable	High: Immediate abatement and resilience benefits where enabling conditions are addressed.

		infrastructure, finance and service availability rather than technology maturity.	energy initiatives). Use precinct or aggregator models where grid upgrades are the limiting constraint.	
Fund regionally embedded demonstration hubs linked to irrigation districts and wine regions	4, 5	All jurisdictions emphasise “what works where”; adoption depends on trusted local evidence and service capability, not generic guidance.	Establish multi-year demonstration hubs (e.g. irrigation districts in Victoria/Tasmania; wine regions aligned with Wine Australia’s roadmap) that integrate electrification, precision irrigation and nitrogen management. Produce short playbooks and starter bundles for each system.	High: Critical for translating technical readiness into sustained uptake across diverse systems.
Use demand-side levers in high-value supply chains to de-risk scaling-constrained options	2	Horticulture and wine have greater scope than broadacre agriculture to leverage branding, domestic procurement and buyer requirements, but only where claims are credible and simple.	Pilot procurement, branding or insetting arrangements for verified low-emissions produce, aligned with Sustainable Winegrowing Australia and state procurement settings. Pair with MRV and advisory support to minimise transaction costs for SMEs.	Medium/High: Unlocks uptake of otherwise stalled precision and nitrogen options in targeted markets.
Operationalise nitrogen optimisation in intensive systems using decision rules, not prescriptions	5, 3	Nitrous oxide dominates emissions in high-input systems, but growers are risk-averse; state programs stress ROI and yield protection over theoretical abatement.	Develop region-specific nitrogen decision support tools (rate reduction thresholds, timing, residue management) validated through Tasmanian and NSW demonstration farms. Integrate these rules into advisory tools and MRV rather than promoting blanket inhibitor use.	Medium: Material abatement where relevant, but system-specific and not universal.
Establish evidence, QA and assurance frameworks for emissions reduction claims in horticulture	6,3,2	Credible uptake of low-emissions practices depends on confidence that claims are evidence-based, proportionate and repeatable across contexts. Variable performance, unclear domains of use, and fragmented assurance risk reputational damage, market retreat and stranded investment across multiple technology classes—not only biologicals.	Develop cross-cutting assurance arrangements that define minimum evidence, QA/QC and domain-of-use expectations for any emissions reduction claim (including nitrogen tools, precision practices, electrification bundles and biological products). Align with existing state and industry MRV approaches; prioritise audit-lite, practice-based verification; and delay claimability until performance is demonstrated in relevant systems. Treat assurance data and protocols as shared public-good infrastructure.	Medium: High leverage for trust and durability; lower direct abatement than MRV or electrification

4.5 Piggeries

4.5.1 Background: Emissions contribution, distribution, trends and drivers

Australia's pig sector produces pork for both domestic and export markets and maintains a national herd of approximately 2.25 million animals. In FY2022, national Scope 1 emissions were estimated at around 0.986 Mt CO₂-e, of which roughly 86% arose from manure management systems (MMS), 10.5% from enteric methane, and 3.4% from on-farm energy. Within MMS, uncovered anaerobic ponds are the dominant source for methane emission, whereas deep-litter systems and covered anaerobic systems contribute substantially less methane per unit of output. Recent LCA benchmarking (FY2020–FY2022) provides these updated emission profiles and system-specific emission intensities, which form the basis for identifying and assessing abatement opportunities in this sector (Copley et al., 2024; Norton et al., 2023).

Table 4.5.1. Pools for abatement purposes used in this assessment

Source pool	Range (lower–upper), kt CO ₂ -e yr ⁻¹	Midrange, kt CO ₂ -e yr ⁻¹	% of Scope 1 emissions from piggeries (mid)	Notes / sources
Uncovered anaerobic ponds	542–740	641	65%	Dominant MMS CH ₄ ; range spans plausible split given national MMS shares (uncovered vs CAP/deep litter/outdoor) and per system intensities (Wiedemann et al., 2021; Poad et al., 2010)
Deep-litter housing & stockpiles	69–128	99	10%	Deep-litter CH ₄ per AU/day is far lower than ponds; national deep-litter activity share is large, so a modest but non-trivial CH ₄ share. (APL, 2022; Wiedemann et al., 2021)
Covered lagoons/digesters (CAL/CAP residual/fugitive)	20–49	39	4%	Residual slip/leaks with destruction; small share in well-managed projects (Poad et al., 2010)
Shed/collection channels	5–15	10	1%	Minor vs ponds; supported by Australian shed measurements.
Short-HRT/tank storage	0–10	6	<1%	Very low relative to ponds; bounded by trial results. (APL, 2022; Wiedemann et al., 2021)
Other manure/treatment CH ₄ (	29–69	54	5.5%	(APL, 2022; Wiedemann et al., 2021)

Subtotal (MMS pools)	—	~849	86%	Matches Table S12 MMS Scope 1 total (accounting identity). (APL, 2022; Wiedemann et al., 2021)
Enteric methane	—	103	10%	(APL, 2022; Wiedemann et al., 2021)

Two broad dynamics shape mitigation outcomes in the pig sector.

- 1) Intensity improvements have largely been driven by productivity gains and progressive upgrades to manure management systems. However, the continued dominance of uncovered anaerobic ponds still constrains the sector’s technical abatement potential.
- 2) Scaling economics remain large operation size-dependent (e.g., need for capital, engineering, labour) making many mitigation options “scaling-constrained” in the absence of demand-side pull or access to project finance.

The assessment presented in this section (and detailed further in Appendix C.5) draws on a limited body of literature and recognises that substantial practical experience and expertise within the industry must inform the design of specific investments and interventions.

Estimating costs and returns of alternative technologies is challenging due to shifting input prices, and the wide diversity of production contexts in which infrastructure changes may reduce emissions. Costs vary significantly with scale, geography and site-specific factors, as well as the operational and business models under which technologies are deployed.

4.5.2 Technology assessment

The assessment indicates that all technology options identified through the review are at high TRL (>8) and almost all high CRL. Two broad families of solutions emerge:

1. MMS interventions that directly reduce methane generated during storage, including covered anerobic lagoons (CAL/CAP), short-HRT, solids separation and minimum solids stockpiling, acidification, and conversion to deep-litter systems.
2. Nutrition and genetics interventions that reduce nitrogen excretion and emissions intensity, such as low-protein diets supplemented with essential amino acids, probiotics and plant-derived additives, dietary organic acids, and selective breeding/genetic improvements.

Some options offer strong high technical leverage to reduce emissions but remain scaling-constrained due to project economics, approval processes and limited supplier capacity. Others are scaling-ready but deliver moderate abatement per unit and depend on consistent performance, quality assurance and robust MRV systems to support widespread adoption.

An overview of the results detailed in the sector technology assessment for piggeries (Appendix C.6) is presented in Table 4.5.2. This demonstrates the tendency of technologies with higher abatement potential to be scaling constrained, especially those with high upfront costs. Investment in R&D was not detected in RDC-funded projects.

Table 4.5.2. Summary of scope 1 abatement technology assessment for piggeries.

Technology name	Archetype	Current investment	Industry abatement potential	Ag Sector abatement potential	Confidence	Key issues (drivers of scaling)
Covered anaerobic lagoons (CAL/CAP)	A5 - Scaling Constrained	No data sourced	HIGH	MEDIUM–HIGH	MEDIUM	ACCU eligibility and price; electricity/LPG tariffs; concessional finance; supplier capacity; approvals and safety; integration with solids removal/CHP.
Short hydraulic retention time (short-HRT)	A5 - Scaling Constrained	No data sourced	MEDIUM	MEDIUM	MEDIUM	Retrofit feasibility (space/hydraulics); nutrient reuse logistics; ACCU method applicability; demonstration and O&M support.
Effluent solids separation (mechanical/floc)	A6 - Scaling Limited	No data sourced	MEDIUM	LOW–MEDIUM	MEDIUM	Chemicals/OPEX vs benefits; operator capability; linkage to CAP/compost; procurement standards for reused nutrients.
Minimum solids stockpiling (aerobic diversion)	A6 - Scaling Limited	No data sourced	LOW–MEDIUM	LOW	MEDIUM	Pads, labour, markets for compost; odour/amenity drivers; classification/transport rules across jurisdictions.
Manure slurry acidification (tanks)	A5 - Scaling Constrained	No data sourced	LOW	LOW	MEDIUM	OHS and dosing logistics; acid supply; development and compatibility of other additives; tank applicability; recognition in accounting/standards; nutrient value realisation.
Deep-litter housing (conversion)	A6 - Scaling Limited	No data sourced	MEDIUM	LOW–MEDIUM	MEDIUM	Climate and litter supply; shed design/ventilation; NH ₃ management; compost outlets.
Low-protein diets + essential AAs	A7 - Scaling Ready	No data sourced	MEDIUM	LOW–MEDIUM	MEDIUM	Ingredient price spreads, Health /FCR benefits; formulation discipline; advisory capacity; assurance that productivity/performance is maintained.
Probiotics & plant-based additives	A6 - Scaling Limited	No data sourced	LOW	LOW	LOW	Product performance variability; cost vs FCR gains; QA and procurement standards; on-farm validation.
Dietary organic acids	A6 - Scaling Limited	No data sourced	LOW	LOW	LOW	Dose/formulation economics; integration with LP diets; supplier QA;

						demonstrable FCR/health benefits.
Genetics (feed/protein efficiency)	A7 - Scaling Ready	No data sourced	MEDIUM	MEDIUM	MEDIUM	Diffusion lag; data systems; alignment with nutrition/health; industry coordination and biosecurity.

Overcoming scaling constraints in piggeries requires coordinated activation across demand-side, intermediating, and supply-side functions. For scaling-constrained (A5) options, such as CAL/CAP, short-HRT, and acidification, demand-side pull is particularly decisive. Measures such as concessional finance, recognition through crediting frameworks, and procurement commitments for low-emission pork can improve ROI and help projects reach final investment decision.

Intermediating mechanisms include practical MRV (e.g., user-friendly frameworks for stacking projects such as solids separation + CAL + composting), the development of nutrient-product specifications to support reliable compost markets, streamlined approvals and safety protocols, and regional coordination to align suppliers, funders and regulators.

On the supply side, capacity building is essential. This may include supplier accreditation, standardised system designs, and shared engineering and techno-economic assessment resources to address the thin market for specialised service providers and reduce execution risk. Development of regionally accessible design templates, pre-approved engineering specifications, and centralised advisory or brokerage services could aggregate demand across smaller piggeries, reduce transaction costs, and provide confidence in performance and compliance. Over time, building a pipeline of trained operators, service contractors, and integrators—supported by demonstration sites and shared data on system performance—will be critical to moving from bespoke project delivery to repeatable, scalable deployment models.

For scaling limited (A6) options, such as solids separation, minimum solids stockpiling, deep-litter systems, and feed additives including organic acids, diffusion depends on cost-fit and system-fit. Useful interventions include benchmarking guides for “what works where and when”; regionally embedded demonstrations; and quality-assurance and procurement standards for nutrient products and feed additives.

For A7 options, such as low-protein diets, genetics, the emphasis shifts to advisory capability, formulation quality assurance, and robust data and market specification and assurance systems. Retailer procurement or market-specific standards may become important to ensure that verified practice change is recognised and valued.

4.5.3 Portfolio analysis

The portfolio spans several archetypes: two scaling-ready (A7) options (e.g., low-protein diets; genetics), several scaling-limited (A6) options (e.g., deep-litter, solids separation, organic acids, probiotics), and three scaling-constrained (A5) capital-intensive options (e.g., CAL/CAP, short-HRT, acidification, and a growing range of other additives). The main bottleneck occurs in the late-emergence and diffusion phase, where ROI depends heavily on incentives, site scale and supplier capacity.

A balanced pathway should therefore integrate:

- (i) demand-side activation, supported by regional demonstrations, to move A5 options into diffusion;
- (ii) quality-assured diffusion of A6 options that complement CAL systems and strengthen nutrient circularity; and
- (iii) scaling of A7 levers to lock in emission-intensity improvements across the herd.

The portfolio of technologies and their scaling constraints suggests a variety of innovation functions and that demand-side, intermediating and supply-side functions can be better aligned through coordinated interventions which are already being implemented to some degree (Section 4.5.7).

4.5.4 System interactions: risks and opportunities

Technological and infrastructure interactions: These are central to determining mitigation feasibility. Energy market conditions such as tariffs, grid export, and supply reliability strongly influence the economics of CAL/CAP systems. Safety protocols and logistical requirements shape the practicality of acidification and alternative additives, while the viability of solids separation and stockpiling depends on effective dewatering and compost-handling logistics. Digital MRV and on-farm data systems are becoming baseline requirements, reducing transaction costs for stacked projects and enabling credible supply-chain emission claims. Innovations in wastewater treatment (e.g., high-rate aeration/short-HRT) have the potential to reconfigure pond design, storage requirements and land-application strategies. A risk is the creation of stranded assets when covers are installed without corresponding solids management; integrated system designs improve gas quality, reduce sludge accumulation and extend asset life.

Cross-system and cross-sector interactions: Real-world abatement is often lower than technical estimates due to substitution (e.g., short-HRT displacing CAL) and competition for shared resources, including labour, capital and regulatory approvals. The viability of composting depends on demand from cropping and horticulture, transport distances and costs, and nutrient quality assurance systems. Co-digestion with food waste can improve CAL yields but adds logistical, biosecurity and approval requirements. Energy projects within the meat-processing sector may compete with, or in some cases aggregate, piggery biogas opportunities. Increasingly, scope 3 disclosure and procurement requirements will shape incentives, risk allocation, and value recognition along the chain.

Socio-cultural interactions: Odour reduction and improved amenity are strong local drivers for CAL and solids separation, while acidification brings additional handling considerations, perceptions and training needs. Deep-litter systems align well with welfare branding but are only feasible in specific systems. For dietary interventions and feed additives, inconsistent performance outcomes can slow uptake; peer learning, quality assurance processes, and transparent cost-benefit guides are essential to support informed adoption.

Cross-sectoral transformation effects: Firmed renewables and lower-cost electricity strengthen the economics of CAL cogeneration, while emerging green-fertiliser markets may reshape feed and nutrient valuations, influencing the competitiveness of compost products. Harmonised waste-regulation frameworks would help reduce solids transport costs, whereas standardised templates

could facilitate the adoption of acidification systems or biogas upgrades. Anticipating these system-wide shifts is essential to minimise the risk of lock-in and stranded approvals.

Piggery-specific headwinds

Tailwinds:

- Industry growth and capitalisation may create economies of scale that assist technology scaling.
- Coherence and organisation of a relatively small and technically capable industry appear to support direction for improved environmental performance, and associated market advantages (e.g., differentiation from imported pork products).

Headwinds:

- High upfront costs and limited supplier competition for CAL/short-HRT.
- Regulatory burden is high, complex, varied across jurisdictions and increasing; compliance costs are prohibitive for small operations, leaving reduced options for investment in GHG emissions reduction.
- Limited practical MRV or existing calculators/models may not suit all operation sizes.
- Tight margins and high retrofit costs for older infrastructure make profitability a major barrier.
- Various technology-specific barriers (see Appendix C.5).

4.5.5 Investment assessment

There was no detected R&D investment in piggeries in the RDC and ZNE-Ag CRC data examined. Australian Pork Limited (APL) has recently invested in some areas, that are not captured in this analysis.

4.5.6 Prioritisation analysis

The absence of investment data meant that no prioritisation analysis could be undertaken formally under the framework.

4.5.7 Pathways for Piggeries

Emissions reduction in the piggery sector is dominated by manure methane, and—unlike grazing livestock—most high-impact mitigation options (e.g. covered anaerobic lagoons, short-HRT systems, solids separation) are technically mature and well understood. The binding constraints are instead capital intensity, project economics, approvals, MRV, supplier capacity, and demand-side value recognition.

The sequencing logic prioritises unlocking investment and reducing execution risk, rather than technology discovery:

- Horizon 1 (now–2030) focuses on enabling project viability: clarifying demand-side signals (credits, procurement, inseting), standardising MRV and stacking rules, streamlining approvals, and building supplier and demonstration capacity. Near-term abatement can be material but is geographically concentrated in larger facilities. Win-win opportunities around energy efficiency, renewables, precision feeding and low protein diets continue to be a focus.
- Horizon 2 (2030–2035) scales deployment by lowering transaction and financing barriers, expanding supplier capacity, enabling regional clustering, and integrating manure systems with energy and nutrient markets.
- Horizon 3 (post-2035) consolidates low-emissions manure management as business-as-usual, embeds mitigation expectations in contracts and finance, and enables further efficiency gains through system optimisation and circular nutrient markets.

