

APPENDIX C.3: Cropping Sectoral Technology

Assessment

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NOTE: The first three technologies are often formulated together as enhanced efficiency fertilisers (EEFs), which often comprise a combination of urease or nitrification inhibitors and slow/controlled release fertilisers. These are treated as separate technologies in this assessment following advice from workshop participants, and in recognition of their differing forms of action of different emissions pools (see Section 4.3.1).

Slow-/Controlled-release nitrogen fertilisers (polymer/biodegradable coatings, chemically bound N)

Slow/controlled-release fertilisers (SRF/CRF) are classes of products that regulate N release from granules in response to soil temperature and moisture. These encompass a

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broad range of technologies including polymer coated fertiliser, resin coated fertilisers, sulfur coated fertilisers, and those with organo-mineral complexes designed to slow the release of the fertiliser elements. These products have different mechanisms of action, but they can broadly reduce emissions by better aligning soil mineral N availability with crop demand, improving NUE, and reducing N lost via volatilisation, leaching and denitrification. Australian adoption is currently limited in broadacre cropping due to cost and variable performance across environments (GRDC, 2025a). Stronger evidence exists in sugarcane systems, reflecting higher rainfall and heavier soil conditions.

1) Annual Abatement Potential (Technical)

CRFs can technically cut direct N_2O emissions where N supply exceeds demand or loss risks are high, by pacing nitrate appearance and reducing denitrification/leaching windows. Field evidence is thinner than for inhibitors, but Australian guidance indicate material reductions are plausible in favourable contexts (Grace et al., 2023). Given the range of factors (seasonal conditions, placement, timing) that affect efficacy a wide technical upper bound for SRF/CRF alone, of 10–40% of fertiliser-derived N_2O is a defensible range.

2) Feasible annual abatement at national scale

We estimate feasible abatement by combining agricultural N_2O totals with grains' share and realistic domains/adoption. Using emissions estimates from Section 4.3, N_2O emissions associated with fertiliser use, total potential emissions abatement is 4.1 Mt $CO_2\text{-e yr}^{-1}$. With a technical abatement range (above, 0.10–0.40) and assuming maximal extent of 60–80% of all cropping area is technically suitable, and 10-year adoption within this range of 0.15–0.30 (upper-end adoption under strong incentives), the feasible abatement range $\approx$ 37–394 kt $CO_2\text{-e yr}^{-1}$. This range reflects uncertainties across adoption, suitability and performance, despite the relative maturity of this technology.

3) Breadth of Application

Ranking: Medium

Technically usable across most broadacre cereals/oilseeds and regions, but practicality is limited by price premiums, supply, and contexts where rapid N availability is needed or where inhibitors/deep banding solve the problem cheaper (Angus and Grace, 2017). GRDC (GRDC, 2025a) notes present adoption is concentrated in high-value or high-risk systems; national work aims to identify “where/when” they fit. Thus, broad technical fit but constrained real-world uptake.

4) Co-benefit Potential

Ranking: Medium

Likely co-benefits include improved NUE by reducing ammonia volatilisation risk through delaying urea release into the soil, thereby reducing peak ammonium concentrations and the rate of volatilisation following rapid hydrolysis. Fewer in-season N applications, and potential N-rate reductions in some contexts without yield penalty may also be an advantage. However, yield gains above best-practice conventional N are uncommon;

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benefits are context-specific and are mostly offset by input product cost. Some operational pressures (e.g. rushed timing of nitrogen application prior to planting) are likely to be alleviated.

5) Barriers and Knowledge Gaps

Ranking: Medium-High

Key barriers: higher cost per tonne N, uncertain ROI across rainfed grains, limited Australian field evidence comparing CRF vs. spatially/temporally targeted urea with inhibitors, and logistics/supply. Knowledge gaps: long-term efficacy across soil-climate zones, emissions outcomes ($\text{N}_2\text{O}/\text{NH}_3$) relative to best-practice alternatives, and polymer environmental profiles.

6) Stacking Potential

Ranking: High

CRF can be bundled with precision N (6Rs/variable rate), N budgeting, legume phases, mid-row/deep placement, and inhibitor-treated products, but these can be complex to manage well. CRF contributes to “avoidance first” while other measures tackle residual emissions. Strong complementarity with digital agronomy has potential to add value through precision application rates.

7) Technology Readiness Level (TRL)

Ranking: TRL 8-9

CRF technologies (e.g., polymer-coated urea) are fully developed and widely used in horticulture/turf, and commercially available for grains, albeit niche. Their reliable integration into broadacre systems remains underdeveloped.

8) Commercial Readiness Level (CRL)

Ranking: CRL 5-6

Products exist and are sold ($\text{CRL} \geq 5$), but no production in Australia, small market size and limited applications mean imports are low, which contribute to high costs and limited knowledge. GRDC investment has a focus on understanding current use and constraints.

9) Enabling Potential

Ranking: Medium

CRF does not transform systems on its own, but it could support lower-emission N programs, reduce operational passes (e.g. single-shot CRF replaces splits), and fit into enterprise-level carbon strategies through prioritising avoidance and fertiliser use efficiency. Like other fertiliser-based methods, it is enabled by digital N diagnostics and accounting frameworks (GroundCover, 2024a).

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10) Estimated cost range (on-farm)

Cost constrains adoption in broadacre pending clearer ROI. For scoping, practitioners report \$40–120 /ha additional input costs at typical N rates when swapping part/all of urea to CRF, highly variable with N rate and product pricing.

11) Estimated c benefits

Benefits are context-specific: potential N-rate reduction without yield loss in some settings; risk management in wet spells; operational savings from fewer passes; reduced N loss risk. Risk reduction may also result in high application rates of N, closing yield gaps. Where inhibitors or well-timed split applications already perform well, marginal benefit will be small versus added cost. Expect benefits from avoided loss and logistics, not consistent yield uplift. . Pending GRDC trials . will improve ROI estimates.

12) Investment in R&D, commercialisation, and scaling (AU + global)

Australia has significant new investment targeted at EEFs (including CRF). Global R&D on SRF/CRF is active (materials science, biodegradable coatings). Evidence below summarises identifiable flows; Australian figures are clear for the GRDC-led program, with additional industry co-investment. Prices of coated urea products are particularly high relative to standard urea due to smaller shipping volumes. Industry experts suggest that until market demand increases significantly prices will remain uncompetitive.

Australia:

- \$17.33 M (2024–28) – GRDC + partners: “Enhanced efficiency nitrogen fertilisers in the grains industry” multi-site field including modelling and economics to better understand what works where and when and the implications for NUE and ROI. R&D with 2. Commercialisation relevance.
- GRDC Future Farm (precision N, 6Rs) – multiple projects (values not consolidated publicly) supporting enabling analytics and targeted N decisions that interact with EEF use. Category: 1. R&D / Enabling.
- ARC Research Hub for Smart Fertilisers is a \$5 million, five-year program from 2022, based at University of Melbourne and La Trobe University. It aims to develop next-generation, sustainable "smart" fertilisers that improve nitrogen use efficiency and reduce environmental losses, spanning CRF, NIs and UIs.

Global

- Growing research pipeline in SRF/CRF materials and biodegradable coatings (numerous 2023–25 studies; bibliometric review shows rapid expansion since 1990). Category: 1. R&D (amounts not consolidated).

Nitrification inhibitors

Nitrification inhibitors are compounds (e.g. 3,4 dimethylpyrazole-phosphate [DMPP]) that slow down bacterial conversion of ammonium to nitrate in soil. By suppressing activity of nitrifying bacteria, NIs preserve the more stable ammonium form for longer, leading to

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144 improved nitrogen use efficiency and potentially reducing nutrient loss through leaching
145 and denitrification.

146 **1) Annual Abatement Potential**

147 Across Australian grains, DMPP has demonstrated large technical abatement of
148 fertiliser-derived N_2O , with meta-analysis showing EF reductions of 55–80% for cropping
149 systems, with large variations depending on wetness (Grace et al., 2023). Given the
150 relatively limited data across conditions a wtechnical range of 60–80% reduction in
151 fertiliser-derived N_2O is plausible under well-targeted conditions, acknowledging that the
152 actual per cent-cut depends on rainfall, soil C/N, timing and rate. These technologies have
153 been shown to be effective in many situations and have the potential to contribute to
154 significant industry improvements in emissions intensity if applied in fit-for-context, and
155 cost and other barriers can be overcome (see below).

156 **2) Feasible annual abatement at national scale**

157 Assuming grains contribute 0.60–0.80 reductions on fertiliser-derived N_2O
158 ($4.1 \text{ Mt CO}_2\text{-e yr}^{-1}$) across 60–80% of all cropping land, and adoption rates of 0.30–0.50
159 (strong adoption under clear ROI and extension), feasible abatement ranges from 443–
160 $1312 \text{ kt CO}_2\text{-e yr}^{-1}$. This upper estimate is comparable to Grace et al. (2023) hypothetical
161 maximum of $802 \text{ kt CO}_2\text{-e yr}^{-1}$ for grains only, which implicitly assumes near-full adoption
162 across applicable systems. Such a level of adoption would require improved ROI through
163 (e.g. via emerging market or reporting mechanisms) or reduced input costs. Note: there is
164 some evidence that NI's can also reduce N_2O emissions associated with residue breakdown,
165 which is not considered here.

166 **3) Breadth of application**

167 Ranking: High

168 DMPP/nitrapyrin/DCD can be applied widely across Australian cereals, oilseeds and
169 irrigated grains, particularly where high soil moisture or heavy rainfall elevates
170 denitrification/leaching risks (Grace et al., 2023). GRDC guidance recommends targeting
171 wet periods, higher rainfall zones ($>600 \text{ mm}$) and higher carbon/N sites; inhibitors are
172 compatible with common fertiliser programs and delivery (GRDC, 2025a).

173 **4) Co-Benefit Potential**

174 Ranking: Medium–High

175 Likely co-benefits: improved NUE, reduced NO_3^- leaching, potential N-rate reduction at
176 equivalent yield under sub-optimal N strategies, and lower environmental impacts (Rose et
177 al., 2018). Yield uplift above well-tuned conventional programs is not consistent, but studies
178 show equal yields at reduced N in some contexts, highlighting the season, system and
179 management dependence of co-benefits (GRDC, 2025a).

180 **5) Barriers and Knowledge Gaps**

181 Ranking: Medium

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Barriers: product costs, variable agronomic ROI in dryland seasons, need for site-specific timing, and supply/extension capacity. Knowledge gaps: multi-season, multi-region economics, interaction with placement/timing and digital N tools, and lack of best-practice targeting rules.

6) Stacking Potential

Ranking: High

Strong synergy with precision N (6Rs), variable rate, split applications, mid-row/deep placement, cover/legume phases, and soil water management. Could stack with digital decision support.

7) Technology Readiness Level

Ranking: TRL 8–9

Some nitrification inhibitors (DMPP, nitrapyrin, DCD) are commercially available and widely tested; Australian EF reductions are reasonably well quantified (Grace et al., 2023). Ongoing trials are being used to refine best-practice integration, but the technology is mature and in operational use in Australian cropping (Friedl et al., 2023).

8) Commercial Readiness Level

Ranking: CRL 6–7

Products are sold nationally via major suppliers; adoption is growing where loss risk and market drivers exist. Wider scale-up awaits improved economics and clearer application advice and demonstration in specific systems, regions and seasons (GRDC, 2024).

9) Enabling Potential

Ranking: Medium

Inhibitors are enablers of “avoidance first” GHG strategies, improving baseline farm footprints and easing reliance on offsets (GroundCover, 2024a). They potentially integrate well with GHG calculators and accounting frameworks.

10) Estimated cost range (on-farm)

Costs vary by product/formulation and rate. Indicatively, adding DMPP to urea or purchasing DMPP-treated product often incurs premiums of ~\$20–60/ha at typical cereal N rates (e.g., 40–80 kg N/ha), but can be higher in irrigated/high-rate systems. Precise premiums depend on supplier and season; robust national price series are not public. ROI hinges on avoided losses.