Table 4.5.3. Key barriers (B), enablers (E), opportunities (O) and non-investment signals (N) for piggeries, synthesised from previous sections, and underpinning action areas listed in Table 4.5.4.

Item	Description
B1. High upfront capital costs	Anaerobic digesters, covered lagoons, biogas utilisation and associated energy infrastructure require large upfront capital investments, often exceeding the risk appetite of individual producers without concessional finance, aggregation, or energy offtake certainty.
B2. ROI sensitivity to energy and policy settings	Project viability is highly sensitive to electricity prices, gas offtake arrangements, renewable energy incentives, and carbon or crediting settings, creating exposure to policy and market volatility.
B3. Regulatory and planning complexity	Environmental approvals, planning processes, grid connection requirements and odour and waste regulations are complex, time-consuming and jurisdictionally variable, delaying projects and increasing transaction costs.
B4. MRV and assurance burden	While technically feasible, manure methane MRV can be costly and administratively complex if not standardised, undermining eligibility for incentives, crediting, or inseting arrangements.
B5. Limited access to tailored finance	Conventional farm finance is often poorly suited to large, lumpy infrastructure investments with long payback periods and unfamiliar risk profiles (e.g. biogas systems).

E1. Concentrated emissions sources	A large share of piggery emissions derive from manure management, making point-source mitigation technically feasible and measurable compared to diffuse biological emissions.
E2. Established technology options	Covered anaerobic lagoons, digesters and biogas utilisation are proven technologies with multiple Australian and international reference cases.
E3. Energy integration potential	Piggeries offer strong opportunities to integrate emissions reduction with renewable energy generation, on-site use, export to grid, and energy cost management.
E4. Industry structure and coordination	The pig industry is comparatively consolidated, with established industry bodies and supply chains that can support coordinated deployment, standard setting and aggregation.
O1. Low-cost, high-confidence abatement	Manure methane abatement offers some of the highest confidence, lowest-uncertainty emissions reductions available in agriculture when operationalised effectively.
O2. Aggregation and precinct approaches	Aggregating projects across regions or using precinct-style energy and waste solutions can reduce unit costs, smooth regulatory processes and improve investment stability.
O3. Supply-chain insetting and Scope 3 alignment	Processors and retailers facing Scope 3 requirements can support investment via insetting, long-term contracts or co-investment in manure methane projects.
O4. Platform for broader decarbonisation	Investment in manure methane systems can act as a platform for further decarbonisation (e.g. electrification, fuel switching, nutrient management).
N1. Premature deployment without finance and approvals alignment	Accelerating deployment without resolving finance, MRV, and approval pathways risks stranded assets, project failure and loss of confidence.

The action areas listed in Table 4.5.4 translate the identified barriers, enablers, and opportunities from Table 4.5.3 into an investment pathway that aims to catalyse long-term impact. Some elements of Table 4.5.3 (e.g. B2, B3) are also addressed through cross-sector/systems-level interventions (detailed in Chapter 5).

Table 4.5.4. Table of recommended investment pathways and prioritised actions across horizons for piggeries (with links to barriers, etc., from the previous table). Note: The order and numbering do not indicate level of importance or priority, but simply to allow cross-reference of ‘aligned action areas’ with best action in Table 4.5.5.

Action area	Problem/Risk Addressed	Indicators of Success	Indicators of Failure	Prioritised Actions
1. Activate demand-side signals for key scaling constrained manure technologies (CAL/CAP, short-HRT, acidification)	High upfront costs and weak access to tailored finance (B1, B5), despite a strong abatement opportunity (O1). ROI sensitivity to energy prices and offtake conditions (B2) limits bankability despite energy potential (E3, O2).	Crediting and procurement frameworks are functioning; projects reach FID; adoption rises at large sites. Stable offtake agreements; integrated energy use.	Slow uptake outside early adopters; fragmented supplier base; stalled demos. Exposure to volatile prices; curtailed generation.	H1 (now–2030): Build from ACCU Scheme methods to align concessional finance; pilot long-term energy offtake and aggregation models for MMS within regional transitions/ circular economy models. Explore pilot processor or retailer procurement options for low-emissions pork. H2 (2030–2035): Expand demand signals and integrate with energy offtake contracts and insetting. Support aggregation models that cluster facilities to achieve scale in energy, nutrient and carbon markets. Integrate biogas production into regional energy systems through offtake arrangements and coordinated infrastructure. H3 (2035+): Embed demand-side signals into standard industry contracts and finance.

2. Practical MRV and standards to unlock stacking (separation + CAL + compost)	MRV burden limiting incentive and crediting pathways (B4), constraining market activation (O3).	Template MRV; clear stacking rules; nutrient QA enabling compost markets.	High transaction costs; double-counting concerns; weak markets.	H1: Publish MRV templates and stacking rules; develop compost and nutrient QA standards. H2: Integrate MRV into processor claims and finance platforms; standardise reporting nationally. H3: Maintain MRV as routine infrastructure supporting advanced system optimisation.
3. Streamline regulatory, planning and environmental approval pathways	Complex, time-consuming and inconsistent approval processes (B3) delay projects, increase costs and discourage investment, even where finance and technology are available.	Reduced approval timeframes, clear and consistent regulatory guidance, and lower transaction costs for repeat projects.	Lengthy delays, regulatory uncertainty, and abandonment of otherwise viable projects.	H1: Clarify regulatory pathways and coordinate guidance across jurisdictions. H2/H3: Normalise approvals for standard manure methane systems through established processes.
4. Scale nutrition & genetics “no-regrets” levers	Opportunity cost and variability limit uptake of low protein diets/additives; genetics diffusion lags (O1).	Higher LP diet penetration, documented feed savings, and herd-level intensity improvement.	Reversion due to performance issues; inconsistent QA.	H1: Strengthen advisory and QA support; align low protein and precision feeding and genetics with manure system upgrades. H2: Link verified performance to procurement and insetting recognition. H3: Normalisation and continuous improvement in low-protein/precision diets and genetic efficiency as baseline practice.

Best-bet actions for piggeries are mapped below to aligned action areas in Table 4.5.4. These sub-sectoral investment priorities aim to strategically advance the industry’s contribution to a low-emissions future. They combine a variety of mechanisms and functions beyond R&D to build a foundation for low-emissions transitions post-2030, by ensuring accountability and MRV are integral to investment, market access and social licence.

Table 4.5.5. Best-bet actions for piggery emissions reduction. Note: The order of the best-bet actions in this table does not indicate their level of importance or priority. A low priority does not indicate that an action is not worth pursuing, just that it has low leverage for emissions reduction.

Priority action	Linked action areas	Rationale (Why this action is needed)	Description (What it involves in practice)	Priority
Scale manure methane capture and utilisation systems	1, 2, 3	Manure methane offers high-confidence, material abatement in a sub-sector with tractable emissions.	Support deployment of covered lagoons and digesters with energy integration, MRV and finance packaged together, and off-take arrangements.	Very high – largest near-term abatement opportunity with high confidence.
Provide concessional finance and risk-sharing mechanisms	1	Capital intensity is the primary barrier to adoption.	Use guarantees, blended finance and aggregation to reduce risk and crowd in private capital.	High – unlocks otherwise stalled projects.

Develop standardised, low-friction MRV for manure methane	2	MRV underpins incentives, crediting and claims credibility.	Create simple, standard protocols aligned with energy and carbon markets.	High – foundational system enabler.
Align planning, environmental and grid approvals	1	Regulatory delays and cross-state differences materially slow deployment timelines.	Coordinate guidance and streamline approval pathways across states for routine systems. De-risk compost markets and support learning across implementation sites.	Medium–High – critical for speed and confidence.
Engage supply chains in insetting and co-investment	1	Supply-chain demand can monetise abatement and stabilise returns.	Link processors and retailers to projects via insetting or contracts.	Medium – important, but reliant on MRV and finance foundations.
Continue BAU investment in ‘no-regrets’ and win-win efficiency measures with GHG co-benefits, such as those associated with feed efficiency, feed sourcing, genetics, low protein diets/additives.	4	Provides a win-win and minimalist option for building greater literacy and MRV capacity in the sector to enable other measures	Ensuring proportionate MRV is built into ongoing industry efforts. Extend LCA through trials and demonstrations and link to market credentialing and industry guidelines and standards.	Medium – important, but likely to happen anyway and not requiring additional coordination.

4.6 Poultry

4.6.1 Sub-sector summary

Australia's poultry sector comprises chicken meat and egg industries and produces a large protein volume with comparatively low emission intensity. Within the sector, Scope 1 emissions are relatively minor, with the majority of emissions occurring under Scope 3, primarily driven by purchased feed. Recent Australian LCAs quantify these patterns clearly and provide the most defensible basis for sector-wide estimates and abatement planning (Copley & Wiedemann, 2022).

The key pathway to overall emissions reduction for both egg and chicken meat industries is via improvements in emissions intensity (CO₂-e/kg product). Copley & Wiedemann (2022) report supply-chain intensities of 3.8 kg CO₂-e/kg for conventional chicken meat and 4.0 kg for free-range production; feed contributes about 77–79% of total supply-chain emissions, and the farm stage (Scope 1 and 2) contributes about 9–12%. Industry sources based on ABARES (2025) figures place annual chicken-meat output at ~1.37 Mt (with forward estimates of ~1.356 Mt in 2023–24 and ~1.5 Mt in 2024–25) (AgriFutures Australia, 2023). Nearly all chicken meat sold in Australia is domestically produced.

The companion LCA reports on egg production reports 1.2 (cage), 1.4 (cage-free) and 1.5 kg CO₂-e/kg (free-range), with hotspots in feed, layer-farm energy and pullet rearing. Using 2022–23 production of 6.68 billion eggs (~387,440 tonne at 58 gram/egg) provides a reasonable national estimate of emissions (Copley et al., 2023; Copley and Wiedemann, 2022).

For both the egg and chicken meat industries considered in this section, scope 3 emissions are a relatively large source of emissions and targeted by many in the industry. Although these are not the focus of this report, they should be outlined for context. Feed manufacture and upstream inputs, particularly soymeal, typically account for ~77–79% of broiler supply-chain emissions, and eggs show a similar profile. Land-use and direct land-use change can be material in total emissions, especially associated with land-use change for soybean production (Copley & Wiedemann, 2022). Scope 3 emissions are thus targeted through feed sourcing and feed-use efficiency.

Because this assessment focuses specifically on scope 1 emissions reduction opportunities, technologies associated with manure management receive greater attention than they might in a whole-of-value-chain assessment. Feed efficiency, nutrition and genetics remain critically important to industry emissions intensity performance but primarily influence emissions sources outside the scope 1 boundary used in this report

Scope 1 (on-farm direct) emissions include nitrous oxide (N₂O) from manure storage and treatment, on-farm fuel use, methane (CH₄), and minimal indirect N₂O arising from volatilisation and leaching when spent material is used on-farm in agricultural applications for mixed farm businesses. Electricity consumption is classified under Scope 2. These sources align with farm-stage categories used in and are consistent with NGGI reporting (Australian Government, 2024). Australian poultry systems are predominantly dry-litter based; alternative manure systems exist but are limited and subject to regulatory and operational constraints. Some treatment pathways may shift emissions between stages rather than eliminate them. Manure-related technologies can contribute to

reducing scope 1 emissions, but for most poultry operations will be complementary to broader efficiency-driven pathways.

It should also be noted that manure, spent litter and compost outputs from poultry systems can substitute synthetic fertilisers and may reduce Scope 3 emissions of other farming operations. Fertiliser replacement and nutrient recovery are important potential contributions to wider circularity in farming systems but are not assessed here as they largely fall outside the Scope 1 boundary.

Trends, drivers and distribution across systems

- **Feed footprint and supply dynamics:** Because feed dominates Scope 3, crop mix and origin (plus LU/dLUC accounting) heavily influence the poultry footprint; the chicken-meat LCA includes a soy LU/dLUC term of ~1.7–1.8 kg CO₂-e/kg. Diet reformulation, improved feed conversion ratios (FCRs), and diversification to low-LU proteins are the largest levers for total (Scope-inclusive) reductions (Copley & Wiedemann, 2022).
- **Farm energy & electrification:** Heating and ventilation of sheds dominate on farm energy use. High-efficiency sheds (especially brooders) and electrification can shift emissions from Scope 1 fuel (gas) to lower-intensity Scope 2 and reduce totals under greener supply (Copley & Wiedemann, 2022).
- **Manure system performance:** Poultry litter in Australian systems is typically managed under dry, aerobic conditions, resulting in relatively low methane formation (compared to other livestock systems). Emissions from manure are dominated by nitrogen pathways, particularly ammonia volatilisation and associated direct and indirect nitrous oxide emissions. Consequently, mitigation options primarily target nitrogen management and emission control during handling (e.g. drying, frequent clean-out, covered storage), with waste-to-energy approaches such as anaerobic digestion offering more limited and system-dependent Scope 1 abatement (Copley & Wiedemann, 2022).

National estimates for Scope 1 emission abatement opportunities

Based on National Greenhouse Gas Inventory reporting and recent Australian life-cycle assessments, Scope 1 emissions in the poultry sector can be disaggregated into key source categories with corresponding indicative abatement levers (Copley & Wiedemann, 2022):

- On-farm fuel emissions present additional abatement opportunities through the adoption of higher-efficiency brooders, electrification, and integration of on-site renewable energy
- Direct nitrous oxide (N₂O) emissions from manure can be mitigated to some degree through carbon-to-nitrogen (C:N) management in composting, and diet optimisation though through precision feeding (adjustment of feed composition to match the changing nutrient requirements), while indirect N₂O emissions are influenced by measures that suppress ammonia (NH₃) volatilisation and reduce runoff losses associated with manure and spent litter used mixed farming.
- Methane (CH₄) emissions from manure management may be reduced through litter moisture control, faster litter turnover, covered storage, and, where feasible, anaerobic digestion.

Using National GHG Inventory categories and recent LCAs (Copley & Wiedemann, 2022), we estimate the relative contribution of these Scope 1 emission pools and base subsequent assessments of technology-specific abatement potential on the estimates presented in Figure 4.6.1.

Table 4.6.1. Emissions pools for abatement purposes used in the assessment of poultry emissions reduction potential

Scope 1 emission pools for poultry	Chicken meat kt CO ₂ -e yr ⁻¹	Eggs kt CO ₂ -e yr ⁻¹	Poultry total kt CO ₂ -e yr ⁻¹
On-farm fuel (diesel/LPG)	134.6	15.3	149.9
Manure CH ₄ (NGGI 3.B.4)	84.2	9.6	93.8
Manure N ₂ O (direct; NGGI 3.B.4)	67.3	7.6	75.0
Manure N ₂ O (indirect; NGGI 3.C.6)	50.5	5.7	56.2
Scope 1 total	336.6	38.2	374.8

4.6.2 Technology assessment

The Sector Technology Assessment (Appendix C.6) for poultry indicates an scope 1 emission mitigation portfolio spanning late-emergence and diffusion phases. Several management-led options are already Scaling Ready (A7) (e.g., shed litter management, feed additives, precision feeding, breeding) and are widely adopted and often embedded within industry best practice. As a result, their potential to deliver substantial emission reductions is limited, except through incremental improvement and additional adoption across a broad-base of the industry. In contrast, higher-capital waste-to-energy options face scaling constraints (A5) due to cost, technical fit with operations, largely dry litter systems, and regulatory complexity (e.g. multiple jurisdictions regulating different aspects of operations). One pathway (gasification/pyrolysis) currently sits in the Development and Trialling (A4) phase. The table below summarises the findings about the poultry sector's technology assessment. A key limitation of this analysis is the very limited availability of information on the financial viability of options for poultry. It should also be noted that while various technologies are rated as having 'medium' feasible potential emissions abatement, this is an artefact of the relatively low emissions of the industry. Costs per tonne of emissions are likely to be high and often commercially unviable.

Table 4.6.2. Summary of technology assessment for the poultry sector using the methods criteria and archetypes.
For details of each technology, see Appendix C.6.

Technology name	Archetype	Current investment	Industry abatement potential	Ag Sector abatement potential	Confidence	Key issues
Methane capture and utilisation	A5 - Scaling Constrained	None identified	MEDIUM	LOW	LOW	Dry litter/ammonia inhibition lowers yields; co-digestion often required; high CAPEX; digestate handling and market maturity/access for products; variable regulation across jurisdictions; limited in-sector expertise
Gasification and pyrolysis	A4 - Development trialling	None identified	MEDIUM	LOW	LOW	High CAPEX; feedstock moisture/variability; emissions controls and permitting; market for biochar uncertain at scale
Combustion of litter	A5 - Scaling Constrained	None identified	MEDIUM	LOW	LOW	Very high CAPEX; stringent air emissions requirements; ash handling/logistics; feedstock variability; site suitability
Covered stockpiles	A5 - Scaling Constrained	None identified	MEDIUM	LOW	LOW	Operational discipline needed; labour requirements; land/cover durability; inconsistent classification/approvals across jurisdictions
Shed litter management	A7 - Scaling Ready	None identified	MEDIUM	LOW	LOW	Operational challenges in-shed; ammonia/dust spikes during turning; biosecurity in reuse; bedding supply constraints; short turnaround between flocks
Feed additives	A7 - Scaling Ready	None identified	MEDIUM	LOW	LOW	Cost of specialised additives; formulation expertise; regulatory processes for approval of novel additives; performance variability across diets
Precision feeding	A7 - Scaling Ready	None identified	MEDIUM	LOW	LOW	Capital/software integration; training and data workflows; limited max-profit/stochastic tools; misaligned KPIs (least-cost vs performance via feed conversion ratios)
Poultry breeding programs	A7 - Scaling Ready	None identified	MEDIUM	LOW	LOW	Dependence on global breeding pipelines; access to genomic tools; need for ongoing performance data; regulatory/market constraints

4.6.3 Portfolio analysis

For scaling-ready technologies (e.g., litter management, feed additives, precision feeding, breeding), diffusion is most likely to accelerate with consistent industry-level information provision, extension services and technical support that reinforce best practice and continuous improvement. Practical MRV, together with targeted supply-chain incentives and standards that reward emission-intensity improvements in products, represent the most plausible pathway for domestic markets. These approaches may further extend market share and could be supported by more proactive demand-side measures, such as coordinated marketing initiatives.

For scaling-constrained waste-to-energy options, market creation and coordination would help. Concessional finance, standardised and transparent permitting pathways, development of offtake markets (e.g., for energy, biochar, ash), and greater policy coherence within and across jurisdictions can all contribute to reducing risk and close the ROI gap. Given the structure and scale of the sector, and the broader evolution of waste-to-energy and circular economy industries, the Australian poultry industry is likely to be an integral participant (rather than leader) in larger initiatives to advance these options. The strongest deployment pathway is likely to be through regional aggregation models, circular-economy precincts or co-processing of multiple waste streams rather than widespread deployment at individual poultry farms.

Workshop participants of this project highlighted that tight margins and high retrofit costs for existing infrastructure present major barrier to infrastructure investment, particularly when coupled with high and rising regulatory and compliance costs. These constraints are especially acute for smaller operations, for which high-upfront capital requirements can be prohibitive, substantially limiting available options for investment in GHG emissions reduction.

Although there is limited evidence of investment and on-ground action, current effort appears skewed to knowledge generation (SF1), particularly around nutrition and litter practices, with comparatively less evident mobilisation (SF3), coordination (IF3) and demand activation (DF1) for high-CAPEX technologies. Priority mechanisms to address these gaps include: regional demonstration of covered storage and litter best-practice (IF4/DF2); standardised approvals and emissions-control guidance for thermal processes (IF3/IF1); development of crediting pathways for biochar and verified nutrient recovery (DF1/DF2); and supply-chain incentives for precision nutrition and welfare co-benefits (IF2/DF2).

The poultry emission mitigation portfolio clusters at Scaling Ready (A7) for management- and genetics-based measures, while high-CAPEX waste-to-energy options face a late-emergence bottleneck, which are classified in this analysis as scaling-constrained.

This pattern points to a near-term emissions reduction through low-cost diffusion measures, while strategic, coordinated effort is required to build the enabling conditions for capital-intensive pathways (see Pathways, below). For example, waste-to-energy systems are often too costly to be viable within a single enterprise, at least in the short to medium-term. As a result, coordination across sites to manage manure logistics (e.g., collection timing, moisture control) and to aggregate product markets for biochar, ash or energy is likely to be decisive enabling progression towards scale.

4.6.4 System interactions: risks and opportunities

Technological and infrastructure interactions: heating and ventilation link on-farm emissions outcomes to energy prices and electrification trajectories; co-location of thermal treatments or digestion facilities with regional waste hubs could improve feedstock consistency and utilisation. Digital monitoring systems could potentially support ammonia control and enable MRV for litter management practices.

Cross-system interactions: Nutrient recovery and fertiliser substitution can shift emissions across sectors; highlighting the need for credible accounting frameworks to avoid double-counting of co-benefits, for example, the use of waste through industrial composting and other downstream applications.

Socio-cultural interactions: Community expectations around animal welfare, odour and biosecurity shape social licence and site approvals, and changes in operations are similarly sensitive. The development of waste-to-energy systems, in particular, is likely to require early and ongoing stakeholder engagement to manage these considerations alongside regulatory compliance.

Cross-sectoral transformation: Declining grid emissions intensity and the potential availability of a crediting mechanism for biochar could materially improve ROI for waste-to-energy systems (AgriFutures Australia, 2023; ARENA, 2023).

4.6.5 Investment assessment

No RDC-style investment program in scope 1 emissions, comparable to those in other agricultural industries, was identifiable for poultry. However, several signals were identified. Precision feeding has been the subject of recent Australian trials (Poultry Hub Australia, with industry and academic partners), while thermal conversion pathways have progressed through pilot and demonstration activity (e.g., ARENA-supported pyrolysis projects; Energy Farmers Australia case studies). Litter management and ammonia control are the focus of AgriFutures best-practice programs.

Across this limited scan, investment appears to be concentrated in knowledge production (SF1) and early-stage pilot demonstrations, with comparatively limited demand-side measures, such as concessional loans and other structured market incentives, to enable commercial scaling of high-CAPEX options.

A deeper, industry-led analysis would be required to more fully understand what specific approaches are being developed and the extent to which they may be positioned for scale.

4.6.6 Prioritisation analysis

While the framework analysis could not be completed due to lack of visible investment data, near-term ‘Scaling Ready’ options (e.g., litter management, feed additives, precision feeding, breeding) are well suited for low-cost diffusion support including extension services, MRV, procurement or market signals. In contrast, ‘Scaling Constrained’ options (e.g., AD, combustion) and ‘Development trialling’ (e.g., gasification/pyrolysis) require demand activation, risk-sharing finance, and streamlined, standardised approvals to close the ROI gap. Covered stockpiles present a high-potential, low-cost industry-level abatement lever, provided that operational discipline and

consistent classification and approvals are addressed. Overall, the current investment in these areas appears limited relative to their potential contribution.

4.6.7 Pathways for Poultry

Poultry is structurally different from other livestock sectors. Scope 1 emissions are modest relative to total supply-chain emissions, and many low-cost, management-led mitigation options are already widely adopted. The largest emissions reduction opportunities for poultry appear to lie in Scope 3 feed systems (Copley & Wiedemann, 2022), but within the scope of this report, Scope 1 emissions are dominated by on-farm energy use and manure management.

This means that poultry is best characterised as a late-diffusion sector: most technically effective Scope-1 options are already available, but scaling depends on infrastructure investment, wider energy transition dynamics, MRV integration, and coordination with supply-chain and waste systems, rather than discovery of new technologies.

The sequencing logic emphasises consolidation and optimisation:

- Horizon 1 (2025–2030) focuses on consolidating and standardising existing best practice, accelerating electrification and energy efficiency, continuing improvements in emissions intensity driven by feed conversion efficiency, precision nutrition and genetics, and building proportional MRV to support credible claims, procurement and insetting without increasing reporting burden.
- Horizon 2 (2030–2035) enables selective scaling of higher-capital manure-to-energy and litter-treatment options where viable, and deeper integration of poultry into regional energy and nutrient systems (circularity).
- Horizon 3 (post-2035) locks in low-emissions poultry as business-as-usual, with energy-neutral or energy-positive sites and fully integrated nutrient circularity, while continuing incremental gains through genetics and management.

In poultry, H1 is about maximising consistency and legitimacy, H2 about selective capital deployment, and H3 about system integration and normalisation. These horizons and actions need to be considered in the context of other (scope 2-3) abatement options which may be more efficient in reducing industry emissions.

As summarised in Table 4.6.3, scope 1 emissions reduction in the poultry sector is constrained predominantly by energy dependence, thin margins, and infrastructure lock-in. Emissions are dominated by energy use in housing and shed operations, alongside manure and litter-related nitrous oxide emissions. Many technically feasible options exist, but adoption is uneven because returns depend on energy prices, capital turnover cycles, biosecurity requirements, and coordinated value-chain signals. Table 4.6.4 presents five priority pathways and identifies the barriers they seek to address. Finally, Table 4.6.5 includes a set of immediate priority actions that map back to this pathway logic.

Table 4.6.3. Key barriers (B), enablers (E), opportunities (O) and non-investment signals (N) for poultry, synthesised from previous sections, underpinning action areas in Table 4.6.4.

Item	Description
B1. Energy-intensive housing systems	Broiler and layer production relies heavily on ventilation, heating and cooling, making gas a dominant scope 1 emissions source. Volatile electricity prices may discourage capital-intensive investments in switching, without strong price or contract signals.
B2. Capital lock-in and long asset lifetimes	Poultry sheds and associated equipment have long depreciation periods. Retrofitting for electrification, automation or heat recovery can be disruptive and is often deferred to major rebuild cycles, slowing uptake despite technical feasibility.
B3. Thin operating margins	Margins are typically narrow, particularly for contract growers. Even cost-effective abatement options face high hurdle rates unless savings are immediate, costs are shared, or contracts explicitly recognise emissions performance.
B4. Limited MRV integration at shed level	While activity data (feed use, energy consumption, stocking rates) are routinely recorded, these are not consistently translated into low-cost, fit-for-purpose emissions metrics usable for incentives, procurement or finance.
B5. Biosecurity and operational risk aversion	High biosecurity requirements make growers cautious about changes to shed design, litter handling or management practices that could disrupt production or animal welfare.
E1. High degree of vertical integration	Poultry supply chains are more vertically integrated than most agricultural sub-sectors, enabling coordinated investment, data sharing, and contract-based cost and benefit allocation.
E2. Mature energy-efficient technologies	Energy-efficient ventilation, lighting, insulation, and climate-control technologies are commercially available and widely proven, offering immediate emissions and cost reductions.
E3. Concentrated point-source emissions	Emissions are spatially and operationally concentrated at sheds and processing nodes, making measurement, energy substitution and infrastructure upgrades more tractable than in diffuse systems.
O1. Electrification and renewable integration	Electrification of heating and cooling, combined with on-site renewables and storage, offers a clear pathway to reduce both scope 1 and scope 2 emissions while managing energy cost volatility.
O2. Litter and manure management innovation	Improved litter handling, reuse pathways and manure treatment can reduce N ₂ O emissions and create value through energy, fertiliser or soil-conditioner markets where logistics are viable.
O3. MRV as operational infrastructure	Integrating emissions metrics into existing production and assurance systems could enable low-cost MRV suitable for inseting, procurement and sustainability-linked finance.
N1. Technology-led retrofits without coordination	Isolated promotion of capital-intensive technologies without contract alignment or energy-system integration risks low uptake, stranded assets and grower resistance.

Table 4.6.4. Summary of pathways for poultry (with links to barriers etc from the previous table). Note: The order and numbering do not indicate level of importance or priority, but simply to allow cross-reference of ‘aligned action areas’ with best action in Table 4.6.5.

Action area	Problem / risk addressed (linked to Table 4.6.2)	Indicators of success	Indicators of failure	Prioritised actions aligned to horizons
1. Reduce energy intensity and exposure in poultry housing	Energy dependence and price volatility (B1), thin margins (B3) despite availability of mature technologies (E2, E3).	Measurable reductions in energy use per kg of product; reduced exposure to peak energy prices; improved operating margins.	Low uptake outside pilot projects; energy savings not captured by growers; continued exposure to price shocks.	H1: Accelerate uptake of energy-efficient ventilation, lighting and insulation through coordinated incentives (concessional finance) and MRV. H2: Shift from guidelines to industry standards to integrate electrification with on-site renewables and storage. H3: Normalise low-emissions shed design in new builds.
2. Align contracts and cost-sharing mechanisms	Capital lock-in (B2) and margin constraints (B3) limit investment despite integrator control (E1).	Contracts reflect emissions performance; shared investment in upgrades; higher adoption rates across grower base.	Grower resistance; fragmented uptake; investments delayed to asset replacement cycles.	H1: Pilot contract structures that share capital and energy risk/costs. H2: Standardise contract provisions recognising emissions performance. H3: Embed low-emissions expectations as business-as-usual.
3. Integrate low-cost MRV into operations	Limited usable emissions metrics (B4) despite rich operational data (E3)	MRV embedded in existing data systems; accepted by buyers and financiers; low transaction cost.	MRV is seen as a compliance burden. Poor data quality; low participation.	H1: Develop proportional shed-level emissions metrics. H2/H3: Embed MRV as shared infrastructure linked to insetting and sustainability-linked finance.
4. Improve litter and manure management pathways	Biosecurity and operational risk (B5) and logistics constraints limit uptake of manure options despite potential value (O2).	Reduced N ₂ O emissions; viable reuse or energy pathways; no compromise to animal welfare or biosecurity.	Operational disruptions; biosecurity incidents; uneconomic handling costs.	H1: Targeted trials in low-risk settings. H2/H3: Scale viable regional manure solutions, and integrate with broader circular-economy systems where viable.
5. Leverage integration for coordinated system change	Fragmented or technology-led interventions (N1) fail to exploit vertical integration (E1).	Coordinated, system-wide uptake; lower transaction costs; faster diffusion of proven options.	Patchy adoption; duplication of effort across firms; under-utilised infrastructure.	H1: Use the existing coordination power of integrated poultry supply chains to align energy, infrastructure, contracts, data (MRV), and investment decisions — instead of relying on piecemeal, farm-by-farm technology adoption. H2/H3: Roll out proven models across networks, and continuous system optimisation.

Best-bet actions for poultry (Table 4.6.5) are defined to strategically advance the sub-sector’s contribution to a low-emissions future. They combine a variety of mechanisms and functions for speeding up low-emissions transitions post-2030. It should be stressed that these priorities are additional to continuing improvements in emissions intensity driven by feed conversion efficiency, precision nutrition and genetics, that primarily target scope 3 emissions.

Table 4.6.5. Best-bet actions for reducing emissions in poultry. Note: The order of the best-bet actions in this table does not indicate their level of importance or priority. A low priority does not indicate that an action is not worth pursuing, just that it has low leverage for emissions reduction.

Best bet actions	Linked action areas	Rationale (why this action is needed)	Description of the action	Priority and rationale
Improve energy efficiency and electrification of farm operations	1, 5	Energy use dominates poultry emissions; efficiency and electrification deliver immediate, low-risk abatement.	Upgrade ventilation, lighting and heating; electrify where feasible; integrate renewables and storage through coordinated programs; develop proportional incentives (concessional loans) linked to abatement outcomes where appropriate.	High – largest abatement opportunity with strong co-benefits and technical readiness.
Build low-cost, fit-for-purpose MRV embedded in production systems	3	MRV is a precondition for incentives, finance and credible claims; poultry is well-placed to implement it efficiently.	Translate existing production and energy data into simple emissions metrics acceptable for inseting and reporting.	High – foundational system enabler.
Align contracts and incentives across vertically integrated supply chains	2, 5	Without cost-sharing and recognition of emissions performance, uptake will remain slow despite technical feasibility.	Pilot and extend contracts that share upgrade costs and reward emissions improvements.	High – addresses core economic barrier.
Targeted investment in litter and manure management where viable, especially via pilots, trials and partnerships at regional scales (e.g. regional bioenergy hubs)	4	Secondary but meaningful source of emissions with potential co-benefits if biosecurity risks are managed.	Demonstrate low-risk handling, reuse or energy recovery pathways suited to regional logistics; build business case for bioenergy at appropriate scale, and industry role in this.	Medium – context-dependent opportunity.
Strengthen coordination between energy, agriculture and finance programs	1, 5	Poultry abatement depends on alignment with broader energy transition and financing mechanisms.	Link on-farm upgrades to energy programs, concessional finance and sustainability-linked lending.	Medium – enabling but indirect abatement.

5 Overcoming barriers and supporting enablers to achieving low-emissions agriculture in Australia: cross-sector and -system priorities

5.1 Introduction

This chapter shifts away from the assessment of individual technologies within industries to cross-sectoral and system-level enablers for technology scaling and adoption. Firstly, it provides a high-level review of investment in enabling measures that are relevant to multiple technologies and industries. Secondly, it addresses three types of cross-cutting issues affecting emissions-reduction technology scaling and adoption in agriculture:

1. Common issues across production systems;
2. Inter-sectoral issues at the interface with energy, land, water and markets; and
3. Emerging issues linked to sector and economic structural, and technological, change

In addressing these issues, the analysis uses the framework outlined in Chapter 3 and draws on the sector assessments (Chapter 4), recent literature, and outputs of stakeholder workshops (Appendix D). These provide evidence of the state and barriers to technology scaling and widespread adoption of low-emissions technologies. The chapter concludes with suggested interventions to guide policy and investment, complementing the sector-specific pathways identified in Chapter 4. These are grouped under four practical areas (see Section 3.4.2) that recur across analyses in Chapter 4 (and align with a related recent report by Cowie et al., 2025), where action will be required to advance the transition to low-emissions agriculture:

- a) Technology and infrastructure;
- b) Markets and regulation;
- c) Coordination and innovation; and
- d) Capability and extension.