11) Estimated financial benefits (on-farm)

Benefits accrue as N loss avoidance (lower N₂O/leaching), NUE gains, and sometimes enabling lower N rates with no yield penalty, and improved risk management in wet seasons. Yield increases over an optimised conventional program are not guaranteed, but at

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217 sub-optimal N, inhibitors can maintain yield. Net benefit depends on season and price,
 218 which is currently being investigated in GRDC trials (GRDC, 2024).

219 **12) Investment in R&D, commercialisation, and scaling**

220 Australia has major new investment targeted at EEFs (including nitrification inhibitors),
 221 plus ongoing precision-N initiatives. Globally, inhibitor R&D and deployment are mature,
 222 with continuous product development and agronomic validation. Summary below lists
 223 identifiable Australian investments and indicative global activity.

224 **Australia**

- 225 - \$17.33 M (2024–28) – GRDC co-investment led by University of Melbourne: field
 226 trials, ¹⁵N tracing, modelling & economics for urease and nitrification inhibitors
 227 and controlled-release fertilisers. Category: 1. R&D, 2. Commercialisation support.
 228 (GroundCover, 2024b)
- 229 - Precision N / Future Farm (2019–ongoing) – GRDC Strategic Initiative
 230 (multi-partner) to improve targeted N decisions (data-driven VRT, sensors, decision
 231 support). Category: 1. R&D / Enabling (amounts not consolidated).
- 232 - ARC Research Hub for Smart Fertilisers is \$5 million, five years program from 2022,
 233 based at University of Melbourne and La Trobe University. It aims to develop next-
 234 generation, sustainable "smart" fertilisers that improve nitrogen use efficiency and
 235 reduce environmental losses, spanning CRF, Nis and UIs.

236 **Global**

- 237 - Continuous product R&D and agronomic validation for DMPP, nitrapyrin, DCD in
 238 crops; numerous trials reported in journals and industry literature; strong
 239 commercial supply chains (amounts not consolidated publicly). Category: 1. R&D, 2.
 240 Industry scaling.

241 **Urease inhibitors**

242 Urease inhibitors can be added to urea-based fertilisers to inhibit the action of the enzyme
 243 urease, which converts urea into ammonia. They reduce ammonia (NH₃) volatilisation
 244 losses which can account for a substantial share of applied nitrogen losses under Australian
 245 conditions. NH₃ loss increases fertilizer costs, and can lead to the formation of particulate
 246 matter that is dangerous to human health. When particulates are redeposited (deposition)
 247 in freshwater or soils they can then indirectly release N₂O. This also has impacts on
 248 biodiversity and eutrophication of waterways in some areas. Urease inhibitors essentially
 249 maintain more nitrogen in a form plants can use for longer, which improves NUE and can
 250 reduce indirect N₂O emissions.

251 **1) Annual Abatement Potential (Technical)**

252 Direct N₂O emissions from fertilizer can be modestly decreased by urease inhibitors
 253 compared with nitrification inhibitors. They primarily target NH₃ loss. Australian evidence
 254 shows large reductions in NH₃ volatilisation (e.g.,) and occasional N₂O decreases where

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255 synchrony improves. As a technical upper bound for fertiliser-derived N₂O, potential
256 abatement of 5–10% is defensible.

257 **2) Feasible annual abatement at national scale**

258 Using GRDC Update metrics: Australian agricultural N₂O associated with fertilizer use ≈
259 4.1 Mt CO₂-e yr⁻¹. With potential abatement at 5–10%, and assuming 60%–80% of cropping
260 applies urea, and that extension/incentives enable 25–40% rates of adoption, feasible
261 abatement is estimated at 31–131 kt CO₂-e yr⁻¹.

262 .

263 **3) Breadth of Application**

264 Ranking: Medium

265 Applicable across cereals/oilseeds where surface-applied urea is common, residues/organic
266 matter are high, or rainfall is uncertain post-application. Breadth is limited where deep
267 placement or immediate incorporation/irrigation already minimises NH₃ losses. Given
268 widespread urea use and variable rainfall in Australian grains, practical scope is Medium–
269 High, with greatest value in higher NH₃-risk systems.

270 **4) Co-Benefit Potential**

271 Ranking: Medium

272 Co-benefits include higher effective NUE, more flexible application windows (risk buffering
273 when rain timing is uncertain), reduced NH₃ odour, and less deposition downwind and
274 associated environmental impact, and potential social license issues. Yield gains vs.
275 well-timed conventional programs are not consistent, but UIs can maintain yield when
276 surface application is unavoidable or at sub-optimal N. Overall, Medium, noting
277 environmental benefits beyond GHG accounting. Improved NUE with the use of UIs could
278 reduce upstream emissions associated with fertiliser manufacture, if total N use declines

279 **5) Barriers and Knowledge Gaps**

280 Ranking: Medium

281 Barriers include the product premium, variable payback where volatilisation risk is low,
282 and the need to target use to residue load, soil conditions and likely rainfall after
283 application. Adoption also depends on operational fit. Urease inhibitors are most attractive
284 where they offer a simple risk-management option within existing top-dressing programs.
285 Uptake is slower where they require extra planning or where the same risk can be managed
286 through incorporation, timing or alternative application methods. More broadly, practices
287 that add decision load during narrow application windows are less likely to be adopted,
288 even when the technical case is sound. Key knowledge gaps include better regional
289 targeting, clearer Australian economics, and stronger evidence on interactions with
290 placement, split applications and retained stubble systems.

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6) Stacking Potential

Ranking: High

UIs stack strongly with precision N (6Rs), variable-rate, split timing (as safeguard), and mid-row/deep placement where some N must remain surface-applied (e.g., top-ups). They also complement nitrification inhibitors in dual-inhibitor formulations that target both NH_3 and N_2O pathways. High stacking, especially with digital decision tools and risk-based N budgeting.

7) Technology Readiness Level (TRL)

Ranking: TRL 9

NBPT and related UIs are fully developed, widely sold, and extensively tested in Australia and globally. Integrative guidance for grains continues to evolve, but from a product perspective the technology is mature and operational.

8) Commercial Readiness Level (CRL)

Ranking: CRL 7

Products are available nationally from major suppliers and are used where NH_3 risk is evident; adoption varies with season, residue load, rainfall certainty and price premium. Clear guidance and incentives, and broader integration is feasible, and could expand scale.

9) Enabling Potential

Ranking: Medium

UIs support avoidance-first pathways by reducing N losses, helping GHG calculators and farm-gate footprints show improvements, and enabling more flexible N logistics. They don't transform systems alone, but as part of EEFs + precision N suites they facilitate verified abatement and reduce reliance on offsets.

10) Estimated cost range (on-farm)

Indicative premiums for NBPT-treated urea or UI additives vary by product and rate. Field advisers report ~\$10–40/ha additional cost at typical cereal N rates (40–80 kg N/ha) when replacing part/all of plain urea; higher in irrigated/high-rate systems. Exact premiums are supplier/season-dependent; robust public price series are limited. Economics hinge on avoided NH_3 loss.

11) Estimated financial benefits (on-farm)

Financial benefits come from NH_3 loss avoidance, NUE gains, and risk reduction when surface application is unavoidable or rain timing uncertain. They are difficult to quantify. Net benefit varies with residue load, temperature, wind and rainfall patterns; Australian multi-site trials will sharpen ROI estimates (GRDC, 2025a). Some studies show equal yields at reduced N rates with inhibitors, though consistent yield uplift over best-practice deep placement/split timing is unlikely (Rose et al., 2018).

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12) Investment in R&D, commercialisation, and scaling (AU + global)

UIs sit within the EEF investment focus in Australia, with substantial new funding to build best-practice rules and ROI. Global R&D and commercial supply are mature, with ongoing formulation and agronomic optimisation. Below are identifiable flows.

Australia

- \$17.33 M (2024–28) — GRDC co-investment led by University of Melbourne: multi-site trials, ¹⁵N tracing, modelling and economics for urease & nitrification inhibitors and controlled-release fertilisers. Category: 1. R&D, 2. Commercialisation support.
- Precision N / Future Farm — GRDC Strategic Initiative improving targeted N decisions, enabling more effective UI deployment (amounts not consolidated). Category: 1. R&D / Enabling.
- ARC Research Hub for Smart Fertilisers is \$5 million, five years program from 2022, based at University of Melbourne and La Trobe University. It aims to develop next-generation, sustainable "smart" fertilisers that improve nitrogen use efficiency and reduce environmental losses, spanning CRF, Nis and UIs.
- Public breakdowns of \$ by UI specifically vs other EEF classes are limited; most AU investment is pre-commercial multi-site R&D aimed at clarified guidance and adoption.

Global

- Long-standing R&D and commercialisation for NBPT and related UIs; extensive trials and supply chains (amounts not consolidated).

Reduced Tillage

Definition: Minimising soil disturbance to preserve soil structure and moisture, maintain residue cover, enhance soil carbon and nitrogen cycling, and reduce fuel use and labour requirements. In practice, reduced tillage operates as part of a broader farming system, where outcomes are strongly influenced by interactions with nitrogen management, soil moisture dynamics, residue levels, and crop sequence (Lilley and Kirkegaard, 2024). This includes no-till systems as well as strategic or occasional tillage within otherwise low-disturbance systems. Evidence from long-term Australian experiments and process-based modelling shows that the effects of reduced tillage cannot be assessed in isolation: soil water and mineral nitrogen carryover between seasons, residue decomposition, and crop demand jointly determine impacts on productivity and emissions (Lilley and Kirkegaard, 2024). Management choices such as nitrogen rate and timing, stubble retention, and sowing strategy can amplify or offset the benefits of reduced disturbance through their effects on water use, mineralisation, and nitrogen losses (He et al., 2026). As a result, reduced tillage is best understood as one element within an integrated system of practices, where outcomes are context-dependent and shaped by cumulative management over multiple seasons rather than single-year interventions (He et

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al., 2026). While recent GRDC Farm Survey (Umbers and Watson, 2025) suggests recent disadoption, this largely reflects a shift in the reporting framework—where growers now report multiple tillage practices within a single system. Low-disturbance systems are complemented by strategic and episodic tillage across part of the farm area.

1. Annual Abatement Potential (Technical)

Summary: Global meta-analyses suggest reductions in total global warming potential (GWP) (Yue et al., 2023). These reductions are consistent across dryland and rice systems. The applicability of these broad findings to Australian dryland systems will be context-dependent.

2. Abatement Potential – Economic/Feasible

Summary: Additional abatement potential is realistically limited. This is due to the already high adoption (Llewellyn and Ouzman, 2019). Economic feasibility is generally well established, although outcomes still depend on weed pressure, herbicide reliance, stubble loads and seasonal conditions. Future adoption and distribution rates are estimated comparably to stubble retention – based on high adoption and therefore a small amount of remaining cropping land (estimated as 5-10%) applicable for further adoption, and rates of adoption within these from 30-50% over the next 10 years. This gives estimates of 50-130 kT CO₂-e/year.

3. Breadth of Application

Summary: High – No-/ minimum- till is already used on about 80% of Australia’s grain crop area, with some adoption exceeding 90% in most regions (Llewellyn and Ouzman, 2019).

4. Co-Benefit Potential

Summary: High – Includes improved water use efficiency, erosion control, labour savings, and yield reliability (Llewellyn and Brown, 2020). Most of these co-benefits have already been realised through high adoption (Llewellyn and Ouzman, 2019).

5. Barriers and Knowledge Gaps

Summary: Medium – Weed, pest, and disease pressures in some systems,, together with the need for strong agronomy around stubble, herbicides, and crop sequencing which can increase input costs and complexity (Yue et al., 2023).

6. Stacking Potential

Summary: High – Forms a foundational platform for conservation agriculture. Synergistic with stubble retention, cover crops, legumes, precision nutrient management, and controlled traffic farming (Yue et al., 2023).

7. Technology Readiness Level (TRL)

Summary: TRL = 9 – Fully mature and widely adopted across Australia. Decades of use, strong research base, and farmer-led innovation.