While these are useful separate categories of action, they should be addressed together to enable technology scaling and adoption, particularly when viewed across the time horizons in this report.

Although this report focuses on Scope 1 emissions reduction technologies, Scope 3 and supply-chain mechanisms are discussed in this chapter where they influence incentives, adoption, financing, procurement, market access or investment in technologies that can significantly influence Scope 1 emissions.

5.2 Current enabling investment beyond technologies and across sectors

While our sample data on investment in emissions reduction projects from RDCs and the ZNE-Ag CRC was limited, it highlights that projects go beyond investment in the technologies examined in Chapter 4. The sample contains a notable and potentially growing emphasis on RDC investment in “enabling technologies”. From the RDC project descriptions obtained, 34 RDC-funded projects (in the period FY22-24, see Section 3.6) were classified in this category. These projects were not aligned with any specific emissions reduction technology but instead focused on activities that underpin the scaling of a range of emissions reduction technologies. Four current projects funded through the ZNE-Ag CRC were similarly classified. These 38 projects, with a total value of just over \$33 million, contribute through a range of enabling mechanisms (Figure 5.2.1) relevant to most of the industries in this study, often developing outputs relevant to multiple industries, and occasionally across all of agriculture (Figure 5.2.2). Among these projects, work focusing on MRV, standards (and the R&D that supports them) was dominant. Much of this investment was driven by the larger commodity sectors, but smaller sectors may experience spill-in advantages from investments. For instance, investments often aim to contribute to common platform technologies like MRV systems or create precedents or practice examples for market mechanisms and insetting.

While these data are partial, they provide a clear indication that the emphasis on intermediating and demand functions, and especially mechanisms such as proportional MRV, is a key focus for RDC investment. That is, these findings suggest that the R&D system has diagnosed a similar set of consistent barriers and bottlenecks across the sectoral analyses.

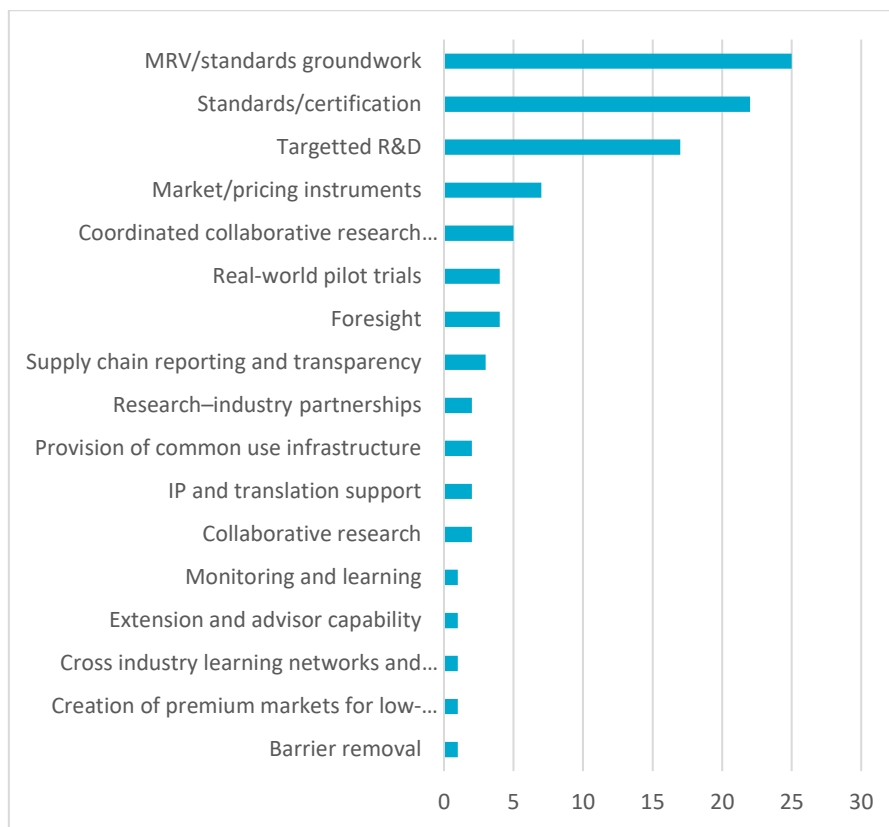


Figure 5.2-1. Alignment of mechanisms with 38 projects focused on ‘enabling technologies’. NB: projects could be classified with up to four associated enabling mechanisms each – the average was just under three (derived from RDC and CRC data described in Section 3.6.4).

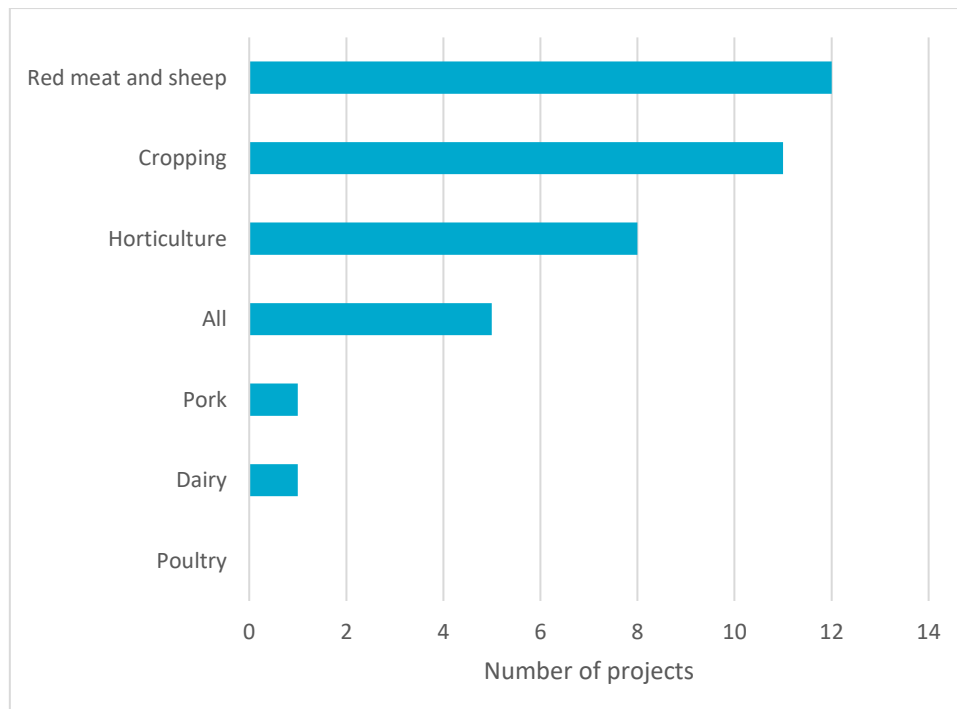


Figure 5.2-2. Alignment of the 38 projects focused on enabling technologies with industry sub-sectors (derived from RDC and CRC data described in Section 3.6.4)..

These findings suggest that the R&D system has diagnosed a similar set of consistent barriers and bottlenecks across the sectoral analyses.

5.3 Common themes across Australian agriculture

Thematic issues recur across red meat and wool, dairy, cropping, horticulture, pigs and poultry sub-sectors. These themes reflect persistent drivers of emissions reduction, constraints to it, as well as enablers. More specifically, they identify how technology, governance, markets and capability interact to influence both emissions intensity and total scope 1 emissions across industries.

5.3.1 Incremental and win-win options are near exhausted

Across sectors, the current suite of scaling-ready technologies tends to be incremental, efficiency-oriented actions that are understood and often widely adopted by producers (for example, minimum till in cropping, low-protein diets in piggeries, nitrogen optimisation and selective breeding in dairy). While there is some potential for these technologies to be further adopted and adapted to new settings, the areas where scaling ready technologies require further investment through R&D are limited, and include delivery mechanisms for anti-methanogens (e.g. 3NOP) or in refinement to applications for machinery usage and nitrogen application in different cropping and horticulture systems. Many of these applications are well supported within existing RDC programs.

5.3.2 Insufficient incentives to unlock significant existing emissions reduction potential from mature technologies.

Demand signals are weak for many technologies across sectors because the costs of adoption are currently high relative to expected returns. A variety of schemes could create incentives for adoption beyond the ROI of the technology itself or provide additional income relative to costs: consumer-facing emissions intensity claims, development of retailer/processor procurement rules, scope 3 reporting along supply chains, insetting, and concessional loans. However, these are generally considered insufficient to drive adoption of many technologies, and many require the additional costs to be absorbed somewhere in the supply chain. Participants in workshops highlighted constraints to engaging in these schemes that ranged from uncertainty arising from the proliferation of schemes, inconsistent eligibility rules and returns, and relatively high transaction costs of participation. These can create asymmetric risk (e.g. long obligations vs short-lived and uncertain benefits, or producers carrying the risk for market valorisation of products that meet downstream aggregator obligations). Workshop and interview discussions for this project suggested that such alignments between relative advantage and incentives, on one hand, and transaction costs and uncertainties of trialling and participation in specific schemes, on the other, are major constraints to scaling.

The result is that numerous scaling constrained technologies, with high abatement potential, remain stuck at the market introduction stage. ROI is weak at the farm-level, MRV is costly or technically challenging, and incentive schemes are unavailable, complex or hard to navigate. Key technology examples here include nitrification inhibitors and controlled release fertilisers in broadacre cropping; digesters/covered lagoons; anti-methanogenic feed additives for grazing herds.

Unlocking such technologies also rests on capability and commitments across industries, regions and supply chains (i.e. intermediating and demand side functions -- see Box 3.1 on incentives, Section 3.4.3). For example, advisory and learning systems could help to coordinate and define the priority “stacks” of technologies and practices that fit within regional and farm system context, reducing uncertainties about what works where. Similar high-level coordination among industries is increasingly recognised as essential. For example, governments and industry groups are exploring how standards and verification might enable market mechanisms outside formal carbon markets (e.g. VEERG [DCCEEW, 2026]). These could be extended to considering the efficacy and efficiency of different incentives, such as public procurement policies or voluntary guidelines to encourage private sector procurement that could, over time, become industry standards.

Larger entities are more likely to be able to navigate and capitalise on opportunities in emissions reduction. Some scaling constrained technologies, particularly high-upfront-cost equipment and infrastructure, have reasonable longer-term ROI. This can create (or reinforce) distributional patterns that become a system risk if left unaddressed – namely, that adoption and emissions reduction are patchy and unequal. Notwithstanding this, in most sectors, the bulk of production is delivered from a relatively small proportion of producers, and driving uptake in this cohort can significantly change the emissions profiles of production in that industry.

The patterns outlined above suggest that greater investment in demand-side and intermediating functions will be needed to unlock scaling constrained technologies.

5.3.3 A broader enabling environment is not yet in place

Across sectors, emissions outcomes depend on enabling infrastructure (both physical and knowledge infrastructure): farm-fit delivery systems, proportional MRV, credible data rules, and extension/supplier/service capacity. For example, in dairy and piggeries, delivery systems and approvals rather than biological efficacy often determine feasibility; covered lagoons depend on integrated solids handling and valorisation of energy offtake. Similarly, the complex approvals for waste-to-energy and biochar reflect the cross-government (e.g. state / local) processes required to unlock on-farm benefit. When coupled with thin supplier markets for capital-intensive systems, high transaction costs for farm-level verification, and schemes that are not interoperable, friction increases and scaling stalls.

Key enablers to address such compound challenges will always be highly context-specific, but common needs identified across sectors include intermediating functions that link research and practice. For instance, regionally grounded trials and/or modelling should translate research into farm-fit packages, in recognition of the distinct differences across regions in terms of the realistic application and stacking of technologies. Consolidation and coordination of emerging digital tools can help make emissions estimation part of normal business accounting and embed it in systems of use. Virtual farm networks could allow producers or their advisors to trial practice combinations in a virtual setting to explore emissions and production outcomes. Where dossiers of product efficacy and safety are required for regulatory approval (such as feed supplements), the availability of common testing facilities (chambers and measurement units) and testing protocols will expedite speed to market.

Beyond such technical resources, there is a long history of research that shows that adoption of technologies can be accelerated by approaches that fuse technical knowledge from researchers with practical and business knowledge from producers (Eastwood et al., 2017; Fliert, 2003; McCown et al., 2009; Nettle et al., 2022; Vanclay, 2004). Together, this locally relevant research and practice facilitated by strong working relationships between farm systems groups and state government agencies (including research farms), can define and address impediments to progress. Such efforts can and should be more systematically targeted to align with differing goals, but especially to build local evidence and capability around new sets of practices and technologies that can be stacked into existing farm systems and that link scientific analyses with local realities (Nettle et al., 2022). In Australia, such practice change will need to be scaled through private sector advisory services that consistently help producers to navigate claims, data, finance, and approvals associated with relevant technology stacks (Nettle et al., 2017). Extension that focuses on individual practices or narrow, productivity-only technological change will be misaligned with this complexity and the opportunities for on-farm emissions reduction.

An overarching capability model and knowledge infrastructure are likely to be integral to scaling emission reduction technology. This would likely rest on regionally embedded demonstrations through the network of research and demonstration farms linked to farm systems and other more applied regional trialling of technologies, underpinned by common data/analysis protocols that produce reusable evidence across seasons and geographies. This common infrastructure would support trusted advisers to integrate agronomy, emissions accounting and business case design for individual producers. Learning and improvement at the systems level and across regions are integral to a low-emissions future for agriculture. Ensuring this learning and practice change is well-connected and coordinated with policy at the state and federal levels will be necessary to accelerate and ensure equity of outcomes.

5.3.4 Sequencing of interventions matters

Across sectors, a consistent pattern is that technologies are constrained less by their technical characteristics than by the absence of enabling conditions, such as trusted and cost-effective MRV, advisory capability, integration within production systems, access to finance, demand-side incentives, and coordination across supply chains. These dependencies mean that the effectiveness of interventions is strongly influenced by their timing and order. In practice, outcomes will depend on the extent to which complementary conditions are established and aligned.

Appropriate sequencing is a practical requirement for success. In many cases, early action is most effective when focused on building capability, evidence, confidence and enabling infrastructure, long before attempting rapid scale-up. This reflects the need to reduce uncertainty and establish credible information flows and decision frameworks that can support later adoption. Premature engagement or deployment of incentives, mandates, or market mechanisms—before other conditions are in place—risks low uptake, weak integrity, and erosion of trust.

This pattern is evident across sectors. For example, in cropping systems, investment in capability, evidence and MRV underpins the later viability of scaling more complex or constrained technologies. In grazing systems, addressing delivery mechanisms and MRV will underpin

rationales for wider adoption of anti-methanogenic additives. In horticulture, early efforts to reduce transaction costs and complexity are necessary before wider adoption can occur.

Across these examples, constraints arise primarily at the interfaces between system components, such as between measurement and decision-making, or between technology availability and its integration into production systems rather than within individual components themselves. As a result, sequencing is not only a matter of putting enabling elements in place, but of ensuring they are connected in ways that support practical use. This includes the role of advisory systems and other intermediaries in translating evidence and capability into operational decisions, particularly where technologies introduce new forms of complexity or risk.

Taken together, these observations suggest that sequencing is closely linked to how uncertainty is reduced over time. Early-stage investments in MRV, evidence and capability shape the conditions under which later-stage interventions, such as incentives or market mechanisms, are interpreted and enacted. Where this progression is incomplete or uneven, later interventions are less likely to achieve their intended effect.

For this reason, the report considers actions across different time horizons, recognising that appropriate sequencing reduces the risk that constraints in the enabling environment limit the scaling of otherwise feasible technologies.

5.3.5 Key findings

- While new technologies with high efficiency and positive return on investment could be game-changing if discovered, many existing technologies are in a scaling-constrained bottleneck. Continuing to develop potential win-win technologies that are not yet mature, in anticipation of future market pressures, may provide some long-term optionality. However, a stronger focus on demand-side activation and coordination is required to scale most technologies. This includes targeted intervention to build monitoring, reporting and verification systems, standards, and regional (e.g. advisory system) capability to enable uptake and change.
- In particular, without interoperable, proportional and stack-aware MRV, incentives and claims cannot work at scale, either under policy, regulatory or market-based drivers of adoption and scaling, making proportional MRV a critical transition infrastructure for Australian agriculture (see Section 5.6.1).
- Learning systems and advisory capacity are decisive. Success will depend on linking scales and networks-- policy, on-farm, business and technical knowledge. In many cases, this will require context and place-based work to assess the feasibility of technologies.
- The sequence of interventions within and across industries is critically important to outcomes and will require ongoing consideration, planning and coordination to avoid pitfalls.

5.4 Inter-sectoral themes (interfaces across agricultural sub-sectors, with energy, supply chains, finance, environment)

5.4.1 Farm management often relies on integrated systems, capability and infrastructure across sub-sectors

Most Australian farms, especially mixed enterprises, will need to assess emissions actions across multiple parts of the business while also managing financial, market and risk considerations. This is currently constrained by a fragmented advisory system, and siloed sector-focussed information systems, which tends to leave producers to integrate agronomic, financial, market and emissions advice themselves.

Widespread uptake of many emissions reduction technologies (beyond win-win options) will ultimately require emissions management to become a core element of farm business decision-making, and for this to be supported by regional capability that links to national MRV systems, standards, and market and regulatory mechanisms.

At present, investment in capability building, coordination across supply chains and provision of enabling infrastructure appears to be low compared with research and development investment in technology. This potentially limits uptake of the very technologies being researched, especially in the complex farming systems that dominate Australian agriculture. Diverse and coordinated investment will be needed to support capability and coordination. We already see research playing a major role in coordination, beyond technological development (see Section 5.2). Further investment is likely to be needed to increase the area of application for some existing technologies. Key examples include developing more viable delivery mechanisms for anti-methanogenic feed supplements so that they can be applied into extensive grazing systems (as is currently being addressed by the Australian Government's MERiL program), and stacking precision nitrogen, nitrification inhibitors, legume integration and other aspects of cropping nutrition in cropping and horticulture industries.

5.4.2 Specific industries are well suited to develop technology suites that can benefit other industries; this will rely on cross-industry coordination mechanisms

Horticulture's strong focus on combined GHG, energy and labour efficiency through electrification, robotisation and automation, often in quite complex settings, provides a potential foundation for technology development and applications which are likely to have spill-in benefit for other industries. Similarly, and perhaps reciprocally, refining and targeting application of enhanced efficiency fertilisers (nitrification inhibitors, controlled release fertilisers) in cropping could create spill-in benefits for horticulture and intensive grazing and dairy. Meanwhile, confined beef and dairy cattle share many feed supplement emissions reduction technologies, and extensive grazing from sheep and beef will share common issues with delivery of feed additives. These sorts of shared and reciprocal medium- to long-term benefits could usefully be mapped and enhanced through cross-RDC or other coordination approaches to ensure RD&I can create international competitive advantage in low-emissions agriculture for the whole agrifood sector.

5.4.3 Agriculture—energy coupling determines feasibility of several high-leverage options

Many options that span sectoral boundaries, especially between agriculture and energy, were identified that have potential importance across emissions reduction, managing sovereign risk and supply chain/food security, and building regionally diversified and robust economic bases. These are largely high-upfront cost infrastructure investments, and commonly require cross-sectoral, cross-portfolio, and sometimes cross-jurisdictional integration and coordination. Digesters and covered lagoons in piggeries and dairies, electrification of on-farm processes and machinery, and bioenergy hubs depend on feed-in tariffs, export rules, grid configurations and access, and planning compliance, safety/approvals. Where these do not align, viable projects fail to reach final investment decision; where they do, economics improve, and adoption rises. Increasingly, the effective costing of long-term risk associated with global supply-chain disruptions for fuel and food are being acknowledged, creating opportunities for biofuel developments in Australia. This is a shared challenge across industries, currently constrained by weak coordination. Progress depends on improved coordination, streamlining regulatory processes, aligning rules across jurisdictions, enhancing public and private sector investment, and improving how lessons are carried from one project to the next, and across regionally focused efforts.

5.4.4 Supply chains can drive action, but without clear protocols for reporting and guardrails to ensure good behaviour, they can also externalise costs and drive inequitable outcomes

Processors, retailers, and financiers increasingly set rules for accountability via procurement, insetting and disclosure that bind producers and other supply-chain actors. In some cases, they are responding to international market signals and trade requirements. These mechanisms can share costs and generate demand pull, but inconsistent data and accounting rules or unclear baselines can make claims non-portable and raise compliance costs. Model supply-shed agreements with agreed baselines, attribution and assurance can reduce burden and increase credibility.

In general, where public coordination or reporting rules lag, private standards and finance will decide who participates, on what terms, and with what burden. There are positive existing efforts to avoid this. For instance, farm-level data is not currently required to inform Scope 3 estimates of larger entities that need to report these emissions under the Australian Sustainability reporting Standards on Climate Related Disclosures. The Australian Government is developing Voluntary Emissions Estimation and Reporting Guidelines (VEERG) for agriculture, fisheries and forestry to provide clarity about how to estimate on-farm emissions (DCCEEW, 2026). Such public frameworks can reduce duplication, lower cost, and sustain social licence for long-term low-emissions transitions.

5.4.5 Intersections with biodiversity and ecosystem markets introduce stacking opportunities, but with additional accounting challenges

There is increasing interest in the co-benefits of abatement, ranging from social, cultural and nature-positive outcomes to reduced nutrient run-off and downstream impacts. Combining

emissions outcomes with nutrient circularity, compost markets, biodiversity benefits and other co-benefits can improve ROI and regional acceptance, but doing so is complicated by complex operating conditions and regimes. Rules for stacking across heterogeneous methods (e.g. ACCU Scheme and Nature Repair Market²) aim to avoid double-counting concerns while encouraging legitimate participation. Trialling and piloting these interactions across these and other schemes at scale (an intermediating function) could build confidence and subsequent demand and is currently being attempted at small scales, with potential to expand.

There is value in regionally based coordination capacity that can support stacking benefits and developing common visions. Examples of such work include the Reef Credit Scheme and Queensland's Land Restoration Fund, which create real incentives for adoption of practices with multiple outcomes. Other examples, which stack different social, cultural and other benefits, are starting to emerge, providing important foundations for cross-regional policy learning and improvement. The lessons of these approaches, which primarily focus on sequestration, will be important for emissions reduction.

5.4.6 Key findings

- Policy decisions at different scales/jurisdictions can create or remove the business case for emissions-reducing infrastructure investment, such as electrification or biogas energy generation. Rules, approvals and tariff/export settings, planning processes and capex support, such as concessional loans, set investment environments.
- Without public guardrails on how supply-chain incentives and markets evolve and efforts to standardise/harmonise MRV across markets, there is less certainty that risks, costs and benefits will be fairly shared across value chains, and risk that claims will not be portable across schemes.
- Clear, stack-aware accounting across outcomes (e.g. co-benefits for water/ reef from greater nitrogen use efficiency) can unlock integrated regional solutions into the future, and enable scaling across stacks of technologies to materially shift on-farm emissions.
- There are significant opportunities for policy learning across scales through regional pilots that address multiple goals and are driven and sponsored by local businesses and champions.

² The Nature Repair Market is specifically designed as a voluntary biodiversity market that aligns with the ACCU scheme, with both schemes administered by the Clean Energy Regulator. Under the first Nature Repair Market method, proponents can design projects on the same area of land as an ACCU project. If they do this, the proponent may be eligible for both a Nature Repair Market biodiversity certificate and ACCUs.

5.5 Emerging issues (structural and wide-scale shifts that will shape the next decade)

Across diverse drivers of agricultural emissions reduction, and their interactions, a variety of issues emerge from system interactions and become integral to the success of transitions.

5.5.1 New value chains are reshaping comparative advantage, rotations, and regions, creating new risks and opportunities

The impacts of value chain reshaping will likely occur at two levels.

The first stems from general land-use allocation decisions associated with shifting priorities. International volatility makes the prediction of agricultural opportunities and stresses particularly difficult, but points to a growing need to manage food, energy, and fertiliser security as sovereign risks. Related policy and industry momentum around low-carbon liquid fuels and biomethane are likely to shift cropping rotations and nutrient regimes; without full system consideration of changes, unintended outcomes, for example, “N₂O rebound”, present real risks. In this case, increasing demand for biofuel feedstocks drives higher fertiliser use, leading to greater scope 1 and 3 emissions, to some degree offsetting emissions reductions in order to create fuel security.

The second is the way that adjacent sector innovation will shape options in Agriculture. For example, electric and low-emissions machinery spill-ins from mining/transport will arrive asynchronously by region and farm scale. Early adopters and beneficiaries are likely to be large, capital-rich enterprises. Stacking such technologies with automation, AI and data intensification of farming has the potential to lead to transformation of rural Australia in coming decades, in ways that recent analysis suggests could be alienating, compounding and irreversible (Roche et al., 2025).

Both these forms of emerging interactions could intersect and support enterprises to engage early in emissions reduction technologies and capture market opportunities, but outcomes are uncertain and require observation and response should perverse outcomes unfold.

5.5.2 Differing pathways highlight key system stressors: from agroecological to precision fermentation

There will be multiple pathways to reduce emissions, but the pathways can have important implications for the role of agriculture in the economy and society.

In part, to manage the risks and strains of high-input agriculture, some Australian producers are exploring less intensive practices and working with and encouraging soil biology to improve carbon and nutrient cycling. Ideas from agroecology internationally and regenerative agriculture in Australia may reduce overall production but lead to lower emissions agriculture, through advances in the use of biostimulants, minimum tillage, control traffic and precision applications of agrichemicals and wider integrated land management.

Meanwhile, novel forms of protein and synthetic meat could substantially disrupt the largest agricultural emitting sectors (red meat and dairy) if they can scale over the next decade. These would not only require significant technological advances, but changes in consumer preferences and management of resistance to change that is already evident from incumbent protein

industries and the communities that rely on them economically and have deep social and cultural links to their history and continuity.

Both these pathways, in very different ways, reflect potential shifts in agricultural and societal choices. They are often coupled with arguments that these options reduce pressure on natural resources and boost carbon and biodiversity in the landscape (i.e. land sparing), sometimes associated with novel revenue streams for farm businesses and land management. While evidence around such claims remains inconclusive for both regenerative agriculture (e.g. Berthon et al., 2025) and novel proteins (e.g. Kaur et al., 2025), there remain many avenues to advance.

A relevant question is how Australia's research funding prioritises these pathways. With RDC revenue strongly linked to export volume or value, the principal funding sources will deprioritise emissions pathways that reduce overall production levels, and especially those that create novel industries which could displace existing ones. This question about the value and importance of incumbent industries and modes of operation goes well beyond the scope of this report but will be integral to the long-term capacity to transition agriculture to a low-emissions future.

5.5.3 Key findings

- New value chains driven by pressing national needs (e.g. sovereign risk) can create tension with goals around farm-level emissions without system-level evaluation.
- Access to opportunities driven by infrastructure availability or enterprise ability to absorb new technologies can create inequalities around adoption of emerging low-emissions technologies.
- How we discuss, explore, and ultimately advance novel, and potentially disruptive, pathways to a low-emissions agriculture future needs careful consideration

5.6 Actions, intervention and investment

This section groups 12 actions under four practical levers. For each lever, the rationale is drawn from Sections 5.2–5.5. Actions are set out across time horizons to build towards a low-emissions agriculture system aligned with the Agriculture and Land Sector Plan.

The focus is on what action is needed, why it is justified, and how it addresses identified system failures, what related activity is already underway, how the suggested actions add value, and how contributions could be aligned across government, industry/RDCs, and research and development.

As in many large, complex and interconnected systems, many actions are to address questions and challenges that have been surfaced in this report and define ways forward through collective action within or beyond agriculture.

5.6.1 Technology and infrastructure

1) Support the consolidation of a national “MRV spine” as enabling infrastructure

Costs, simplicity and practicality of demonstrating outcomes of technology adoption and practice change are key constraints. The ongoing, coordinated development of an MRV spine is needed to build a cohesive backbone that makes a fragmented ecosystem (calculators, tools, supply-chain data requests, ACCU methods, private insetting, procurement rules) operate more coherently, and

builds confidence by ensuring that claims made in one context are trusted in another (see Section 1.4). This MRV spine would act as enabling infrastructure in that it supports learning, incentives, markets, finance, procurement and accountability systems to catalyse emissions reduction.

An interoperable, stack-aware MRV spine would reduce cost, enable portability of claims, and turn multiple small, inconsistent requests into a single coherent data workflow. This directly unlocks opportunities and options where ROI depends on verified outcomes, and it reduces duplications and inefficiency that producers currently face. This critical infrastructure requires public sector leadership, supported by industry coherence.

The direction of development could be accelerated by government-backed market opportunities that support the development of enabling data infrastructure. This, in turn, should drive assessment consistent with market or payment requirements, balancing integrity and operational feasibility when setting standards (ANAO, 2024), harmonising downstream market/consumer systems with on-farm measurement feasibility and cost, and funding research on interactions between actions to enable stacking and appropriate crediting.

What's already happening in Australia? DCCEEW is developing voluntary estimation and reporting guidelines for agriculture, fisheries and forestry with a Common Requirements Framework and Methodological Guidance through the VEERG (DCCEEW, 2026), which includes activities under the ZNE-Ag CRC; open source code and an API aligned with the Guidelines is being provided for free by Agriculture Innovation Australia with grant funding from the Australian Government; various programs are trialling lower-cost MRV (soil sensing, MRV-Plus); the GRDC funded LEIFS program is looking at approaches to assessing regional benchmarks; the AASF is creating a national sustainability narrative that links to sector initiatives with market and ESG expectations.

How does this action add value? It connects currently separate pieces—voluntary standards, calculator engines, jurisdictional pilots and national frameworks—into an interoperable, stack-aware MRV spine with shared schemas, assurance tiers and APIs, which lowers transaction costs and enables claim portability across schemes and applications where this is possible. This would support staged participation ranging from on-farm learning and benchmarking to engaging in inseting, finance and procurement markets, to implementation of methods under SBTi and ACCU Schemes, for example.

Who could contribute? Recognising the complexity and importance of this activity area, contributions are usefully mapped under different objectives. Below, the first entity is suggested as the 'lead' with others contributing, and priority actions are provided as indicative, concrete options.

Objective A: Reusable emissions data across uses

Ensure farm data can be captured once and reused (with permissions) across advisory services, processor reporting, finance and incentive schemes via common definitions and calculation cores.

Priority actions

- Government/ Industry: Require VEERG-aligned conformance statements for major calculators and tools, so outputs clearly declare method version, boundaries and emission-factor sets, enabling safe reuse across advisory, supply-chain and finance contexts.

- Industry: Expand use of shared calculation cores, allowing multiple tools and service providers to draw on common logic and datasets while retaining different user interfaces and service models.

Objective B: Coherent scaling across tiers and levels

Support a method ladder where improved Tier 2 EFs and proxies and Tier 3 derived surrogates allow consistent movement from paddock to national reporting, with agreed averaging windows for episodic processes such as N₂O.

Priority actions

- Government/Research/ Industry: Document and stabilise a national method ladder specifying when proxies and surrogates are acceptable at farm scale, and how results roll up to regional and national views without breaking NGGI alignment.
- Research/Industry/Government: Embed agreed temporal averaging rules (e.g. rolling means for N₂O and soil carbon) within shared calculation cores and guidance.

Objective C: Stack-aware accounting rules

Formalise rules for interaction effects across industries and technologies, including substitution and non-additivity, so mixed systems are neither penalised nor over-credited.

Priority actions

- Government/Research/Industry: Establish conservative national default rules for stacking and interaction effects, applied consistently across tools to prevent double-counting and unintended penalties.
- Research/Industry: Progressively refine these defaults using validated system-level evidence from ZNE-Ag CRC and LEIFS as confidence improves.

Objective D: Proportional verification pathways

Enable broad and equitable participation through conservative, audit-lite assurance³ for most uses, with higher-rigour pathways where claims, payments or regulation require it.

Priority actions

- Research/Government: Explicitly map use cases to assurance tiers (e.g. advisory, benchmarking, supply-chain reporting, finance, regulated crediting), clarifying minimum evidence requirements for each.
- Government/Research/Industry: Align verification burden with consequence, preserving integrity while avoiding unnecessary barriers to participation, particularly for smaller enterprises.

Objective E: Governed updates and transparency

Manage method and factor updates (e.g. NGGI revisions) transparently so comparability is preserved and historical claims are not destabilised.

³ Audit-lite refers to VEERG-aligned conservative estimation using documented assumptions, transparency, version disclosure and reviewability, but without independent third-party assurance unless financial or regulatory claims are attached.