8. Commercial Readiness Level (CRL)

Summary: CRL = 6 – Commercially viable and scalable, with widespread adoption. No-till equipment and advisory services are well established.

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9. Enabling Potential

Summary: High – Enables other technologies and practices, including digital agriculture and emissions accounting.

10. Estimated Cost Range

Summary: Estimated at \$10–\$30/ha/year, primarily for machinery upgrades and weed control. Costs vary by region and farm size; long-term savings in fuel and labour.

11. Estimated financial Benefits

Estimated return of \$40–\$100/ha/year through improved yield reliability, reduced erosion, and fuel savings. Benefits are enhanced in dryland systems and large-scale farms.

12. Investment in R&D and Commercialisation

Australian Investment:

- R&D: \$5–10 million (GRDC, CSIRO, DPI NSW)
- Commercialisation: \$1–5 million (machinery, agronomy services)
- Industry Scaling: \$5–10 million (WANTFA, SANTFA, GRDC extension)

Global Investment:

- Extensive investment in conservation tillage research (FAO, CGIAR, EU Horizon) and machinery development (John Deere, etc.)

Precision Nitrogen Applications

Description: Precision nitrogen applications involve tailoring the rate, timing, placement, and formulation of nitrogen fertilisers to match crop demand and site-specific conditions. This includes variable rate technology (VRT) or defining management zones, split applications across seasons (tactical management), or at different depths, and sensor-guided decision tools. The goal is to improve nitrogen use efficiency (NUE), reduce losses (e.g. N_2O , NH_3 , NO_3^-) and therefore costs, while maintaining productivity.

1. Annual Abatement Potential (Technical)

Precision nitrogen may reduce or increase total emissions depending on whether productivity gains are accompanied by increased nitrogen inputs (Sevenster et al., 2022). However, it typically improves emissions intensity (Sevenster et al., 2022), with a strong likelihood that the level of productivity optimization implied by precision systems would lead to increased overall emissions accompanied by significant improvement in emissions intensity. For the purpose of this analysis we assume these changes could potentially range from -10–+10% at a national scale.

2. Abatement Potential – Economic/Feasible

Feasible abatement is estimated on the basis of large assumptions about rates of application and adoption. Split applications and VRT are already used in some systems, and sensor-guided tools are increasingly accessible. However, uptake varies by region and crop type, with high up-front costs, challenges with timing and compatibility with systems of use, and

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other barriers limiting adoptability. We use N₂O emissions as previously, and applicable extents of 60-80% of cropping areas, but with relatively low rates of adoption (10-20%, on the basis that system shifts to precision application are often difficult or poor fit) to estimate feasible ER at -23-61 kt CO₂-e yr⁻¹. Assumptions here are based on very limited data and need to be tested.

3. Breadth of Application

Ranking: High

Technical applicability is high, but effective use depends on capability, advisory support and system fit. This applies across all major broadacre crops, including cereals, pulses, cotton, and sugar. They are largely compatible with existing machinery and agronomic practices, making them broadly scalable, but require high levels of technical skill and interest among farming populations and advisors – these tend not to be limiting in most Australian settings.

4. Co-Benefit Potential

Ranking: High

Co-benefits can include improved yield, reduced input costs, enhanced soil health, and reduced nitrate leaching. Economic returns of \$7–38/ha have been reported, and improved NUE supports long-term sustainability (Balafoutis et al., 2017).

5. Barriers and Knowledge Gaps

Ranking: Medium

Barriers include upfront costs, limited advisory support and seasonal forecast development sufficient to guide applications (potentially due to limits of predictability), and variability in sensor performance. Poor fit with systems of use and practices of many cropping enterprises often make applications unviable. Knowledge gaps exist in emission factor variability and long-term soil N dynamics. For example, Nitrous oxide emissions are highly sensitive to nitrogen input rates and timing, so emissions factors can under or over-estimate emissions (He et al., 2026). Regional development and calibration of decision tools and MRV are needed to build emissions and productivity cases for applications.

6. Stacking Potential

Ranking: High

Precision nitrogen applications stack well with enhanced efficiency fertilisers, cover cropping, and digital farm management platforms. They can enable synergistic gains in emissions reduction and productivity (Aderale et al., 2025).

7. Technology Readiness Level (TRL)

Ranking: 8

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475 Most components (VRT, sensors, split application) are commercially available and widely
 476 tested. Ongoing refinements in AI-driven decision support tools are pushing TRL toward full
 477 deployment.

478 **8. Commercial Readiness Level (CRL)**

479 Ranking: 5

480 Precision nitrogen technologies are commercially available and adopted in parts of
 481 Australia. However, broader uptake is constrained by cost, advisory capacity, and regional
 482 calibration of approaches with systems.

483 **9. Enabling Potential**

484 Ranking: High

485 Precision nitrogen applications enable better benchmarking, carbon accounting, and
 486 integration with farm management systems. They support broader emissions reduction
 487 strategies and data-driven decision-making.

488 **10. Estimated Cost Range**

489 Range: \$20–80/ha/year

490 Costs vary by system complexity. VRT retrofits and sensor systems range from \$20–
 491 80/ha/year depending on farm size and equipment. Assumes existing machinery and basic
 492 advisory support is in place, and generally has high upfront costs and relatively low RoI,
 493 depending on systems (Bahmutsky et al., 2024).

494 **11. Estimated financial Benefits**

495 Range: \$7–50/ha/year or higher have been reported, even among highly skilled growers
 496 (GRDC, 2025b). Yield increases of 1–10% and fertiliser savings of 4–37% have been
 497 reported. Benefits depend on crop type, soil variability, and seasonal conditions. Economic
 498 returns are strongest in variable soils.

499 **12. Investment in R&D and Commercialisation**

500 Australian Investment

- 501 • R&D: >5 million (GRDC, CSIRO, Fertilizer Australia)
- 502 • Industry Scaling: GRDC trials, DPIRD modelling, numerous private sector businesses
- 503 and corporates advancing VRT and other precision approaches.

504 Global Investment

- 505 • R&D: >\$10 million (EU Horizon, ESA FertEyes project)
- 506 • Commercialisation: Trimble, Yara, John Deere sensor platforms
- 507 • Scaling: ESA remote sensing for nitrogen mapping

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Controlled Traffic Farming (CTF)

Technology Description: Controlled Traffic Farming (CTF) is a system that confines machinery movement to permanent traffic lanes, reducing soil compaction and improving consistency of operations. Soil compaction increases N₂O emissions indirectly. In wet conditions, compaction increases water-filled pore space and the likelihood of denitrification. Avoidance of compaction therefore reduces emissions primarily under wet conditions (Antille et al., 2015). In broadacre systems, CTF can improve soil structure, water infiltration, input efficiency, and reduce fuel use (Antille et al., 2015; Masola et al., 2026). CTF is enabled by precision guidance systems and machinery matching across operations. CTF reduces fuel use primarily through decreased rolling resistance and improved traction on permanent traffic lanes; reductions in motion resistance of ~25% and fuel savings of ~20% or more have been reported under Australian conditions (Jensen et al., 2025). Controlled traffic farming is a long-horizon infrastructure transition embedded within normal machinery replacement cycles. In Australia, strongest adoption is in Queensland and Western Australia.

1. Annual Abatement Potential (Technical)

CTF has been reported to have the potential to reduce fuel use by up to 40% and nitrous oxide emissions by 30–50% in fertilized soils with higher estimates associated with irrigation (Tullberg et al., 2018), with additional gains from improved soil carbon sequestration. The estimated technical abatement potential is up to 1.7 Mt CO₂-e/year nationally (Tullberg et al., 2018). Evidence indicates that CTF can reduce N₂O emissions by ~20–50% compared with non-CTF systems, primarily through compaction avoidance in crop zones (Antille et al., 2015, p. 707). Field-scale measurements show reductions of up to ~50% under wet soil conditions, while differences may be negligible under dry conditions where denitrification is limited (Masola et al., 2026, pp. 1, 9). We assume a range from 20-30% reductions in both N₂O emissions across operations associated with diesel use.

2. Abatement Economic/Feasible

Feasible abatement is lower than technical potential because further uptake depends on machinery compatibility, replacement cycles and whole-of-system economics. According to Sevenster et al. (2022) current adoption ~38%; projected to reach ~50% by 2030. At this rate, we might estimate feasible 10-year emissions reduction based on assumptions of 20-30% reduction in both operations and N₂O emissions, over 60-80% of cropping lands and 20-30% adoption rate above the current levels. Indicative estimates suggest 137-410 kt CO₂-e/year, assuming adoption is relatively evenly spread across cropping industries.

3. Breadth of Application

Summary: High – It is best suited to large-scale non-till farming systems where machinery scale and mechanization suit integration. It is therefore potentially applicable across most broadacre cropping systems, especially in cereals and oilseeds. Suitable for dryland cropping across all GRDC regions. Requires machinery compatibility but is adaptable to various soil types (Sevenster et al., 2022).

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4. Co-Benefit Potential

Summary: High – Yield improvements under CTF (10–30% in some systems) can reduce emissions intensity, but absolute emissions outcomes depend on nitrogen management and soil moisture conditions (Antille et al., 2015; Kingwell and Fuchsbichler, 2011)

reduced run-off and erosion, better water use efficiency, and lower machinery costs. Profit increases of up to 67% are reported due to combined benefits ranging from fuel efficiency to reduced compaction (Kingwell and Fuchsbichler, 2011).

5. Barriers and Knowledge Gaps

Summary: Medium – Barriers include high upfront costs of capital investment, machinery alignment within fleet and with contractors, operational vulnerabilities associated with reliance on dealer support and software, and the cognitive and management transaction costs associated with moving to a fully matched system. CTF is easiest to implement when machinery replacement or major system changes are already planned. There is limited data on GHG impacts across soil types, lack of ACCU methods. There is limited empirical data on GHG reductions in some regions.

6. Stacking Potential

Summary: High – Synergistic with precision nutrient management, reduced tillage, and cover cropping in that CTF can enhance effectiveness of other abatement technologies (Antille et al., 2015; Jensen et al., 2025) and support soil carbon and nitrogen efficiency strategies (Balafoutis et al., 2017).

7. Technology Readiness Level (TRL)

Summary: 9 – Fully mature and widely deployed in Australian cropping systems. Commercially available and proven in paddock conditions.

8. Commercial Readiness Level (CRL)

Summary: 5 – Commercially viable with moderate adoption; scaling supported by industry. Adoption at least 38% nationally, with; projected to increase. Supported by GRDC and machinery manufacturers (Sevenster et al., 2022).

9. Enabling Potential

Summary: High – Facilitates adoption of other precision agriculture technologies and supports system-level transformation. Enables precision input application and data-driven management. Reduces variability in paddock conditions, and can save significant labour time (Balafoutis et al., 2017).

10. Estimated Cost Range

Summary: Estimated at \$15–\$40/ha/year, depending on machinery retrofit and farm scale, based on amortized investment over 5–10 years. Includes GPS guidance and tramline setup. Retrofitting existing equipment can reduce costs. Figures are largely based on European estimated and may be significantly different in different areas and out of date (Balafoutis et al., 2017).

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11. Estimated financial Benefits

Summary: Estimated financial return of \$57–\$115/ha/year, including yield gains associated with avoided compaction and input savings, with larger gains predicted for larger operations (Kingwell and Fuchsbichler, 2011).

12. Investment in R&D and Commercialisation

Investment in CTF is integral to largescale machinery R&D and commercialization and relies on integrated technology and practice (e.g. machinery, tracking, planning, data integration).

Australian Investments include

- Research & Development: GRDC-funded studies
- CSIRO soil and systems modelling
- Estimated: <\$5million

Commercialisation investment include machinery manufacturers (e.g., Horsch, John Deere), GPS and guidance system providers

Global Investments include significant machinery development and trials:

- EU Horizon 2020 projects on precision agriculture such as (DEMETER, 2021)
- USDA conservation tillage and traffic farming trials

Lime Application Management

Lime application is a core soil amelioration practice used to address soil acidity, improve nutrient availability and maintain crop productivity. This is particularly important in Australian broadacre systems where subsurface and topsoil acidity continue to constrain yield and nitrogen use efficiency. From an emissions perspective, lime is better understood as a productivity and soil-function practice with emissions trade-offs, because application releases CO₂ but can improve nutrient use and support lower emissions intensity over time. This is not a direct abatement technology, but it has implications for on-farm emissions.