Priority actions

- Government: Use the VEERG governance (DCCEEW, 2026) or similar as the standing advisory forum to signal, sequence and document updates across methods, factors and calculators.
- Government: Adopt explicit versioning and transition conventions, including disclosure of method versions in outputs and non-retrospective treatment for advisory and learning uses.

Horizon logic and sequencing.

- H1 (2025–30): publish MRV spine v1.0 (interfaces, assurance tiers); embed standards in priority calculators; pilot stack-aware programs such as LEIFS in 3–4 key regions to build proportional MRV aligned with context-appropriate technologies and incentive pathways.
- H2 (2030–35): scale calculator interoperability, reduce verification burden via agreed proxies, and link to procurement/insetting claim formats.
- H3 (2035+): consolidate nationwide portability across market and supply-chain schemes, enabling low-cost outcome-linked finance and insurer products.

2) Develop guidelines about the readiness and contexts of applicability and adoptability of technology stacks

To support producers and advisors, clear best practice guides should be developed and regularly updated for the incorporation of low-emissions technology stacks, with guidance on related ACCU Scheme, SBTi and other pathways to valorise action. These should aim to decrease the risks of implementation through clear, regularly updated information and build awareness of synergistic benefits and trade-offs. Guidelines should recognise and support integrated or stacked technology assessment at the business level (for example, solids separation plus covered lagoon plus compost with nutrient QA; or delivery devices plus herd-level MRV for additives), reducing approval friction and engineering risk, crowding-in suppliers, and improving long-run performance and safety.

What's already happening in Australia? VEERG is providing consistent accounting logic (DCCEEW, 2026); AIA's EAP will enable tools aligned with VEERG via API and code (AIA, 2026). DAFF's Carbon Farming Outreach Program aims to equip farmers and trusted advisers with the knowledge and skills to integrate emissions management and carbon storage into farm decision-making. Central to this is the development of an online knowledge hub and a train-the-trainer program that helps trusted advisers to provide producers with information that is consistent and tailored to different production systems and contexts. GRDC/CSIRO have enterprise-footprint guidance suitable as templates for stacked interventions. Through the Decarbonisation Innovation Hub's Land and Primary Industries Network, NSW Government is doing substantial work to implement actionable pathways for farmers and land managers to reduce greenhouse gas emissions while boosting productivity.

How does this action add value? It moves from single-measure factsheets to stack-aware playbooks that specify sequencing, compatibility, MRV implications and TRL/CRL by context, linking directly to calculators and market rules via the MRV spine.

Who could contribute?

Industry /RDCs: Lead, and own guides at industry level

Government: Commission cross-commodity stack guides via RDCs;

Research and Development: curate evidence and update cycles; ensure alignment with accounting standards and voluntary reporting

Horizon logic and sequencing.

- H1: publish first three stack guides (dairy manure; grazing enteric methane; cropping nitrogen/EEFs) and embed into outreach (e.g. CFOP) training within target geographical areas reflecting the regional applicability/fit of different technology stacks.
- H2: expand to mixed-enterprise stacks; codify default sequencing and performance ranges; align with procurement/insetting templates.
- H3: maintain a living catalogue of stacks and business archetypes with outcomes data.

3) Target thin markets with first-of-kind support, through targeted finance, public investment and/or concessional loans, and supplier accreditation

Where supplier and service markets are thin (i.e. poorly developed due to low supply/demand), early input development projects carry execution risk premiums that stall diffusion. Time-bound concessional finance can address capital constraints without picking winners, justified by positive externalities of early learning. Accreditation of suppliers can build trust in products and services for early adopters.

What's already happening in Australia? Australian Government funding established the *Asparagopsis* National Hatchery Network and sector RD&E (ASSA/FRDC; JCU & SARDI); CEFC co-finance with banks (e.g., NAB Emissions Reduction Incentive; Rabobank environmental plantings) lowers capital costs for emissions-reducing investments. There is some evidence that large downstream agribusiness is looking to create similar incentives to support their scope 3 emission reduction goals (e.g. the Cargill SustainConnect program).

How does this action add value? It generalises beyond a single input to a portfolio approach for thin markets (e.g., additive delivery systems, integrated manure packages, compost QA), pairing supplier accreditation with first-of-a-kind guarantees and time-bound concessional finance to accelerate supplier entry and reduce execution risk.

Who could contribute?

Industry / RDCs: Lead. Validate performance specs and co-fund demos; lenders/insurers offer discounted products and performance guarantees tied to MRV; agribusiness defines supply-chain insetting pathways. Develop standards and processes for industry accreditation of suppliers where appropriate.

Government: identify gaps and run first-of-a-kind/accreditation rounds; support agribusiness initiatives with guidelines/standards to ensure equitable distribution of costs and benefits.

Horizon logic and sequencing.

- H1: map thin markets; launch two first-of-a-kind/accreditation rounds (probably additive delivery; manure-to-energy packages).
- H2: scale accredited supplier base; standardise warranties and service models.
- H3: mature competitive markets; taper concessionality as costs fall (Energy.gov.au 2025; DAFF 2025).

5.6.2 Coordination and innovation

4) Invest in coordination for energy–agriculture transitions through regional infrastructure, and alignment of rules with mechanisms to advance outcomes

The viability of bioenergy, electrification and manure-to-energy projects depends on rules such as energy tariffs, grid access and export rules, which sit largely outside the agriculture portfolio. These issues are becoming more pressing given global instability and the need for energy security. Viewing this as a cross-portfolio (within government) and cross-jurisdictional (Federal-State) connected task may assist in addressing current coordination gaps, reducing the risk of stranded assets and strengthening business cases. Multiple goals, beyond emissions reduction, need to be considered together. For example, the following ag-energy interventions align across our analysis, CEFC roadmap priorities, and the AgriFutures Roadmap for Alternative Energy in Agriculture. These are plausible action areas that need to be confirmed through focused, consultative roadmapping. Plausible actions include:

- Identify 3–5 priority place-based / regional ag-energy clusters drawing on the AgriFutures Australia Roadmap, and publish clear connection, tariff and participation guidance to enable early adoption and learning. These pilots would enable producers to trial low-emissions energy options—such as electrified machinery, alternative fuels, on-farm renewables, biofuel hubs and locally optimised grid configurations—under real operating conditions. By being regionally focused, they build local skills and capability, create mutual benefits across energy and farming systems, and ensure solutions are shaped by local infrastructure, workforce capacity and enterprise mix.
- Support access to renewable diesel that can be used in existing machinery without engine modification, leveraging national fuel initiatives (e.g. Cleaner Fuels Program) to build supply and uptake. This provides immediate exposure to lower-emissions fuels while reducing vulnerability to global diesel supply shocks and price volatility, offering both emissions and risk management benefits to farm businesses.
- Reform electricity distribution and connection rules to enable local generation and use of biogas from anaerobic digestion, particularly in intensive systems. This allows producers to convert waste into energy, reduce emissions, improve nutrient management, and create new income or cost-saving opportunities. Such regulatory reform would harmonise standards across jurisdictions and give producers confidence to invest without fear of being constrained by grid limitations.
- Trial fringe-of-grid energy distribution and storage solutions at freight hubs, processing centres and regional aggregation points. This improves resilience of agricultural supply chains, supports electrification of logistics and processing, and reduces the vulnerability of remote producers to grid constraints. These trials should be coordinated with existing state and utility-led microgrid projects and national grid upgrade initiatives to ensure lessons are shared and regulatory insights are fed into broader network planning.

While these interventions recur across multiple sectors and therefore form the core of a coordinated national strategy, our engagement and sectoral analysis also identified a small number of place-based opportunities where infrastructure, aggregation and circular-economy

approaches could accelerate emissions reduction while delivering broader energy, waste and resilience benefits. These opportunities are particularly relevant to intensive livestock industries in localities where sufficient scale exists to support shared investment and operating models. Plausible actions include.

- Support place-based pilot and demonstration programs for circular waste-to-energy systems, particularly where piggeries, dairies, feedlots, food-processing facilities and other organic waste streams can be aggregated to improve project scale, economics and learning.
- Develop and test integrated anaerobic digestion and covered anaerobic lagoon (CAL) models that combine emissions reduction, renewable energy generation, nutrient recovery and waste management outcomes, with a focus on identifying replicable business models and delivery pathways.
- Invest in common-user measurement, reporting and verification approaches for biogas and circular-economy systems, reducing transaction costs and improving confidence for producers, investors, energy providers and supply-chain participants.
- Enable aggregation, clustering and coordination mechanisms that allow multiple enterprises to participate in bioenergy, nutrient-recovery and circular-economy projects, recognising that many individual enterprises may be below economically viable scale when assessed in isolation.
- Use regional pilots to identify regulatory, grid-connection, planning and operational barriers, creating evidence to inform future scaling of biogas, renewable energy integration and circular nutrient-management systems across intensive agricultural industries.

What's already happening in Australia? ARENA's Bioenergy Roadmap and project portfolio provide direction; biomethane grid injection (Malabar) demonstrates regulatory interfaces; CEFC programs and finance support on-farm energy upgrades; AgriFutures Australia commissioned the *Australian Agriculture, Fisheries and Forestry Sector Energy Transition Roadmap 2026–2035* and published *The Diesel Transition*. Significant investment has also occurred through State Government programs supporting on-farm energy audits, grants, rebates and concessional loans (NSW, VIC, QLD, SA, TAS, ACT and NT), while the Commonwealth's Rewiring the Nation initiative and the \$1.1 billion Cleaner Fuels Program modernise regional grids and support advanced biofuels.

How does this action add value? It targets the institutional gaps between agriculture and energy – focusing on challenges that state programs alone cannot resolve. Rather than duplicating the on-ground incentives already offered by states and territories (audits, grants, loans), the above actions centre on harmonising tariffs, connection standards and export rules across jurisdictions and portfolios, and on coordinating regional solutions so that local farm energy projects can proceed at scale without stranded-asset risk. They address structural barriers, which include cross-border regulatory mismatches and a lack of integrated planning, creating a broader systemic change that will support State action. They embed agriculture's needs into energy market settings and infrastructure planning, maintaining food security and managing sovereign risk while the energy transition accelerates.

Who could contribute?

Government: task a cross-portfolio energy–ag transitions group; align and co-fund clustered connection solutions with State programs; streamline approvals across regulators; lead governance.

Industry /RDC: cross-industry engagement with regional initiatives and State/national governance; resource sectoral and cross-sectoral innovation and aggregation of demand (e.g. equipment, fuel) to drive down costs.

Research and Development: Monitoring and evaluation to support cross-scale (regional/state/national) learning, continuous improvement and scaling; address specific technical questions (e.g. grid integration, fuel quality) as the transition scales.

Horizon logic and sequencing.

H1: Examine the adequacy of existing cross portfolio coordination on energy and agriculture, and create mechanisms where necessary; identify 3–5 priority regional ag-energy clusters (drawing on AgriFutures Roadmap); publish baseline participation, connection and governance standards; and seed initial pilot projects (in partnership with existing state programs) to build proof-of-concept and engagement.

H1/H2: Scale proven approaches beyond place-based pilots by delivering shared infrastructure (e.g. biomethane upgrading, microgrids), aligning regulation, energy tariffs and market settings, and embedding coordination into mainstream programs and investment frameworks.

H3: Lock in mature systems through enduring standards, stable market signals and integrated governance, with agricultural bioenergy providing grid services and widespread electrification operating as part of the core energy system.

5) Build learning loops as program infrastructure via existing regional demonstrations

Linking regionally embedded demonstrations with common protocols for collecting evidence can convert local trials into portable evidence for policy, guidelines, standards and market rules. For example, regional demonstrators of agrivoltaics can yield state and national insights only if they have comparable monitoring and evaluation data. Existing demonstrators operating as hub-and-spoke models centred on state-owned research farms (see action #7) thereby become the foundation of learning infrastructure, rather than isolated projects. This applies across many different forms of transition intervention and is an area where agricultural transitions, because of their significant complexity, can benefit substantially. Supporting ongoing connectivity and data collection among pilots and demonstrators would systematically reduce uncertainty and accelerate adoption, trialling and improvement of technologies and practices within and across farming systems and regions.

What's already happening in Australia? GRDC's Low Emissions Intensity Farming Systems (LEIFS) Program is building regional demonstrators, modelling capability and action learning with states; DAFF's Carbon Farming Outreach Program expansion and knowledge hub can host and support information delivery and learning; ZNE-Ag CRC producer demonstration network is trialling different abatement options with producers; NSW DPI operates integrated low-emissions RD&E across regions, and there are similar initiatives in other states. Other state-based farming systems, NRM, Drought Hub and sectoral examples of demonstrators with some emissions reduction focus

are numerous. Connections through to state and national policy processes often appear to be informal.

How does this action add value? This intervention would create comparable datasets and feedback loops into MRV standards, stack guides, and program and policy design, making local trial data and lessons portable and decision-relevant at different scales.

Who could contribute?

Government / Industry and RDCs: Co-lead. Develop and fund the national networking of existing regional demonstrators and resource data integration and evaluation, building from existing projects and programs, with a long-term (e.g. to 2040) ambition.

Research: provide design and meta-analysis to support implementation and analysis to inform regular formative evaluation of the wider extension/advisory system and enabling environment

Horizon logic and sequencing.

- H1: develop shared data protocols and open dashboards or other tools that can support regional demonstrators across agroecological zones – starting with 4-6 zone, and building from existing LEIFS program and state-owned farm network.
- H2: expand coverage and embed dashboards in well-specified policy/ planning processes
- H3: maintain the network as national infrastructure informing policy, standards and financing of transition.

5.6.3 Markets and regulation

6) Explore and extend incentives and supporting resources such as procurement, concessional loans, and insetting templates

Time-bound incentives via innovation niches (see Box 3.1) will be critical to scaling many technologies and require careful design to ensure benefit sharing across supply chains and optimisation for participation, legitimacy and credibility, especially in early phases. The design of incentives should enhance the adoptability of technologies in general (rather than target specific technologies), thereby reducing GHG emissions efficiently. For instance, model insetting agreements can create demand pull without prescribing technologies and, in doing so, unlock on-farm innovation to create new options, while concessional loans can support scaling on well-understood infrastructure and high-upfront cost technologies. Outcome-linked finance can preserve technology neutrality and reward measured performance under MRV, creating scaling pathways by improving effective ROI while avoiding lock-in risk to an initial set of technologies (CCA, 2023). Setting industry benchmarks to support industry procurement can also foster innovation and healthy competition in markets. All these incentives rely on market or compliance appropriate levels of MRV and move beyond using a single instrument (e.g. ACCUs) to drive change. This can create high transaction costs but also provide multiple entry points and pathways for innovation, adoption and scaling.

What's already happening in Australia? CEFC–NAB discounted finance reduces borrowing costs for emissions-reducing investments; CPR updates enable environmental criteria in Commonwealth procurement; sector plans set expectations for low-emissions commodities; some supply-chain

aggregators like Cargill SustainConnect™ are providing financial incentives for low-emissions produce.

How does this action add value? It operationalises demand by standardising inseting templates and embedding emissions-intensity criteria in public procurement, aligned to MRV-ready claim formats—linking financing, purchasing and on-farm MRV. It builds on and embeds pilots through Outcome-Linked Grants/Loans where rebates or interest reductions are triggered by measured intensity improvements or verified abatement using MRV spine outputs—strengthening incentives without prescribing technologies

Who could contribute?

Government: issue guidance and provide model agreements or guidelines/ standards underpinning them for inseting, procurement, and other instruments;

Finance/Banks: expand concessional products, potentially to drive low-emissions products into supply chains either by supporting the adoption of products at the farm-level or injecting support into supply chains.

Processors/Retailers: pilot and extend inseting using MRV outputs.

Horizon logic and sequencing.

- H1: publish model inseting templates and CPR guidance for food retail/catering; scale out existing and pilot novel outcome-linked finance options.
- H1/H2: scale private inseting through preferred-supplier programs, and outcome-linked products; align with ACCU/IFLM where relevant. Integrate finance with inseting/procurement where appropriate.
- H3: mainstream intensity-based procurement and verified claims portability. Mainstream outcome-linked finance with actuarial risk-sharing

5.6.4 Capability and extension

7) Fund regional advisory nodes as a hub-and-spoke model to integrate agronomy, emissions technologies, accounting, and business models (Links to intervention #5)

Complexity and the need for solutions that fit farm-systems contexts mean traditional single-practice extension is not a fit model. Neither are blunt regulatory instruments. Integrated development, trialling, advisory capacity could reduce perceived risk, curate low-complexity stacks and normalise emissions accounting as part of business decisions, increasing demand for scaling-ready technologies and capacity to address farm- and regional-scale issues. Embedding additional capability, as a hub-and-spoke model, centring on existing state research farms (for development and trialling), and utilising a wider network of farm systems groups and embedded organisations to demonstrate proven technologies. This presents a feasible avenue to advance technology development and uplift the advisory capability of specific regions. This model could be trialled in priority target areas, particularly as part of wider regional demonstrators within a net-zero transition (see Section 5.3.2). This model requires sustained (long-term) investment to build capability, refine regionally and farm system fit technology stacking, and sustain this complex transition. As described in action #5, it will require consistent data standards and metadata to

ensure outputs from sites can feed into national MRV systems, extension support (e.g. CFOP) and longitudinal analysis, and evaluation for continuous improvement and cross-scale learning.

What's already happening in Australia? State and other public research facilities already provide a key focus for activity in Australian agriculture and are variously resourced and connected with wider farm systems groups and farming communities. They have significant potential to be key levers for building capacity and developing technologies and deployment pathways that are regionally appropriate. NSW DPI operates integrated low-emissions RD&E; LEIFS builds inter-disciplinary and national collaboration to link place-based action research with technical development and policy; DAFF's expanded Carbon Farming Outreach Program (CFOP) provides a scaffolding of shared materials and a common knowledge base. It has the potential to facilitate learning among regional 'nodes' as they activate technology/ practice stacks and accrue lessons that enable scaling.

How does this action add value? It instigates and develops multi-disciplinary advisory infrastructure with service charters to support regional capacity and improve accessibility and participation. It ensures regional capacity for data-sharing so learning consistently feeds back to the MRV spine and stack guides (see interventions #1 and #5).

Who could contribute?

Government Industry /RDCs: co-fund linked state nodes as embedded capability through a hub and spoke model that, or possibly NRM regions

Industry / RDCs: provide secondees and publish regional case studies; convene and build capability and link to intervention #8.

Horizon logic and sequencing.

- H1: examine adequacy and opportunities in existing advisory system and initiatives (e.g. CFOP), and develop prioritisation with states and RDC; establish nodes in priority regions with accessible dashboards that summarise regional practice and learning and create connection points (see intervention #5).
- H2: expand regional network aligned with demand and integrate with temporary incentives (e.g. procurement/insetting pilots) to catalyse innovation niches for scaling constrained technology scaling; formalise referral pathways to finance.
- H3: maintain nodes as enduring farm business services tied to outcome-linked instruments, and potentially resourced through market mechanisms.

8) Build national curricula and micro-credentials for advisers on MRV, stacking and supply-chain claims

Diffusion is constrained by advisory silos and uneven quality. Targeted training increases network capability and legitimacy for market-ready pathways and ensures advice aligns with program rules, market mechanisms and opportunities.

What's already happening in Australia? The CFOP training package and knowledge hubs associated with CFOP provide a baseline curricula and continuous updates. Many universities have bespoke offerings about climate adaptation and mitigation within their agricultural coursework.

How does this action add value? It converts training from producer-facing information packages into national micro-credentials (MRV basics, stack accounting, ACCU & claims,

procurement/insetting, and understanding of transitions phases and innovation system requirements) aligned to voluntary guidelines and calculator logics, to build and embed wider advisory system capability and embed this within the private sector.

Who should lead and contribute?

Government with the Tertiary Education Sector: develop and accredit a national suite of training for the next generation of agricultural advisors to support development and scaling of emission-reduction technologies and related innovation system capability.

Industry and RDCs, with Government: align curricula with VEERG (DCCEEW, 2026), ACCU Scheme rules and other emerging guidance.

Horizon logic and sequencing.

- H1: design and accredit core micro-credentials; embed in CFOP and similar state-based programs.
- H2: consider accreditation across adviser networks; add advanced modules and sector specifics.
- H3: internationalise modules and recognition as Australian best practice.

5.7 Closing synthesis

Across industries, the pervasiveness of scaling-constrained technologies reflects an environment with limited incentives to adopt or scale emissions reduction technologies for their own sake. On the other hand, many of the win-win, scaling-ready technologies already have high levels of adoption and are reasonably well embedded for continuous or incremental improvement within sectoral R&D and advisory systems.

This system state means that abatement of agricultural scope 1 emissions is unlikely to significantly accelerate without incentives for adoption and scaling, and these are unlikely to be effective without systems that allow for accountability, low-friction participation, and capability development to effectively implement change. Taken together, these would create greater imperatives to innovate consistently, through R&D, MRV, standards, and advisory system capability.

The decisive moves in the current time horizon are to build the “MRV spine”, publish integrated delivery templates, create demand signals for the current bottleneck of scaling constrained options, and reduce coordination and participation costs through default rules and bolstering regional learning and advisory systems. These interventions particularly target intermediating and demand-side functions in the innovation system, which are already gaining greater attention and support relative to the specific technological directions emphasised in Chapter 4. In particular, low-friction, proportional MRV, appropriate incentives and capability and extension are integral to overcoming technology bottlenecks illuminated by sector assessments and cross-sector synthesis. Overcoming these while maintaining productivity, profitability and social licence will require an uplift in coordination and intermediation.

6 Limitations and next steps for national priority setting

As the first national assessment of investment priorities to reduce scope 1 emissions across Australian agriculture, this project provides input for short-, medium- and longer-term decision-making and prioritisation across relevant industries and government portfolios. The report includes a range of agriculture industries ranging from those with the largest to some of the smallest scope 1 emission profiles Australia's agriculture sector. This allowed development and refinement of an approach that will be applicable across agriculture, forestry, and fisheries industries, providing a foundation for deliberation, assessment, and decision-making in a variety of scales and contexts.

The report emphasises that good outcomes will often rely on investment across diverse areas of R&D, capability advisory system development, and regulatory and market change, and sets up useful ways to consider coordination of innovation functions to crowd in investment to achieve these. The idea that these need to operate together in a complex transition setting is consistent with leading international perspectives yet has rarely been applied with the sort of analytical consistency and practical orientation that is the central focus of this report.

With the many uncertainties in play, these applications are not prescriptive formula, but actions and heuristics that are most useful in thinking through coordination of technological pathways, defining programmatic agendas, and ensuring industry and cross-industry efforts consistently contribute to an effective, efficient and appropriately paced low emissions future for Australian agriculture. This practical combination of technology pathways and effective enabling environments will need to be consistently supported to make low-emissions agriculture possible and profitable.

On more specific technologies, the report and Sector Technology Assessments (Appendices C.1-6) especially contain a level of granularity or detail that is targeted to being able to understand and compare investment options, but not the granularity to design specific RD&E projects to advance any specific technology itself. Being able to strategically inform wider programmatic design and cross program coordination is critically important to making consistent progress. This is especially the case where technologies are relatively mature (TRL/CRL levels are high) and diverse groups need to contribute differently to build adoption and scaling pathways.

6.1 Limitations and caveats

The relatively short time frame and limited resources applied to this project are reflected in a level of assessment that attempts to balance breadth and detail. Trade-offs needed to be found across the large number of technologies and industries, the need for relatively consistent coverage of sub-sector relevant technologies, the drilling into relevant aspects of technologies at diverse stages of maturity, and the assessment of distinctly different potential development, trialling, adoption and scaling pathways.

Without access to a significant and diverse body of expertise across technological and farm systems, the authors relied primarily on available literature and peer review. The project's Reference Group and expert workshops conducted during the project provided useful additional information. But much was also unavailable, especially regarding costs and prospective financial benefits of adoption. We tried to avoid using outdated and out-of-context information in the analyses, but in many instances, little well-targeted information was available. While every effort has been made to ensure that both credible, best available information was used, the reality is that information is patchy, rarely focused at a national level, often targeted to very specific research questions, or very generic and not aligned with our purposes. This means that our analysis is not as rigorous or robust as would be ideal.

Nevertheless, as a first attempt, we would argue that the approach and output are robust and adaptable, highlighting the key considerations to take into account across very diverse technologies, stages of development (archetypes) and sectors. Also, while there may be some discrepancies, the consistency in the analysis across sub-sectors and technology portfolios provides confidence that the analysis is robust enough to inform current investment priorities at these scales. Some additional confidence is provided by peer review of many sections of the report, which led to substantial improvement. Limited resources and time meant peer review could not be done to an ideal level of rigour for all industries, and for one – Horticulture – no peer reviewer was found within the requisite timeframe. Two other reviewers (poultry, pigs) were only able to review the relevant contents of the report and not the associated STAs.

The key challenge now is to build on this analysis and improve upon its methods, workflows and applications in the coming years as Australia progresses on a long road towards low-emissions intensity agriculture. We are confident that the approach and analysis in this report can provide a pivotal piece of infrastructure on this road, through enabling ongoing improvement in understanding enablers, options and investment priorities, and doing so, forming both methods for analysis and a platform to support decision. We explore these options in the next and final section of the report.

6.2 Actions for next steps in building on this analysis and approach

1. Translate the Sector Technology Assessments (Appendix C.1-6) into a wiki and develop a collective impact model of engagement with it that supports ongoing/regular updating of information, and transparent but simple processes for coordinating investment/intervention priorities.
 - a. To be useful across the time horizons in this report, the STAs should be updated regularly, or on an as-needed basis. Without this regular refresh this resource will be out-dated in 2-3 years. AI workflows, trialled in the development of the report, are increasingly effective in supporting such work. These cannot and should not replace human input but supplement it. As a wiki, the STAs could provide a sectoral focal point that is consistent and structured to support enquiry, debate and decision-making. Collectively, these STAs provide a foundation for investment and direction-setting across and beyond agriculture, and ultimately to support the evaluation of such investment and intervention.

- b. Processes should be developed and refined by which the basic information in the STA and the frameworks provided in this report can be readily applied to targeted decision-making at (for example) sectoral, national or regional levels. The current report focuses on national and agriculture-wide actions, but the STA differentiates between the abatement potential of technologies related to the individual sector and all of agriculture. There is potential to experiment with and learn from different approaches to using the information in these assessments to inform decision-making, and in the process improve both the quality of the information and prioritisation processes.
 - c. A long-lived custodian, such as the ZNE-Ag CRC , would be well placed to oversee a wiki as a moderator for input from an expert community. Federal and State Government agencies and RDCs would be beneficiaries of the wiki as a shared knowledge base and might contribute a small amount to its upkeep as a central piece of infrastructure to support direction-setting and investment prioritisation.
 - d. Acknowledging that, as a decision/ discussion support approach to prioritising investment, the information in the proposed wiki has the potential to be manipulated to the benefit of special interest groups. Governance to ensure ongoing legitimacy and continuous improvement in credibility would be sensibly handled by the Board of the ZNE-Ag CRC or similar, ensuring key principles of collective governance (e.g. inter-dependence of interests, and diverse interests) are in place to avoid information being skewed towards any particular interest.
2. Apply the methods from this report to a wider range of sectors (forestry, fisheries, including more targeted sub-sectors (e.g. cotton) where there is industry interest.
 3. Test the veracity of outputs as a foundation for targeted (e.g. industry level, regional) prioritisation, through 1) development of robust and portable processes to facilitate collective learning and direction-setting, and underpins coherent investment plans and pathways across entities (i.e. coordination), and; 2) engagement with RDCs, ZNE-Ag CRC , States and other key stakeholders, knowledge holders and rightsholders (i.e. including Indigenous leaders in agriculture) in such processes.

7 References

- ABARES, 2025. Australian chicken meat industry review 2025: Issues paper. Australian Government, Department of Agriculture, Fisheries and Forestry, Canberra. <https://doi.org/10.25814/bar5-4k29>
- AgriFutures Australia, 2023. Emission reduction technologies and potential use in the chicken meat industry. AgriFutures Australia - Chicken Meat Industry.
- AIA, 2026. Environmental Accounting Platform [WWW Document]. Environmental Accounting Platform. URL <https://www.aiaeap.com> (accessed 6.12.26).
- Allan, C., Cooke, P., Higgins, V., Leith, P., Bryant, M., Cockfield, G., 2022. Adoption; a relevant concept for agricultural land management in the 21 century? *Outlook Agric* 51, 375–383. <https://doi.org/10.1177/00307270221126540>
- ANAO, 2024. Issuing, Compliance and Contracting of Australian Carbon Credit Units, Auditor-General Report No. 24 of 2023–24. Australian National Audit Office, Canberra, Australia.
- Antille, D.L., Moody, P.W., 2021. Nitrogen use efficiency indicators for the Australian cotton, grains, sugar, dairy and horticulture industries. *Environmental and Sustainability Indicators* 10, 100099. <https://doi.org/10.1016/j.indic.2020.100099>
- ARENA, 2023. Energy from Waste Through Pyrolysis. Australian Government, Australian Renewable Energy Agency (ARENA).
- Australian Government, 2026. National Inventory Report 2024, Volume 1. Department of Climate Change, Energy, the Environment and Water., Canberra, Australia.
- Australian Government, 2024. National Inventory Report 2022, Volume 1. Department of Climate Change, Energy, the Environment and Water., Canberra, Australia.
- Baird, J., Schwenke, G., C, G., Macdonald, B., & Suter, H. 2025. In-crop fertiliser application improved nitrogen recovery in irrigated cotton: a multi-year field study with ¹⁵N-labelled urea. *Crop & Pasture Science*, 76(5), CP24334.
- Baird, J., Macdonald, B., Schwenke, G., Constable, G., Suter, H., 2025. Nitrogen sources and sinks – Understanding the fate of nitrogen fertiliser when applied at various times and quantifying internally remobilised nitrogen in cotton. *The Crop Journal*. <https://doi.org/10.1016/j.cj.2025.06.006>
- Beck, S., Jasanoff, S., Stirling, A., Polzin, C., 2021. The governance of sociotechnical transformations to sustainability. *Current Opinion in Environmental Sustainability* 49, 143–152. <https://doi.org/10.1016/j.cosust.2021.04.010>
- Bell, L.W., Hayes, R.C., Pembleton, K.G., Waters, C.M., 2014. Opportunities and challenges in Australian grasslands: pathways to achieve future sustainability and productivity imperatives. *Crop Pasture Sci.* 65, 489–507. <https://doi.org/10.1071/CP13420>
- Bell, M., Schwenke, G., & Grace, P. 2025. *Nitrogen loss pathways and levers to mitigate losses* GRDC Grains Research Updates, Wagga Wagga and Dubbo, NSW.
- Berthon, K., Wade, R., Chapman, P., Jaworski, C.C., Leake, J.R., McHugh, N., Collins, L., Daniell, T., Zhao, Y., Watt, P., Doherty, B., Jackson, P., Dicks, L.V., 2025. Measuring the socio-economic and environmental outcomes of regenerative agriculture across spatio-temporal scales. *Philos Trans R Soc Lond B Biol Sci* 380, 20240157. <https://doi.org/10.1098/rstb.2024.0157>
- Bowen, F., Newenham-Kahindi, A., Herremans, I., 2010. When Suits Meet Roots: The Antecedents and Consequences of Community Engagement Strategy. *Journal of Business Ethics* 95, 297–318.
- Bowen, M.K., Chudleigh, F., Dixon, R., Sullivan, M.T., Schatz, T., Oxley, T., 2019. The economics of phosphorus supplementation of beef cattle grazing northern Australian rangelands. *Animal Production Science* 60, 683–693.
- Bray, S.G., Walsh, D., Rolfe, J.W., Broad, K.C., Cowley, R.A., Daniels, B., English, B.H., Ffoulkes, D., Gowen, R., Gunther, R., 2015. Northern grazing carbon farming—integrating production and greenhouse gas outcomes 1: Climate Clever Beef Final Report.