1. Annual Abatement Potential (Technical)

Summary: Optimised lime use, including variable-rate application, can indirectly influence nitrous oxide (N₂O) emissions by modifying soil pH, with downstream effects on nitrogen cycling processes (nitrification and denitrification) and nitrogen use efficiency (NUE) (Hénault et al., 2019). System modelling in Australian grain systems indicates that liming typically increases total emissions, with limited abatement potential except where it avoids higher-emission land-use transitions (Kharel et al., 2024). Lime application also contributes to direct CO₂ emissions, as carbonate minerals (e.g. CaCO₃) dissolve and release CO₂ during neutralisation reactions. These emissions are proportional to the quantity of lime applied and are treated as a direct source under IPCC accounting frameworks. On balance, the net technical abatement potential of optimised liming is small and uncertain. Indicative abatement is likely slightly negative, leading to slight (5-7%) increases in

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emissions associated with current liming practices (~1.3 Mt CO₂ e/ yr). This will be dependent on soil conditions, climate and nitrogen management.

2. Abatement Potential – Economic/Feasible

Summary: Realistic scope 1 abatement is expected to be negative (i.e. increasing overall emissions) but reducing emissions intensity by 5-15% through increased productivity (Page et al., 2009; Sevenster et al., 2022). Thus, liming is treated as a productivity and soil health-enhancing solution with abatement implications, and will be critical to improved emissions intensity of crops, especially in acid soils (Kharel et al., 2024). In the absence of good evidence, absolute feasible abatement is estimated to be slightly negative at -8 and -27 kT CO₂-e/year.

3. Breadth of Application

Summary: High applicability across broadacre cropping regions with acidic soils. Soil acidification is a widespread issue in Australian cropping systems.

4. Co-Benefit Potential

Summary: High

Co-benefits include improved soil structure, nutrient availability, and crop yields. Lime enhances soil health and productivity, indirectly improving NUE and reducing fertiliser losses.

5. Barriers and Knowledge Gaps

Summary: Medium – Barriers include product and freight cost, application logistics, and limited evidence on the full emissions implications of different liming strategies. While liming is well established agronomically, uptake is often delayed by cash-flow pressures, competing capital demands and the lag between investment and response. Key knowledge gaps for abatement include how different rates, placement strategies and lime sources affect both productivity and emissions outcomes across soil types

6. Stacking Potential

Summary: High – can be stacked with precision agriculture, NUE strategies, and alternative ameliorants. Lime use complements other soil health and nutrient management practices.

7. Technology Readiness Level (TRL)

Summary: TRL 9 – fully mature and widely adopted, although variable rate and targeted applications still remain a challenge in cropping industries.

8. Commercial Readiness Level (CRL)

Summary: CRL 6 – fully commercialised.

9. Enabling Potential

Summary: Medium – does not directly enable other abatement technologies, except through improved fertiliser use efficiency. It supports soil health, enables crop rotation choices, and as such can support reduced emissions intensity.

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10. Estimated Cost Range

Summary: \$30–\$80/ha/year depending on lime type, transport, and application method. Assuming application rate: 1–2 t/ha every 3–5 years. Lime cost: \$15–\$40/t; transport and spreading: \$15–\$40/t.

11. Estimated financial Benefits

Summary: \$100–\$300/ha/year in yield improvements especially from fertiliser efficiency.

12. Level of Investment in R&D and Commercialisation

Summary: Estimated investment: Lime is a mature technology with limited recent R&D, but some investment in precision application and alternatives.

- R&D: \$500,000–\$5 million

Commercialisation: \$0–\$100,000

- Industry Scaling: \$1–\$5 million

Legume Integration

Legume integration involves rotating legumes with non-leguminous crops to biologically fix atmospheric nitrogen (N_2), reducing the need for synthetic nitrogen fertilisers. The set of practices is diverse, ranging from including legumes in rotations as cash crops (currently increasing) to including legumes in pasture fallows (decreasing). These practices can variably enhance soil fertility, and contribute to more sustainable cropping systems.

Legume integration can reduce system-level N_2O emissions by lowering the requirement for synthetic nitrogen inputs, although emissions associated with residue decomposition may be higher due to the lower C:N ratio of legume residues (Officer et al., 2015). Common legumes include field peas, lentils, chickpeas, lupins, and pasture legumes such as serradella and biserrula. Each has its own growing requirements, product value and nitrogen fixing ability, and very different applications and outcomes are expected in different regions and cropping systems (Sevenster et al., 2022, pg. 46). GRDC (2025b) indicate that including legumes in the pasture phase can significantly reduce fertiliser demand. The opposite trend is apparent with a rise in intensive cropping and a reduction in the use of a pasture phase in cropping systems.

1. Annual Abatement Potential (Technical)

Due to lack access to relevant data, we focus on legume integration in pasture phase of pasture crop rotations, or through rotation of cereal and legume crops, which has been reported internationally as reducing GHG emissions by 10–30%, across N_2O and CO_2 (Prajapati et al., 2025), and in the Australian context able to reduce synthetic nitrogen fertiliser demands by producing up to 20–25 kg N/tonne of legume dry matter (Peoples et al., 2021). Australian systems do not provide clear figures of abatement potential of legume integration, as it is necessarily seen as part of a wider mix of nitrogen and soil management considerations (Bell et al., 2025).

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2. Abatement Potential – Economic/Feasible

Estimating feasible abatement for legume integration is complicated by interacting factors, and diverse options. With international figures above for potential abatement, and assumptions of this being relevant for 30-80% of cropping lands and including potential decline (dis-adoption) under current industry trends ranging from negative 10% (disadoption) to 50%, a wide range of emissions is estimated: from -11- 456 kt CO₂-e/year depending on the opportunity costs of ley pastures. This assessment acknowledges large data gaps and a limited scope. There may be much wider application as demand for pulses grows and the reliability of legume crops (e.g. lentils) improves, creating pathways for adoptable legumes within rotations.

3. Breadth of Application

Ranking: Medium

Legume integration is applicable (and used) across many broadacre cropping zones in Australia, including wheat, barley, canola, and sugarcane systems. Legumes are already part of rotations in most agro-ecological zones, but are declining in intensive cropping systems (Bell et al., 2024). Suitability and form of application varies by climate, soil, and cropping system. Legumes only provide benefit when soil N is a constraint.

4. Co-Benefit Potential

Ranking: High

Co-benefits include improved soil health, reduced pest and disease pressure, enhanced biodiversity, and increased livestock feed quality. Legumes also contribute to reduced input costs and diversified farm income. They contribute organic matter, support microbial activity, and can reduce nitrate leaching (Bezner Kerr et al., 2023).

5. Barriers and Knowledge Gaps

Ranking: Medium

Barriers include inconsistent legume performance, poor nodulation, seedbank depletion, and market volatility. Knowledge gaps exist in long-term nitrogen dynamics and optimal integration strategies and there is generally limited capacity in providing advice around the systems of use for legume integration (Bell et al., 2025). Optimisation approaches for multiple outcomes, based on values of landholders, are still in development (Hochman et al., 2021). Trends toward more intensive systems are leading to reduction in legume integration (Peoples et al., 2021). Legumes can require increased use of fungicides, adding to cost and reducing soil microbial action.

6. Stacking Potential

Ranking: High

Legume integration generally stacks well with reduced tillage, non-legume cover cropping, and precision nutrient management (Bezner Kerr et al., 2023). It is potentially

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733 complemented by abatement technologies like precision nutrient management, to improve
734 nitrogen cycling and soil structure. Legumes support reduced fertiliser reliance.

735 .

736 **7. Technology Readiness Level (TRL)**

737 Ranking: 9

738 Legume integration is a mature practice widely adopted in Australian agriculture. Ongoing
739 improvements in legume breeding, rhizobia strains, and tailoring seed mixes and practices
740 to systems continue to enhance effectiveness (Hochman et al., 2021; Norton et al., 2023).

741 **8. Commercial Readiness Level (CRL)**

742 Ranking: 5

743 Commercial viability is high in regions with established legume markets and agronomic
744 support. However, profitability varies with legume type, system, seasonal conditions and
745 market prices of synthetic fertiliser. Commercial viability is high in mixed systems. Legumes
746 are commercially grown but face market and agronomic limitations (Norton et al., 2023).

747 **9. Enabling Potential**

748 Ranking: medium

749 Legume integration enables reduced fertiliser dependence and can improve system
750 resilience (Bezner Kerr et al., 2023). It facilitates broader adoption of sustainable practices.
751 This requires advisory systems and rotational planning to optimize diverse benefits, which
752 is currently lacking (Hochman et al., 2021).

753 **10. Estimated Cost Range**

754 Range: \$20–\$80/ha/year

755 Costs include seed, inoculant, and agronomic management. Variability depends on legume
756 species, establishment success, and grazing integration. Opportunity costs can be large.

757 **11. Estimated financial Benefits**

758 Range: \$50–\$150/ha/year.

759 Benefits include fertiliser savings which vary significantly with price volatility, improved
760 yields in subsequent crops, and livestock feed value (GRDC, 2025c). High-value legumes like
761 can lentils offer strong gross margins, but there are often trade-offs between these and
762 value in offsetting fertilizer costs. Economic viability depends on costs of fertilisers, legume
763 yield, market access, and rotational benefits, with lentils and faba beans showing strong
764 returns. Hochman et al. (Hochman et al., 2021) show that legume N may be more efficiently
765 used in some systems, and have quite different trade-offs, creating a need for targeted
766 extension and capacity building within systems and regions.

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12. Investment in R&D and Commercialisation

Australian Investment:

- R&D: \$5–10 million there is currently numerous trials of legume crop integration within different systems and geographical contexts
- Commercialisation: Rhizobia strain development, legume breeding programs
- Industry Scaling: Farming systems trials, extension programs

Global Investment:

- R&D: >\$10 million (FAO, CGIAR, EU Horizon)
- Commercialisation: Global legume breeding and inoculant technologies
- Scaling: Integrated legume systems in Africa, Europe, and South America

Cover/Catch Cropping

Description: Cover crops can be used to ‘catch’, or capture, residual nitrogen and reduce N₂O emissions, thereby reducing direct emissions through denitrification. This involves establishing fast-growing crops (e.g., phacelia, oilseed radish) immediately after crop or pasture termination. This is particularly relevant in high rainfall zones where the risk of nitrate loss is elevated, and there is enough moisture and time to produce useful biomass. The practices can enhance nutrient retention, reduce Scope 1 emissions, and improve soil organic matter, soil health and yield in high rainfall areas.

1. Annual Abatement Potential (Technical)

Summary: Limited evidence is available on the degree to which catch crops may increase N₂O emissions in some contexts, with recent international studies indicating that these can increase where catch crops are grown compared to winter fallow (Nasser et al., 2025). Their value for GHG abatement may be more in sequestration than emissions reduction, but abatement potential is estimated at 1-2% of fertiliser-related emissions.

2. Abatement Potential – Economic/Feasible

Summary: Feasible abatement is likely to be modest because the technical potential appears limited and the area of practical fit is relatively small (estimated at 5-20%). In practice, uptake will depend heavily on seasonal moisture, sowing opportunity, rotational fit and whether the practice can be implemented without compromising the main crop, which suggests low 10-year adoption rates (assumed 20-40%), which gives 1-8 kT CO₂-e/year.

3. Breadth of Application

Summary: Medium applicability. Best suited to high rainfall zones and mixed farming systems with pasture phases. Less applicable in dryland continuous cropping.

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4. Co-Benefit Potential

Summary: High co-benefit potential, and mostly used for agronomic advantage. Improves soil structure, reduces erosion, enhances nutrient cycling, and supports biodiversity (Selzer and Schubert, 2021). May improve yield stability of subsequent crops (Basso et al., 2021).