- Burrett, B., Sevenster, M., 2025. Australian Grains GHG baseline. Updated 2024. CSIRO, Canberra, Australia.
- CCA, 2023. 2023 Review of the National Greenhouse and Energy Reporting Legislation. Climate Change Authority, Commonwealth of Australia, Canberra, Australia.
- Chancellor, W., 2023. Agricultural research and development investment in Australia, ABARES research report. ABARES, Canberra, Australia.
- Christie, K., 2019. Greenhouse gas emissions and potential mitigation options for the Australian dairy industry (thesis). University of Tasmania. <https://doi.org/10.25959/23238227.v1>
- Conti, C., Parida, P., Hall, A., Rao, N., Gopi, G., King, E.D.I.O., Swaminathan, S., 2026. Reinterpreting scaling as synchronising and sequencing: A case study of food system innovation in eastern India. *Agricultural Systems* 237, 104831. <https://doi.org/10.1016/j.agsy.2026.104831>
- Copley, M.A., Wiedemann, S.G., 2022. Environmental impacts of the Australian poultry industry. 1. Chicken meat production. *Animal Production Science* 63, 489–504. <https://doi.org/10.1071/AN22230>
- Copley, M.A., Wiedemann, S.G., McGahan, E.J., 2023. Environmental impacts of the Australian poultry industry. 2. Egg production. *Animal Production Science* 63, 505–521. <https://doi.org/10.1071/AN22297>
- Cowie, A., Carlson-Perret, N., Nakamichi, N., England, M., Adkins, M., Badgery, W., Cacho, O., Coleman, M., Cowley, F., Fawcett, S., Hutton, L., McCann, V., Mortimer, S., Scott, F., Simmons, A., Ximenes, F., Golding, J., Crean, J., Jenkins, B., Johnston, E., Medway, J., Sharwood, R., Wilson, B., 2025. NSW Land and Primary Industries Low Emissions Options Report: Land and Primary Industries Emissions Abatement Roadmap. NSW Department of Primary Industries and Regional Development.
- CRDC, 2025. CRDC Annual Operational Plan 2025-26 | CRDC [WWW Document]. URL <https://crdc.com.au/publications/crdc-annual-operational-plan> (accessed 4.24.26).
- DAFF, 2025. Agriculture and Land Sector Plan. DAFF, Canberra, Australia.
- DCCEEW, 2026. Voluntary emissions estimation and reporting guidelines – agriculture, fisheries and forestry - DCCEEW [WWW Document]. URL <https://www.dcceew.gov.au/climate-change/emissions-reporting/voluntary-emissions-estimation-reporting-standards> (accessed 9.10.26).
- Dixon, J., Rola-Rubzen, M. F., Timsina, J., Cummins, J., & Tiwari, T. P. 2020. Socioeconomic Impacts of Conservation Agriculture based Sustainable Intensification (CASI) with Particular Reference to South Asia. In *No-till Farming Systems for Sustainable Agriculture: Challenges and Opportunities* (pp. 377–394). https://doi.org/10.1007/978-3-030-46409-7_22
- Eastwood, C., Klerkx, L., Nettle, R., 2017. Dynamics and distribution of public and private research and extension roles for technological innovation and diffusion: Case studies of the implementation and adaptation of precision farming technologies. *Journal of Rural Studies* 49, 1–12. <https://doi.org/10.1016/j.jrurstud.2016.11.008>
- Fitch, P., Battaglia, M., Lenton, A., Feron, P., Gao, L., Mei, Y., Hortle, A., Macdonald, L., Pearce, M., Occhipinti, S., Roxburgh, S., Steven, A., 2025. Australia's sequestration potential. CSIRO.
- Fliert, E. van de, 2003. Recognising a climate for sustainability: extension beyond transfer of technology. *Aust. J. Exp. Agric.* 43, 29–36. <https://doi.org/10.1071/ea01067>
- Garba, I.I., Buss, W., Wang, E., O'Sullivan, C.A., Gupta, V.V.S.R., Bentley, A.R., Verburg, K., 2026. A modelling framework for assessing the *plausible* impacts of biological nitrification inhibition in cropping systems. *Agricultural Systems* 232, 104569. <https://doi.org/10.1016/j.agsy.2025.104569>
- Geels, F.W., 2011. The multi-level perspective on sustainability transitions: Responses to seven criticisms. *Environmental Innovation and Societal Transitions* 1, 24–40. <https://doi.org/10.1016/j.eist.2011.02.002>
- Grace, P., Rosa, D.D., Shcherbak, I., Strazzabosco, A., Rowlings, D., Scheer, C., Barton, L., Wang, W., Schwenke, G., Armstrong, R., Porter, I., Bell, M., 2023. Revised emission factors for estimating direct nitrous oxide emissions from nitrogen inputs in Australia's agricultural production systems: a meta-analysis. *Soil Res.* 62, NULL-NULL. <https://doi.org/10.1071/SR23070>
- Hall, A., Gopalakrishnan Nair, R., Raman, S., O'Dwyer, J., Brown, S., Hart, T., Harris, P., Turner, J., Kruger, H., Nelson, R., Burrows, S., Leith, P., 2024. Reframing the conversation on agricultural innovation in Australia. CSIRO, Canberra, Australia.

- He, D., Wang, E., Sevenster, M., Kirkegaard, J., 2026. Process-based modelling in farm greenhouse gas assessment reveals site-specific dynamics and limitations of emission factor methods. *Agronomy for Sustainable Development* 46, 31. <https://doi.org/10.1007/s13593-026-01104-y>
- Hedayati, M., Brock, P.M., Nachimuthu, G., Schwenke, G., 2019. Farm-level strategies to reduce the life cycle greenhouse gas emissions of cotton production: An Australian perspective. *Journal of Cleaner Production* 212, 974–985. <https://doi.org/10.1016/j.jclepro.2018.11.190>
- Hekkert, M.P., Suurs, R.A.A., Negro, S.O., Kuhlmann, S., Smits, R.E.H.M., 2007. Functions of innovation systems: A new approach for analysing technological change. *Technological Forecasting and Social Change* 74, 413–432. <https://doi.org/10.1016/j.techfore.2006.03.002>
- Henry, B., Charmley, E., Eckard, R., Gaughan, J.B., Hegarty, R., 2012. Livestock production in a changing climate: adaptation and mitigation research in Australia. *Crop and Pasture Science* 63, 191–202.
- Hergoualc’h, K., Mueller, N., Bernoux, M., Kasimir, Ä., van der Weerden, T.J., Ogle, S.M., 2021. Improved accuracy and reduced uncertainty in greenhouse gas inventories by refining the IPCC emission factor for direct N₂O emissions from nitrogen inputs to managed soils. *Global Change Biology* 27, 6536–6550. <https://doi.org/10.1111/gcb.15884>
- Jackson, D., Dixon, R. M., Quigley, S. P., Schatz, T., Rolfe, J. W., Corbett, E., English, B. H., Sullivan, M. T., Chudleigh, F., & Wellington, M. 2023. Phosphorus management of beef cattle in northern Australia
- Jackson, D., Dixon, R.M., Quigley, S.P., Schatz, T., Rolfe, J.W., Corbett, E., English, B.H., Sullivan, M.T., Chudleigh, F., Wellington, M., 2023. Phosphorus management of beef cattle in northern Australia.
- Jarmul, S., Dangour, A.D., Green, R., Liew, Z., Haines, A., Scheelbeek, P.F., 2020. Climate change mitigation through dietary change: a systematic review of empirical and modelling studies on the environmental footprints and health effects of ‘sustainable diets.’ *Environ Res Lett* 15, 123014. <https://doi.org/10.1088/1748-9326/abc2f7>
- Jewell, J., Cherp, A., Geels, F.W., Suzuki, M., Nacke, L., Tosun, J., Bhowmik, S., Kazlou, T., Jakhmola, A., Vinichenko, V., 2026. Policy-driven growth of technologies to accelerate climate action. *Nat Rev Earth Environ* 1–18. <https://doi.org/10.1038/s43017-026-00765-3>
- Kaur, S.P., Sagar, N.A.A., Rani, N., 2025. Alternative proteins: innovations in sources, processing, and consumption. *Front. Sustain. Food Syst.* 9. <https://doi.org/10.3389/fsufs.2025.1641712>
- Kuehne, G., Llewellyn, R., Pannell, D.J., Wilkinson, R., Dolling, P., Ouzman, J., Ewing, M., 2017. Predicting farmer uptake of new agricultural practices: A tool for research, extension and policy. *Agricultural Systems* 156, 115–125. <https://doi.org/10.1016/j.agsy.2017.06.007>
- Macdonald, B.C.T., Latimer, J.O., Schwenke, G.D., Nachimuthu, G., Baird, J.C., 2018. The current status of nitrogen fertiliser use efficiency and future research directions for the Australian cotton industry. *Journal of Cotton Research* 1, 15. <https://doi.org/10.1186/s42397-018-0015-9>
- Mayberry, D., 2024. Greenhouse gas emissions update 2021 (No. B.CCH.2124). Meat and Livestock Australia (MLA), Sydney, Australia.
- Mazzucato, M., 2016. From market fixing to market-creating: a new framework for innovation policy. *Industry and Innovation* 23, 140–156. <https://doi.org/10.1080/13662716.2016.1146124>
- McCown, R.L., Carberry, P.S., Hochman, Z., Dalgliesh, N.P., Foale, M.A., 2009. Re-inventing model-based decision support with Australian dryland farmers. 1. Changing intervention concepts during 17 years of action research. *Crop Pasture Sci* 60, 1017–1030. <https://doi.org/10.1071/CP08455>
- Moallemi, E.A., Miller, M., Szetey, K., Chakori, S., Conti, C., Hammond, P., Palmer, J., Battaglia, M., Bryan, B.A., Gao, L., Hall, A., Leith, P., Raven, R., Reed, P.M., 2025. Entry points for driving systemic change toward a more sustainable future. *One Earth* 8. <https://doi.org/10.1016/j.oneear.2025.101287>
- Moate, P.J., Deighton, M.H., Williams, S.R.O., Pryce, J.E., Hayes, B.J., Jacobs, J.L., Eckard, R.J., Hannah, M.C., Wales, W.J., 2016. Reducing the carbon footprint of Australian milk production by mitigation of enteric methane emissions. *Animal Production Science* 56, 1017–1034. <https://doi.org/10.1071/AN15222>
- Munidasa, S., Cullen, B., Eckard, R., Talukder, S., Barnes, L., Cheng, L., 2024. Comparative enteric-methane emissions of dairy farms in northern Victoria, Australia. *Anim. Prod. Sci.* 64. <https://doi.org/10.1071/AN22330>

- Nettle, R., Klerkx, L., Faure, G., Koutsouris, A., 2017. Governance dynamics and the quest for coordination in pluralistic agricultural advisory systems. *The Journal of Agricultural Education and Extension* 23, 189–195. <https://doi.org/10.1080/1389224X.2017.1320638>
- Nettle, R., Major, J., Turner, L., Harris, J., 2022. Selecting methods of agricultural extension to support diverse adoption pathways: a review and case studies. *Anim. Prod. Sci.* 64. <https://doi.org/10.1071/AN22329>
- Norton, R., Gourlay, C., Grace, P., 2023. Fertiliser Australia White Paper: Nitrogen Fertiliser Use and Greenhouse Gases – An Australian Assessment. Fertilizer Australia, Canberra, Australia.
- Oberlack, C., Sietz, D., Bürgi Bonanomi, E., de Bremond, A., Dell’Angelo, J., Eisenack, K., Ellis, E., Epstein, G., Giger, M., Heinemann, A., Kimmich, C., Kok, M., Manuel-Navarrete, D., Messerli, P., Meyfroidt, P., Václavík, T., Villamayor-Tomas, S., 2019. Archetype analysis in sustainability research: meanings, motivations, and evidence-based policy making. *Ecology and Society* 24. <https://doi.org/10.5751/ES-10747-240226>
- Pannell, D.J., 2006. Flat Earth Economics: The Far-reaching Consequences of Flat Payoff Functions in Economic Decision Making. *Applied Economic Perspectives and Policy* 28, 553–566. <https://doi.org/10.1111/j.1467-9353.2006.00322.x>
- Poad, G., McGahan, E., Redding, M., 2010. Low Cost Options for Reducing Effluent Pond Methane - Final Report APL Project 2009/2299. Australian Government, Department of Agriculture; Australian Pork Limited.
- Quayle, W., Marston, E., Lambert, J., Grace, P., Hornbuckle, J., 2025. Baseline greenhouse gas emissions from conventional flood and more water-efficient Australian rice production Baseline greenhouse gas emissions from conventional flood and more water-efficient Australian rice production. Agrifutures.
- Roche, R., Welti, N., Gopalakrishnan Nair, R., Leith, P., Taylor, J., 2025. Ag2050 scenarios and innovation system approaches. *Farm Policy Journal* 22.
- Rochester, I.J., 2011. Assessing internal crop nitrogen use efficiency in high-yielding irrigated cotton. *Nutrient Cycling in Agroecosystems* 90, 147–156. <https://doi.org/10.1007/s10705-010-9418-9>
- Rogers, E.M., 2003. *Diffusion of Innovations*, 5th Edition. Simon and Schuster.
- Roth, G., Harris, G., Gillies, M., Montgomery, J., & Wigginton, D. 2013. Water-use efficiency and productivity trends in Australian irrigated cotton: a review. *Crop & Pasture Science*, 64(12), 1033–1048.
- Murphy, A., Sharpe, S., Geels, F., Lilliestam, J., Patt, A., 2025. First build then break. A policy framework for accelerating zero carbon transitions.. S-Curve Economics, London.
- Rotmans, J., Loorbach, D., 2009. Complexity and Transition Management. *Journal of Industrial Ecology* 13, 184–196. <https://doi.org/10.1111/j.1530-9290.2009.00116.x>
- Scheer, C., Rowlings, D.W., Antille, D.L., De Antoni Migliorati, M., Fuchs, K., Grace, P.R., 2023. Improving nitrogen use efficiency in irrigated cotton production. *Nutrient Cycling in Agroecosystems* 125, 95–106. <https://doi.org/10.1007/s10705-022-10204-6>
- Scheer, C., Rowlings, D.W., Firrel, M., Deuter, P., Morris, S., Grace, P.R., 2014. Impact of nitrification inhibitor (DMPP) on soil nitrous oxide emissions from an intensive broccoli production system in sub-tropical Australia. *Soil Biology and Biochemistry* 77, 243–251. <https://doi.org/10.1016/j.soilbio.2014.07.006>
- Scoones, I., Stirling, A., Abrol, D., Atela, J., Charli-Joseph, L., Eakin, H., Ely, A., Olsson, P., Pereira, L., Priya, R., van Zwanenberg, P., Yang, L., 2020. Transformations to sustainability: combining structural, systemic and enabling approaches. *Current Opinion in Environmental Sustainability*, Advancing the science of actionable knowledge for sustainability 42, 65–75. <https://doi.org/10.1016/j.cosust.2019.12.004>
- Schwenke, G., Nachimuthu, G., Baird, J., Mercer, C., MacDonald, B., Bell, M., Bischof, C., Bai, M., & Suter, H. 2021. More Profit from Nitrogen: Enhancing nutrient use in cotton. Cotton Research and Development Corporation, Narrabri, NSW, Australia
- Sevenster, M., Bell, L., Anderson, B., Jamali, H., Horan, H., Simmons, A., Cowie, A., Hochman, Z., 2022. Australian Grains Baseline and Mitigation Assessment. Main Report. CSIRO, Canberra.
- Sevenster, M., Burrett, B., 2024. Australian Grains GHG account 2020. Version 2024. CSIRO.

- Sevenster, M., Islam, N., Weaver, T., Antille, D., 2025. Greenhouse gas mitigation options in the Australian cotton sector. <https://doi.org/10.25919/gbe1-gj67>
- Sovacool, B.K., Geels, F.W., Andersen, A.D., Grubb, M., Jordan, A.J., Kern, F., Kivimaa, P., Lockwood, M., Markard, J., Meadowcroft, J., Meckling, J., Moore, B., Raven, R., Rogge, K.S., Rosenbloom, D., Schmidt, T.S., Schot, J., Sharp, D., Stephenson, J., Vormedal, I., Yang, K., 2025. The acceleration of low-carbon transitions: Insights, concepts, challenges, and new directions for research. *Energy Research & Social Science* 121, 103948. <https://doi.org/10.1016/j.erss.2025.103948>
- Swarts, N., Montagu, K., Oliver, G., Southam-Rogers, L., Hardie, M., Corkrey, R., Rogers, G., Close, D., 2016. Benchmarking nitrous oxide emissions in deciduous tree cropping systems. *Soil Res* 54, 500–511. <https://doi.org/10.1071/SR15326>
- Smith, J., Fukai, S., & Bell, M. 2023. Soil and fertiliser nitrogen performance indicators for irrigated cotton in Australia. *Soil Research*, 61(4), 329–344. <https://doi.org/10.1071/SR21323>
- Tongwane, M., Mdlambuzi, T., Moeletsi, M., Tsubo, M., Mliswa, V., Grootboom, L., 2016. Greenhouse gas emissions from different crop production and management practices in South Africa. *Environmental Development* 19, 23–35. <https://doi.org/10.1016/j.envdev.2016.06.004>
- Vanclay, F., 2004. Social principles for agricultural extension to assist in the promotion of natural resource management. *Aust. J. Exp. Agric.* 44, 213–222. <https://doi.org/10.1071/ea02139>
- Wiedemann, S., McGahan, E., McCormack, K., Muller, T., 2021. Low Carbon Emission Roadmap for the Australian Pork Industry: Manual (Project Report), Final Report. Integrity Ag and Environment, Highfields, Queensland, Australia.
- Wilson, L.J., Whitehouse, M.E., Herron, G.A., 2018. The management of insect pests in Australian cotton: an evolving story. *Annual Review of Entomology* 63, 215–237.