5. Barriers and Knowledge Gaps

Summary: Medium barriers. The main constraints are seasonal fit, frost and moisture risk, and sowing opportunity. Adoption is more likely where catch crops can be integrated into lower-pressure windows and where machinery, livestock integration or mixed-farming benefits justify the extra management. Better local evidence and decision support are needed to show where the practice adds value without increasing operational risk. A key knowledge gap is limited region-specific evidence on both N₂O outcomes and whole-of-system economics.

6. Stacking Potential

Summary: High stacking potential. Can be combined with reduced tillage, pasture phases, and enhanced efficiency fertilisers in some circumstances. Combinations of practice have potential to produce synergistic abatement, soil health and agronomic benefits, but these will be highly system/season specific (Basso et al., 2021).

7. Technology Readiness Level (TRL)

Summary: TRL 7 – Demonstrated in relevant environments.

Catch cropping is well-studied and trialled in semi-controlled and paddock settings, but not widely adopted.

8. Commercial Readiness Level (CRL)

Summary: CRL 3 – Commercial trials underway. Limited commercial uptake, but supported by initiatives like Cool Soil and LEIFS. Requires market signals and advisory support.

9. Enabling Potential

Summary: Low enabling potential. Supports broader nitrogen management and carbon accounting frameworks. Needs integration into advisory systems and carbon calculators.

10. Estimated Cost Range

Summary: Estimated cost: \$40–\$90/ha/year, depending on species, seed cost, sowing method, and termination. Costs include seed, sowing, and potential opportunity cost. Lower for self-seeding or volunteer species.

11. Estimated financial Benefits

Summary: Estimated benefit: \$60–\$150/ha/year, from reduced fertiliser needs, improved soil health, and potential yield gains. Financial benefits accrue through nutrient retention, and improved productivity of subsequent crops. Benefits will vary substantially by region and system and be absent in many systems.

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12. Investment in R&D and Commercialisation

Australian Investments: \$100,000–\$5 million range.

Research & Development:

- GRDC-funded trials on nitrogen cycling and catch cropping (GRDC 2024a, 2025) 2 6.
- NSW DPI studies on abatement strategies (NSW DPI 2023) 1.

Commercialisation:

- Cool Soil Initiative supports catch cropping indirectly (GroundCover 2024)4.

Industry Scaling:

- LEIFS initiative (\$39M) supports low-emissions cropping.

Global Investments \$1–\$10 million range.

- Research & Development: EU and US studies on nutrient retention and cover crops.
- Commercialisation: Limited direct investment; mostly through regenerative agriculture programs.
- Industry Scaling: Increasing recognition in carbon markets and sustainability certifications.

Arbuscular Mycorrhizal Fungi (AMF) Inoculation

Description: AMF inoculation involves adding arbuscular mycorrhizal fungi to support root-soil interactions, particularly for phosphorus and nitrogen uptake, soil biological function and soil structure. A key challenge in understanding the effects of AMF inoculation is that soils already contain various AMF communities, so baselines vary widely.

1. Annual Abatement Potential (Technical)

Summary: There is currently limited evidence, but early studies (Li et al., 2023; Teutscherova et al., 2019) indicate high (46% and 63%) reduction in N₂O emissions in AMF-inoculated plots compared to controls after urea application. While more research is needed, an initial estimate of 10-20% reduction in fertiliser-related N₂O emissions has been applied as a first pass.

2. Abatement Potential – Economic/Feasible

Summary: Feasible abatement is likely to be lower than the technical range because field performance is variable and broadacre adoption would require reliable colonisation, demonstrable long-term value, and affordable products and practical delivery systems (Abbott et al., 2018). These uncertainties lead us to estimate that AMR could reduce N₂O emissions associated with fertilizer and liming across 10-50% of cropping areas, with 10 year an adoption rate of 5-30%, to give an abatement range of 13– 220 kt CO₂e/year.

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3. Breadth of Application

Summary: Medium – Applicable across many broadacre crops, but effectiveness varies with soil type, crop species, and existing microbial communities. AMF inoculum form symbioses with most crops, but colonization success and benefits vary.

4. Co-Benefit Potential

Summary: High – Includes improved nutrient uptake, soil health, drought resilience, and reduced fertilizer dependence. AMF enhances root biomass, microbial nitrogen, and reduces nitrate leaching (Teutscherova et al., 2019).

5. Barriers and Knowledge Gaps

Summary: Medium – Includes variability in paddock performance, inoculum quality, and lack of standardized protocols. Colonization success is inconsistent; long-term effects and interactions with other microbes are not fully understood (Teutscherova et al., 2019).

6. Stacking Potential

Summary: Medium – Where systems integration is understood, AMF inoculum have potential to be combined with cover cropping, and biofertilizers to build synergistic effects of biological inputs and regenerative practices.

7. Technology Readiness Level (TRL)

Summary: TRL 6 – Demonstrated in limited controlled and field trials, but not yet widely adopted commercially.

8. Commercial Readiness Level (CRL)

Summary: CRL 3 – Commercial inoculants exist, but market penetration and farmer uptake are low. Limited standards are being developed for some products (Norton et al. 2023).

9. Enabling Potential

Summary: Medium – AMF can support system-level functioning, rather than delivering consistent standalone benefits. AMF could contribute to system-level improvements but requires integration with advisory and monitoring systems, and improved standards and regional testing of applications at paddock scale (Abbott et al., 2018).

10. Estimated Cost Range

Summary: \$20–\$60/ha/year depending on inoculum type, application method, and frequency. Commercial inoculants vary in cost; application may require specialized equipment or timing.

11. Estimated financial Benefits

Summary: \$30–\$100/ha/year through reduced fertilizer use, improved yield stability, and soil health. Benefits depend on crop type, soil conditions, and integration with other practices.

12. Level of Investment in R&D and Commercialisation

Australian Investments:

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- 906 • R&D: \$100,000–\$5 million, GRDC-supported trials on biological inputs and
- 907 microbial inoculants. DPIRD consultation and modeling
- 908 • Commercialisation: \$0–\$100,000. Limited commercial scaling; mostly small biotech
- 909 firms.
- 910 • Industry Scaling: Not yet evident.

911 Global Investments:

- 912 • R&D: \$5–\$50 million. EU Horizon projects on microbial soil amendments. US-based
- 913 trials on AMF in maize and soybean systems, and large corporate interest in
- 914 regenerative systems.

915 **Biochar Application**

916 Description: Biochar is a class of carbon-rich materials produced via pyrolysis of organic
 917 biomass in low-oxygen conditions. When applied to soils, it can improve soil health and
 918 function, support carbon sequestration, reduce greenhouse gas emissions (particularly
 919 nitrous oxide), and improve crop productivity. Understanding of the effectiveness of
 920 biochar in reducing farm emissions is limited and depends on the biochar type (feedstock x
 921 pyrolysis conditions), application rate, placement/incorporation method, and underlying
 922 production constraints (soil type x climate). These variations and interactions with carbon
 923 and nutrient cycling make the agronomic and abatement case hard to quantify and strongly
 924 site and context-specific. It is largely considered a sequestration and negative emissions
 925 option.

926 **1. Annual Abatement Potential (Technical)**

927 Summary: Estimated technical abatement of non-CO₂ GHG emissions from soils have been
 928 assessed as ranging from 12-50% (Joseph et al., 2021), upper limits are unlikely to be
 929 applicable at scale, and there remains significant uncertainty about efficacy across a limited
 930 range of experiments globally (Kaur et al., 2023). A 12-38% range of emissions reduction
 931 associated with nitrogen application is defensible (Kaur et al., 2023).

932 **2. Abatement Potential – Economic/Feasible**

933 Summary: Feasible emissions abatement is likely to be much lower than the technical
 934 potential because adoption in broadacre systems is constrained by product cost, freight,
 935 spreading logistics and uncertainty around consistent responses. Feasible abatement of
 936 scope 1 emissions is thus assumed at an adoption rate of 5-10% of population, on 5-10% of
 937 cropping land within 10 year with a reduction of 1 – 16 kT CO₂-e/year nationally. This may
 938 be optimistic given the current costs of application, and the difficulty in demonstrating
 939 efficacy and developing supporting MRV and incentives.

940 **3. Breadth of Application**

941 Summary: Medium

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942 Applicable across many cropping systems, especially acidic and sandy soils, but limited by
943 cost and logistics.

944 **4. Co-Benefit Potential**

945 Summary: High

946 Improves soil structure, water retention, nutrient cycling, and microbial activity, which can
947 contribute to improved yield, but results of applications vary widely (Joseph et al., 2021).
948 Pyrolysis and biochar manufacture could form an important negative emissions industry,
949 potentially creating significant reduction in costs of application, particularly if integrated
950 with fertilizer manufacture. Recent synthesis suggests targeted applications could be
951 effective for sequestration, as a negative emissions technology, but are costly and not
952 mature technically. NSW DPI estimates biochar could reduce economy wide emissions by
953 1.6 Mt CO₂-e/year in NSW alone, with broader national potential likely exceeding 5 Mt CO₂-
954 e/year (Cowie et al., 2025).

955 **5. Barriers and Knowledge Gaps**

956 Summary: High Cost, supply chain constraints due to limited market development,
957 variability in performance, uncertainty about longevity of response, lack of standards, and
958 limited field trials (Joseph et al., 2021).

959 **6. Stacking Potential**

960 Summary: High

961 Can be combined with compost, fertilisers, and precision agriculture for synergistic effects,
962 however understanding of appropriate formulations remains limited, and context specific.
963 Its applications are not simply through stacking but site-specific integration with farm
964 systems and practices (Macdonald et al., 2016).

965 **7. Technology Readiness Level (TRL)**

966 Summary: 7

967 Proven in trials and some commercial use, but not yet widely adopted in broadacre
968 cropping. Multiple field trials and commercial demonstrations exist, but substantial
969 uncertainties remain (Zhong et al., 2025).

970 **8. Commercial Readiness Level (CRL)**

971 Summary: 3

972 Early commercialisation with limited market penetration. ANZBIG roadmap identifies need
973 for investment to prove up technologies and bring to scale-up phase (ANZBIG, 2023).

974 **9. Enabling Potential**

975 Summary: Medium

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976 Supports carbon accounting and soil health frameworks but not a systemic enabler. There
 977 appears to be at least one proponent-led ACCU Scheme method in development at the time
 978 of writing (unverified).

979 **10. Estimated Cost Range**

980 Summary: \$150–\$2000/ha depending on feedstock, transport, and application method.
 981 Costs vary widely and are lower for on-farm production at scale.

982 **11. Estimated financial Benefits**

983 Summary: The benefits of biochar use in cropping vary widely and include agronomic
 984 benefits, carbon sequestration, emissions reduction and soil health benefits. Total benefits
 985 are estimated at ~\$600 – 800 / Ha as a one-off benefit – as a majority come from carbon
 986 sequestration with ~1/3 from yield and savings in fertilizer costs. The ways benefits accrue
 987 varies substantially by context making these estimate of low confidence.

988 **12. Investment in R&D and Commercialisation**

989 Australian Investments:

990 R&D: Estimated: <\$5M including:

- 991 • GRDC-funded trials with CSIRO and UWA
- 992 • DAFF national biochar initiative

993 Commercialisation: Estimated: \$100K–\$5M

- 994 • Small-scale trials by Energy Farmers Australia, Green Man Char 2

995 Industry Scaling: Estimated: \$10M+ in planned investment

- 996 • ANZBIG targets \$1–\$5B industry by 2030 (ANZBIG, 2023)

997 Global Investments: Estimated: \$100M+ globally

- 998 • Significant research in US, EU, and China; IPCC recognises biochar as a negative
 999 emissions technology (NET)

1000 **Stubble Retention**

1001 Description: Stubble retention refers to retaining crop residues (stubble) on the paddock
 1002 after harvest rather than burning or removing them. As a core component of conservation
 1003 farming in Australia, it is used to support groundcover, erosion control, water retention and
 1004 soil structure and function. It is widely adopted in Australian dryland cropping systems. On
 1005 this basis, further abatement advantages would come from optimizing stubble retention.

1006 **1. Annual Abatement Potential (Technical)**

1007 Summary: Stubble retention can reduce emissions by avoiding burning and enhancing SOC
 1008 sequestration. Estimated technical abatement potential is modest, especially in dryland
 1009 cropping (Janke et al., 2025) increases in N₂O emissions that offset gains can occur (Abalos

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1010 et al., 2022). Residue retention can contribute to SOC accumulation, but the rate is
 1011 constrained by climatic and soil factors, and particularly the availability of nutrients. A
 1012 rough estimate of 1-5% reduction of residue-associated emissions is justifiable.

1013 **2. Abatement Potential – Economic/Feasible**

1014 Summary: Feasible abatement is difficult to estimate. There is already very high adoption.
 1015 Economic viability depends on yield impacts, nutrient availability, and water use efficiency.
 1016 In low rainfall areas, benefits may be marginal (Janke et al., 2025). Gains will mostly come
 1017 from reduced stubble burning in cane growing areas where this is still practiced. Overall
 1018 cropping we assume marginal adoption gains of 3-5% over ten years to reach almost
 1019 complete adoption in the remaining 5-10% of relevant cropping land, giving very low rates
 1020 of emissions reduction of 0.4-0.7 kT CO₂-e/year.

1021 **3. Breadth of Application**

1022 Summary: High – Applicable across most broadacre cropping systems in Australia. Stubble
 1023 retention is already widely practiced in cereals, pulses, and oilseeds under conservation
 1024 agriculture .

1025 **4. Co-Benefit Potential**

1026 Summary: High – high adoption reflects strong but largely realised co-benefits, including:
 1027 water retention, erosion control, and nutrient availability associated with increased
 1028 microbial activity. Stubble retention improves resilience to drought and supports long-term
 1029 productivity (Janke et al., 2025). There are potential opportunities to use a fraction of
 1030 stubble as a feedstock for bioeconomy (e.g. biofuels/plastics) production, offsetting fossil
 1031 fuel use and creating new markets for agricultural products but these need to be balanced
 1032 with risks of impacting SOC, nutrient recycling, erosion control and other ecosystem
 1033 serviced that stubble provides .

1034 **5. Barriers and Knowledge Gaps**

1035 Summary: Medium – The main constraints are nutrient tie-up, disease carryover, sowing
 1036 and establishment issues in heavy residue loads, and variable soil organic carbon responses
 1037 - particularly in lower rainfall environments (Janke et al., 2025). In practice, stubble
 1038 retention is generally easiest to maintain where it fits existing seeding systems and residue
 1039 handling capacity. Better understanding of stcking is also need, for example how stubble
 1040 load interacts with emerging EEFs – there is limited quantitative understanding of how this
 1041 may influence emissions in differing agroecological conditions ..

1042 **6. Stacking Potential**

1043 Summary: High – Can be combined with no-till, cover crops, legumes, and nutrient
 1044 management. Potential use with nitrification inhibitors and other EEF to reduce associated
 1045 emissions (Abalos et al., 2022)

1046 **7. Technology Readiness Level (TRL)**

1047 Summary: 9 – Fully mature and widely adopted. Established practice with decades of use
 1048 and research support.

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1049 **8. Commercial Readiness Level (CRL)**

1050 Summary: 6 – Fully commercial and scaled.

1051 **9. Enabling Potential**1052 Summary: Medium – Stubble retention can create conditions for other practices, such as the
1053 use of EEFs (discussed above), but does not directly enable them.1054 **10. Estimated Cost Range**1055 Summary: There is a wide range of possible practices and technologies and associated costs
1056 (including opportunity cost of residue removal and nutrient tie-up) which we estimate
1057 between \$0–\$20/ha/year. Costs are often indirect, such as reduced grazing or nutrient
1058 immobilisation.1059 **11. Estimated financial Benefits**1060 Summary: Benefits are similarly indirect and associated with different options in different
1061 locations and cropping systems, estimated here as \$20–\$80/ha/year. These include indirect
1062 benefits from yield stability, reduced erosion, improved water use. Benefits vary by region
1063 and rainfall; higher in medium–high rainfall zones.1064 **12. Investment in R&D and Commercialisation**

1065 Australian Investments

1066 Research & Development:

- 1067 • Numerous GRDC-funded studies on stubble management and SOC have aimed to
- 1068 evaluate options and improve targeted practices for multiple outcomes, but these
- 1069 have yet minimally addressed scope 1 emissions reduction. Of particular relevance,
- 1070 “Quantifying greenhouse gas emissions from the decomposition of crop residue” is
- 1071 examining GHG emissions from stubble (cereals, oilseeds, legumes) breakdown
- 1072 under field conditions.
- 1073 • This topic also is a partial focus of GRDC Low Emissions Intensity Farming Systems
- 1074 (LEIFS): \$39M over 5 years.

1075 Commercialisation:

1076 Industry Scaling:

- 1077 • Fertcare® and GRDC extension programs.

1078 Investment Range:

- 1079 • \$5M (R&D and extension combined)

1080 Global Investments

- 1081 • FAO and IPCC reports on conservation agriculture and SOC.

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1082 **Electric Farm Machinery (Electric Tractors, etc.)**

1083 Electric farm machinery involves replacing diesel-powered tractors and equipment with
 1084 battery-electric or fuel-cell-powered alternatives. These machines produce zero on-site
 1085 exhaust emissions and, when powered by renewable electricity, can operate with near-zero
 1086 carbon emissions. They are increasingly available in Australia, particularly for light and
 1087 medium-duty applications, and are being trialled in orchards, vineyards, and broadacre
 1088 settings.

1089 **1. Annual Abatement Potential (Technical)**

1090 Summary: Electric tractors can theoretically eliminate 100% CO₂ emissions from diesel
 1091 combustion in machinery, which accounts for about 11% of cropping emissions in Australia
 1092 (~1.5 Mt CO₂-e/year in 2005 and 2020, (Sevenster et al., 2022; Sevenster and Burrett,
 1093 2025).

1094 **2. Abatement Potential – Economic/Feasible**

1095 Summary: Feasible abatement is lower due to high upfront costs, limited availability of
 1096 heavy-duty models and infrastructure gaps. Estimated feasible is difficult to predict with
 1097 rapid changes but is estimated at between 240-720 k T CO₂-e/year, based on assumptions
 1098 of applicability across much of cropping (50-90%) , though constrained in heavy-duty
 1099 broadacre systems of the cropping area leading to relatively low (20-50%) 10-year
 1100 adoption rates.

1101 **3. Breadth of Application**

1102 Ranking: Medium. Electric machinery is currently applicable to small-medium vehicles and
 1103 specialty crops; limited for large-scale broadacre operations.

1104 **4. Co-Benefit Potential**

1105 Ranking: High. Electric tractors reduce noise, improve air quality, lower fuel costs, and
 1106 enhance safety.

1107 **5. Barriers and Knowledge Gaps**

1108 Ranking: High Key barriers include battery limitations, high capital costs, lack of charging
 1109 infrastructure, and limited servicing expertise, and long duty cycles.

1110 **6. Stacking Potential**

1111 Ranking: High. Electric tractors stack well with solar PV, precision agriculture, and
 1112 controlled traffic farming. Can be integrated with GPS auto-steer, variable rate tech, and
 1113 solar-powered charging.

1114 **7. Technology Readiness Level (TRL)**

1115 Ranking: 7–8. Electric tractors are commercially available for light-medium duty; heavy-
 1116 duty models are in prototype or early deployment. Multiple models in market; ongoing
 1117 trials for larger units.

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1118 **8. Commercial Readiness Level (CRL)**

1119 Ranking: 4. Commercialisation is underway, limited by cost and infrastructure. Sales are
1120 growing, but market penetration remains low 6.

1121 **9. Enabling Potential**

1122 Ranking: Medium. Potentially enables smart farming and integration with renewables.

1123 **10. Estimated Cost Range**

1124 Estimate: \$150–\$400/ha/year (varies by farm size and duty cycle). High upfront costs;
1125 lower operating costs over time. Assumptions: Includes capital amortisation, electricity, and
1126 maintenance.

1127 **11. Estimated financial Benefits**

1128 Estimate: \$100–\$300/ha/year in fuel and maintenance savings. .

1129 **12. Investment in R&D and Commercialisation**

1130 Australian Investment

1131 Total Range: \$5M–\$20M

- 1132 • Hort Innovation & Bluewhite: \$220M portfolio includes autonomous electric tractor
- 1133 retrofits.
- 1134 • CEFC Pathfinder: Funding guidance for electric farm vehicles.

1135 Global Investment: Range: \$100M+

- 1136 • Monarch Tractor, Solectrac, CNH Industrial, John Deere – active in electric tractor
- 1137 development.

1138 **Alternate Fuels (Biodiesel & Others)**

1139 Description: Alternate fuels such as biodiesel and renewable diesel (HVO) offer low-carbon
1140 or carbon-neutral substitutes for conventional diesel in agricultural machinery. Biodiesel is
1141 derived from vegetable oils, animal fats, or waste cooking oils via transesterification, while
1142 renewable diesel is produced through hydrotreatment and is chemically similar to fossil
1143 diesel. These fuels still emit GHG when burnt, but they contribute to lower Scope 1
1144 emissions under current accounting conventions, due to lower emissions factors. They can
1145 generally be used in existing diesel engines with minimal modifications.

1146 **1. Annual Abatement Potential (Technical)**

1147 Summary: Biodiesel and renewable diesel can reduce emissions by up to 99% compared to
1148 fossil diesel, based on the emissions factors of biodiesel (0.024 kg CO₂-e/L) and fossil diesel
1149 (2.704 kg CO₂-e/L) as given in Australian NGA factors for scope 1 emissions.

1150 **2. Abatement Potential – Economic/Feasible**

1151 Summary: Feasible abatement is lower due to technical, infrastructure and supply
1152 constraints, which constrain supply, make costs uncompetitive, and slow adoption. If we

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1153 assume this pathway scales and becomes cost-competitive (or supported by incentives)
 1154 then the application area could be from 50-90% of cropping machinery and adoption rates
 1155 ranging from 20-90% by 2035, we arrive at a potential of 238-713 kT CO₂-e/year.

1156 **3. Breadth of Application**

1157 Summary: High. Applicable across all broadacre cropping systems using diesel-powered
 1158 machinery.

1159 **4. Co-Benefit Potential**

1160 Summary: High. Supports rural economies through new agricultural opportunities in
 1161 feedstock production and industrial production of LCLFs, reduces reliance on imported
 1162 fuels, and enhances energy security.

1163 **5. Barriers and Knowledge Gaps**

1164 Summary: Medium. Barriers include limited commercial-scale production, feedstock
 1165 competition, and lack of awareness.

1166 **6. Stacking Potential**

1167 Summary: High. Can be combined with electrification, biogas, and precision agriculture for
 1168 cumulative emissions reduction, and incorporated in hybrid systems (Gjerek et al., 2021).

1169 **7. Technology Readiness Level (TRL)**

1170 Summary: 8–9. Biodiesel is mature and widely used; renewable diesel is commercially
 1171 proven overseas and in pilot stages in Australia.

1172 **8. Commercial Readiness Level (CRL)**

1173 Summary: 3–4. Biodiesel is available but limited in scale; renewable diesel is emerging with
 1174 pilot plants and early market entry.

1175 **9. Enabling Potential**

1176 Summary: Medium. Supports transition to net zero by enabling immediate emissions
 1177 reductions without infrastructure overhaul.

1178 **10. Estimated Cost Range**

1179 Summary: Costs vary by feedstock and production method; renewable diesel shows
 1180 promise for cost parity, but is currently prohibitively expensive due to low supply, technical
 1181 and scaling challenges.

1182 **11. Estimated financial Benefits**

1183 Summary: \$150–\$300/ha/year in fuel savings and carbon credits. Reduced fuel costs,
 1184 carbon credit eligibility, and potential income from feedstock supply.

1185 **12. Investment in R&D and Commercialisation**

1186 Australian Investments

1187 Research & Development:

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- 1188 • ARENA Bioenergy Roadmap (2021): >\$5M
- 1189 • NSW Net Zero Commission submissions: active support for biodiesel and renewable
- 1190 diesel, Priority under Future Made in Australia
- 1191 Commercialisation:
- 1192 • Australian Federal Government has committed \$1.1 Billion to the Cleaner Fuels
- 1193 Program
- 1194 • Viva Energy and Ampol pilot facilities
- 1195 • Paradigm Fuels biodiesel production from sorghum
- 1196 Industry Scaling:
- 1197 • Bioenergy Australia alliances (LCFAANZ, RGA)
- 1198 Global Investments
- 1199 • EU & US: Biodiesel dominates low-carbon liquid fuel markets
- 1200 • Boeing & Wagner SAF Roadmap: SAF and biodiesel integration in aviation 8
- 1201 **Nitrogen-Fixing Non-Legume Crops**
- 1202 Description: Nitrogen-fixing, non-legume crops are genetically engineered to fix
- 1203 atmospheric nitrogen directly, bypassing the need for synthetic nitrogen fertilisers. This is
- 1204 achieved by transferring bacterial nitrogenase pathways into plant mitochondria. The
- 1205 approach aims to reduce nitrous oxide (N₂O) emissions from fertiliser use and CO₂
- 1206 emissions from fertiliser production, while improving nutrient efficiency and reducing input
- 1207 costs.
- 1208 **1. Annual Abatement Potential (Technical)**
- 1209 Summary: Synthetic nitrogen production and use of fertilisers contribute ~13 Mt CO₂-e
- 1210 annually in Australia (Climate Change Authority, 2024), including ~4.1 Mt CO₂-e scope 1
- 1211 emissions on farm associated with N₂O emissions. Reducing the need for fertiliser
- 1212 production and use would be potentially transformative for reducing emissions, costs of
- 1213 production and boosting productivity. As this technology is in an early experimental phase a
- 1214 potential annual abatement range of 5-50% of scope 1 emissions is provided as an estimate.
- 1215 Reduced emissions from operations changes are not included due to the high uncertainties
- 1216 around this technology.
- 1217 **2. Abatement Potential – Economic/Feasible**
- 1218 Feasibility cannot yet be estimated on this unproven but highly prospective technology.
- 1219 Beyond significant technical challenges, scaling would require regulatory approval, public
- 1220 acceptance, and integration into cropping systems (Climate Change Authority, 2024). A
- 1221 wide range of estimates is used to demonstrate the range of feasible emissions – application
- 1222 areas ranging from 10-90% of Australian cropping lands, and comparable rates of adoption
- 1223 within these provide a range of 2-1661 kt CO₂-e/year.

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1224 **3. Breadth of Application**

1225 Summary: High

1226 Applicable across broadacre crops including wheat, barley, sorghum, and cotton, which
1227 dominate Australian cropping.

1228 **4. Co-Benefit Potential**

1229 Summary: High

1230 Reduces input costs, improves soil health, lowers water contamination risk, and enhances
1231 resilience to climate variability. Dramatic reduction in scope 3 emissions from fertilizer
1232 manufacture.

1233 **5. Barriers and Knowledge Gaps**

1234 Summary: High. Major barriers include technical complexity, biosafety regulation,
1235 intellectual property, and public perception of GMOs.

1236 **6. Stacking Potential**

1237 Summary: High. Could be combined with precision agriculture, low-till systems, and
1238 microbial inoculants for synergistic benefits.

1239 **7. Technology Readiness Level (TRL)**

1240 Summary: 4–5. Proof-of-concept demonstrated in model plants; field trials in cereals are in
1241 early stages.

1242 **8. Commercial Readiness Level (CRL)**

1243 Summary: 2. Not yet available; technical, regulatory and market pathways under
1244 development.

1245 **9. Enabling Potential**

1246 Summary: Medium. Could enable broader decarbonisation by reducing fertiliser
1247 dependence and supporting carbon accounting frameworks.

1248 **10. Estimated Cost Range**

1249 Summary: N/A at this stage of research.

1250 **11. Estimated financial Benefits**

1251 Eliminating synthetic fertiliser use and improving nitrogen use efficiency can deliver
1252 significant economic returns.

1253 **12. Investment in R&D and Commercialisation**

1254 Australian Investments

1255 Research & Development: There is a global race to develop this technology and associated
1256 rights

- 1257 • CSIRO Synthetic Biology FSP: >\$5M (2020–2025)

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- 1258 • ARC Centre of Excellence in Synthetic Biology: ~\$35M (2020–2027)
- 1259 Commercialisation:
- 1260 • Early-stage partnerships with seed companies and biotech firms
- 1261 Industry Scaling:
- 1262 No current large-scale deployment; pilot trials underway
- 1263 Global Investments
- 1264 • US & EU: SynBio nitrogen fixation projects by Pivot Bio, Joyn Bio, and EU Horizon
- 1265 2020
- 1266 • Estimated Global R&D Investment: >\$100M across public and private sectors
- 1267 **Biological Nitrification Inhibition (BNI) Crops**
- 1268 Biological nitrification inhibition (BNI) crops are crop genotypes selected or engineered to
- 1269 release root compounds that suppress nitrification in the rhizosphere. In principle, this
- 1270 slows conversion of ammonium to nitrate and reduces the risk of N loss as N₂O or leached
- 1271 nitrate. The concept is attractive because the mitigation is embedded in the crop rather than
- 1272 added as a separate input, but for Australian broadacre systems the technology is still at an
- 1273 early stage, and commercial cultivars are not yet available. BNI traits have been identified in
- 1274 tropical grasses (e.g. *Brachiaria humidicola*) and cereals like sorghum, rice, and wheat (Leon
- 1275 et al., 2022).
- 1276 **1. Annual Abatement Potential (Technical)**
- 1277 BNI crops can theoretically reduce nitrification-driven N₂O emissions by 30–50%, based on
- 1278 suppression of ammonia monooxygenase activity in soils. This is comparable to chemical
- 1279 nitrification inhibitors but achieved biologically. Effectiveness depends on root exudation
- 1280 rates, soil type, and N fertiliser regime. Unlike chemical inhibitors, BNI acts continuously
- 1281 during crop growth, offering season-long mitigation potential once plants are established
- 1282 (Leon et al., 2022).
- 1283 **2. Feasible Annual Abatement (ABfeas)**
- 1284 We assume a 20-40% reduction in N₂O emissions as feasible for BNI crops, within 20 years.
- 1285 This extends to wheat and sorghum (~60-90% of total cropping land (based on Sevenster et
- 1286 al., 2022)) and are developed and extended to achieve 20-80% adoption by 2045, feasible
- 1287 abatement could be between 148-738 kt CO₂e/year. While reliability is increasing for
- 1288 sorghum applications, wheat is still in the early development phase, which accounts for high
- 1289 uncertainty, expressed here as wide adoption rates.
- 1290 **3. Breadth of Application**
- 1291 Summary: Medium. Currently limited to specific genotypes of wheat, rice, sorghum, and
- 1292 tropical grasses. Expansion to other crops is under research.

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4. Co-Benefit Potential

Summary: High. BNI crops improve nitrogen use efficiency (NUE), reduce nitrate leaching, and may enhance root development and soil health (Beeckman et al., 2024) leading to yield advantages.

5. Barriers and Knowledge Gaps

Summary: High. If the biological development need to ensure trait can be delivered through competitive varieties that fit existing farming systems without sacrificing other traits (yield, disease resistance, etc). There are also likely to be regulatory, stewardship and market acceptance hurdles depending on the breeding pathway used. There is currently limited understanding of BNI compound transport, variability in trait expression, and a lack of commercial cultivars (Beeckman et al., 2024).

6. Stacking Potential

Summary: High. In theory, BNI could be combined with legume rotations, and precision N management, and may reduce reliance on applied nitrification inhibitors, but potentially work well with UI and other slow-release formulations.

7. Technology Readiness Level (TRL)

Summary: TRL 4. Proof-of-concept demonstrated in lab and limited field trials.

8. Commercial Readiness Level (CRL)

Summary: CRL 2. Early-stage breeding programs exist; no widespread commercial cultivars yet.

9. Enabling Potential

Summary: Medium. BNI crops could support broader nitrogen management strategies and carbon accounting if it provides consistent results in reducing N₂O losses, but it is too soon to predict these results.

10. Estimated Cost Range

Summary: Currently unknown; expected to be minimal if BNI traits are embedded in existing cultivars. Costs would be embedded in seed purchase; no additional inputs required.

11. Estimated financial Benefits

Summary: Potential yield increases through improved NUE, reduced fertiliser requirements, and reduced N losses could enhance profitability.

12. Investment in R&D and Commercialisation

Australian Investments

- Research & Development: GRDC-funded trials on BNI wheat and sorghum (est. \$500,000–\$5 million). CSIRO collaborations on NUE and BNI traits (est. \$1–2 million)

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- 1329 • Commercialisation: Early-stage breeding programs with GRDC and universities (est.
1330 \$100,000–\$500,000)
- 1331 • Industry Scaling: None identified yet

1332 Global Investments

- 1333 • Research & Development: JIRCAS (Japan) and CIMMYT (Mexico) on BNI in tropical
1334 grasses and cereals (est. \$5–10 million)¹. Bill & Melinda Gates Foundation support
1335 for BNI in rice (est. \$1–5 million)
- 1336 • CIMMYT's BNI wheat mission aims to integrate traits into high-yielding varieties for
1337 sustainable intensification and climate-smart agriculture.

1338 **Green Cane Harvesting (No Burn in Sugarcane)**

1339 Green cane harvesting involves mechanically harvesting sugarcane without pre-harvest
1340 burning of the trash (leaves and tops). Instead of incinerating residues, the trash is left on
1341 the paddock as mulch. This practice avoids direct emissions of methane (CH₄) and nitrous
1342 oxide (N₂O) from combustion and contributes to soil health and moisture retention. It is
1343 widely adopted in Australia and globally.

1344 **1. Annual Abatement Potential (Technical)**

1345 Eliminating burning avoids direct CH₄ and N₂O emissions, with technical abatement
1346 potential estimated at 0.5–1.5 t CO₂-e/ha/year depending on region and burn intensity.

1347 **2. Abatement Potential – Economic/Feasible**

1348 Feasible abatement is low due to high existing adoption, with industry estimates of small
1349 (~10,500 Ha in NSW) areas still subject to burning, due to regional constraints, which may
1350 be difficult to overcome. Estimated ER is thus in the 5-10 kt CO₂-e/year range.

1351 **3. Breadth of Application**

1352 Summary: High. Applicable and adopted across most sugarcane regions in Australia,
1353 especially Queensland and NSW. Trials conducted across 12 regions demonstrate value
1354 (Patane et al., 2020).

1355 **4. Co-Benefit Potential**

1356 Summary: High. Improves soil health, reduces erosion, retains moisture, and enhances
1357 biodiversity.

1358 **5. Barriers and Knowledge Gaps**

1359 Summary: Low

1360 Barriers include harvester settings, operator training, and management of increased EM
1361 (extraneous matter), as well as cultural barriers (Patane et al., 2020). In the remaining burn
1362 systems, adoption may also be constrained by seasonal conditions, harvest logistics and mill
1363 requirements. As a result, the final increment of adoption can be operationally difficult even
1364 where the technical case is clear.

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- 1365 **6. Stacking Potential**
 1366 Summary: High
- 1367 Can be combined with enhanced efficiency fertilisers, nitrification inhibitors, and precision
 1368 agriculture (Friedl et al., 2023).
- 1369 **7. Technology Readiness Level (TRL)**
 1370 Summary: 9
- 1371 Fully commercial and widely used in Australia.
- 1372 **8. Commercial Readiness Level (CRL)**
 1373 Summary: 6
- 1374 Commercially viable with proven economic benefits and industry support.
- 1375 **9. Enabling Potential**
 1376 Summary: Medium
- 1377 Supports broader emissions accounting frameworks and practice improvement.
- 1378 **10. Estimated Cost Range**
 1379 Summary: \$61–101/ha/year additional harvesting cost
- 1380 Reduced ground speed increases harvesting time and cost (Patane et al., 2020).
- 1381 **11. Estimated financial Benefits**
 1382 Summary: \$116–151/ha/year net benefit
- 1383 Justification: Increased cane and sugar yield offsets higher harvesting costs (Patane et al.,
 1384 2020).
- 1385 **12. Investment in R&D and Commercialisation**
 1386 Australian Investments:
- 1387 • Research & Development: Sugar Research Australia (SRA) trials (2017–2020): >\$1M
 - 1388 • DAF economic modelling and field trials: ~\$500K
 - 1389 • Commercialisation: Wilmar Sugar and Herbert River Canegrowers support for
 - 1390 demonstrations
 - 1391 • Industry Scaling: Adoption programs across 12 regions
- 1392 Global Investments:
- 1393 • Brazil: Native Green Cane Project – multi-million dollar investment in harvester
 - 1394 development and regenerative systems.
 - 1395 • Nestlé: Regenerative agriculture handbook and supply chain transformation (2025)

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References

- Abalos, D., Recous, S., Butterbach-Bahl, K., De Notaris, C., Rittl, T.F., Topp, C.F.E., Petersen, S.O., Hansen, S., Bleken, M.A., Rees, R.M., Olesen, J.E., 2022. A review and meta-analysis of mitigation measures for nitrous oxide emissions from crop residues. *Science of The Total Environment* 828, 154388. <https://doi.org/10.1016/j.scitotenv.2022.154388>
- Abbott, L.K., Macdonald, L.M., Wong, M.T.F., Webb, M.J., Jenkins, S.N., Farrell, M., 2018. Potential roles of biological amendments for profitable grain production – A review. *Agriculture, Ecosystems & Environment* 256, 34–50. <https://doi.org/10.1016/j.agee.2017.12.021>
- Aderale, M.O., Haas, E., Smerald, A., Blicher-Mathiesen, G., Butterbach-Bahl, K., Rahimi, J., 2025. The environmental trade-off of fertiliser, residue and catch crop management in Danish cropping systems. *Agricultural Systems* 229, 104433. <https://doi.org/10.1016/j.agry.2025.104433>
- Angus, J.F., Grace, P.R., 2017. Nitrogen balance in Australia and nitrogen use efficiency on Australian farms. *Soil Res.* 55, 435–450. <https://doi.org/10.1071/SR16325>
- Antille, D.L., Chamen, W.C.T., Tullberg, J.N., Lal, R., 2015. The Potential of Controlled Traffic Farming to Mitigate Greenhouse Gas Emissions and Enhance Carbon Sequestration in Arable Land: A Critical Review. *Transactions of the American Society of Agricultural and Biological Engineers* 58.
- ANZBIG, 2023. Biochar 2030 Roadmap |.
- Bahmutsky, S., Grassauer, F., Arulnathan, V., Pelletier, N., 2024. A review of life cycle impacts and costs of precision agriculture for cultivation of field crops. *Sustainable Production and Consumption* 52, 347–362. <https://doi.org/10.1016/j.spc.2024.11.010>
- Balafoutis, A., Beck, B., Fountas, S., Vangeyte, J., Wal, T.V. der, Soto, I., Gómez-Barbero, M., Barnes, A., Eory, V., 2017. Precision Agriculture Technologies Positively Contributing to GHG Emissions Mitigation, Farm Productivity and Economics. *Sustainability* 9, 1339. <https://doi.org/10.3390/su9081339>
- Basso, B., Jones, J.W., Antle, J., Martinez-Feria, R.A., Verma, B., 2021. Enabling circularity in grain production systems with novel technologies and policy. *Agricultural Systems* 193, 103244. <https://doi.org/10.1016/j.agry.2021.103244>
- Beeckman, F., Annetta, L., Corrochano-Monsalve, M., Beeckman, T., Motte, H., 2024. Enhancing agroecosystem nitrogen management: microbial insights for improved nitrification inhibition. *Trends in Microbiology* 32, 590–601. <https://doi.org/10.1016/j.tim.2023.10.009>
- Bell, M., Schwenke, G., Lester, D., Grace, P., Barton, L., Farrell, M., Verburg, K., 2025. Predicting nitrogen cycling and losses in Australian cropping systems (No. UOQ 2204-010RTX). GRDC.
- Bezner Kerr, R., Postigo, J.C., Smith, P., Cowie, A., Singh, P.K., Rivera-Ferre, M., Tirado-von Der Pahlen, M.C., Campbell, D., Neufeldt, H., 2023. Agroecology as a transformative approach to tackle climatic, food, and ecosystemic crises. *Current Opinion in Environmental Sustainability* 62, 101275. <https://doi.org/10.1016/j.cosust.2023.101275>
- Climate Change Authority, 2024. Sector Pathways Review | Climate Change Authority. Canberra, Australia.
- 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.,

APPENDIX C.3: Priorities for Low Emissions Agricultural Solutions Investment

- 1445 Sharwood, R., Wilson, B., 2025. NSW Land and Primary Industries Low Emissions
1446 Options Report: Land and Primary Industries Emissions Abatement Roadmap. NSW
1447 Department of Primary Industries and Regional Development.
- 1448 DEMETER, 2021. Demeter - EMPOWERING FARMERS. URL <https://h2020-demeter.eu/>
1449 (accessed 10.14.25).
- 1450 Friedl, J., Warner, D., Wang, W., Rowlings, D.W., Grace, P.R., Scheer, C., 2023. Strategies for
1451 mitigating N₂O and N₂ emissions from an intensive sugarcane cropping system.
1452 Nutr Cycl Agroecosyst 125, 295–308. [https://doi.org/10.1007/s10705-023-10262-](https://doi.org/10.1007/s10705-023-10262-4)
1453 4
- 1454 Gjerek, M., Morgan, A., Gore-Brown, N., Womersley, G., 2021. Diesel Use in NSW Agriculture
1455 and Opportunities to Support Net Zero Emissions. Australian Alliance for Energy
1456 Productivity for NSW DPI, Sydney, Australia.
- 1457 Grace, P., Rosa, D.D., Shcherbak, I., Strazzabosco, A., Rowlings, D., Scheer, C., Barton, L., Wang,
1458 W., Schwenke, G., Armstrong, R., Porter, I., Bell, M., 2023. Revised emission factors
1459 for estimating direct nitrous oxide emissions from nitrogen inputs in Australia's
1460 agricultural production systems: a meta-analysis. Soil Res. 62, NULL-NULL.
1461 <https://doi.org/10.1071/SR23070>
- 1462 GRDC, 2025a. Enhanced efficiency fertiliser [WWW Document]. Grains Research and
1463 Development Corporation. URL [https://grdc.com.au/resources-and-](https://grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2025/02/enhanced-efficiency-fertiliser)
1464 [publications/grdc-update-papers/tab-content/grdc-update-](https://grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2025/02/enhanced-efficiency-fertiliser)
1465 [papers/2025/02/enhanced-efficiency-fertiliser](https://grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2025/02/enhanced-efficiency-fertiliser) (accessed 11.28.25).
- 1466 GRDC, 2025b. Better targeted, more precise fertiliser decisions as a counter to rising
1467 fertiliser prices – focusing on 3 of the 6 Rs [WWW Document]. Grains Research and
1468 Development Corporation. URL [https://grdc.com.au/resources-and-](https://grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2022/02/better-targeted-more-precise-fertiliser-decisions-as-a-counter-to-rising-fertiliser-prices-focussing-on-3-of-the-6-rs)
1469 [publications/grdc-update-papers/tab-content/grdc-update-](https://grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2022/02/better-targeted-more-precise-fertiliser-decisions-as-a-counter-to-rising-fertiliser-prices-focussing-on-3-of-the-6-rs)
1470 [papers/2022/02/better-targeted-more-precise-fertiliser-decisions-as-a-counter-](https://grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2022/02/better-targeted-more-precise-fertiliser-decisions-as-a-counter-to-rising-fertiliser-prices-focussing-on-3-of-the-6-rs)
1471 [to-rising-fertiliser-prices-focussing-on-3-of-the-6-rs](https://grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2022/02/better-targeted-more-precise-fertiliser-decisions-as-a-counter-to-rising-fertiliser-prices-focussing-on-3-of-the-6-rs) (accessed 10.1.25).
- 1472 GRDC, 2025c. Nitrogen and other legacies of pasture legumes grown in crop rotations
1473 [WWW Document]. Grains Research and Development Corporation. URL
1474 [https://grdc.com.au/resources-and-publications/grdc-update-papers/tab-](https://grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2023/02/nitrogen-and-other-legacies-of-pastures-legumes-grown-in-crop-rotations)
1475 [content/grdc-update-papers/2023/02/nitrogen-and-other-legacies-of-pastures-](https://grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2023/02/nitrogen-and-other-legacies-of-pastures-legumes-grown-in-crop-rotations)
1476 [legumes-grown-in-crop-rotations](https://grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2023/02/nitrogen-and-other-legacies-of-pastures-legumes-grown-in-crop-rotations) (accessed 9.23.25).
- 1477 GRDC, 2024. Off-site losses and nitrogen use efficiency – swings and roundabouts and the
1478 potential impact of stabilised fertilisers on nitrogen recovery in northern
1479 production systems [WWW Document]. Grains Research and Development
1480 Corporation. URL [https://grdc.com.au/resources-and-publications/grdc-update-](https://grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2024/03/off-site-losses-and-nitrogen-use-efficiency-swings-and-roundabouts-and-the-potential-impact-of-stabilised-fertilisers-on-nitrogen-recovery-in-northern-production-systems)
1481 [papers/tab-content/grdc-update-papers/2024/03/off-site-losses-and-nitrogen-](https://grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2024/03/off-site-losses-and-nitrogen-use-efficiency-swings-and-roundabouts-and-the-potential-impact-of-stabilised-fertilisers-on-nitrogen-recovery-in-northern-production-systems)
1482 [use-efficiency-swings-and-roundabouts-and-the-potential-impact-of-stabilised-](https://grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2024/03/off-site-losses-and-nitrogen-use-efficiency-swings-and-roundabouts-and-the-potential-impact-of-stabilised-fertilisers-on-nitrogen-recovery-in-northern-production-systems)
1483 [fertilisers-on-nitrogen-recovery-in-northern-production-systems](https://grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2024/03/off-site-losses-and-nitrogen-use-efficiency-swings-and-roundabouts-and-the-potential-impact-of-stabilised-fertilisers-on-nitrogen-recovery-in-northern-production-systems) (accessed
1484 10.13.25).
- 1485 GroundCover, 2024a. GHG emissions avoidance a preferred strategy [WWW Document].
1486 GroundCover. URL [https://groundcover.grdc.com.au/innovation/climate/ghg-](https://groundcover.grdc.com.au/innovation/climate/ghg-emissions-avoidance-a-preferred-strategy)
1487 [emissions-avoidance-a-preferred-strategy](https://groundcover.grdc.com.au/innovation/climate/ghg-emissions-avoidance-a-preferred-strategy) (accessed 8.22.25).
- 1488 GroundCover, 2024b. \$17M project to unlock enhanced efficiency fertiliser potential [WWW
1489 Document]. GroundCover. URL
1490 [https://groundcover.grdc.com.au/grdc/announcements/\\$17m-project-to-unlock-](https://groundcover.grdc.com.au/grdc/announcements/$17m-project-to-unlock-enhanced-efficiency-fertiliser-potential)
1491 [enhanced-efficiency-fertiliser-potential](https://groundcover.grdc.com.au/grdc/announcements/$17m-project-to-unlock-enhanced-efficiency-fertiliser-potential) (accessed 10.1.25).
- 1492 He, D., Wang, E., Sevenster, M., Kirkegaard, J., 2026. Process-based modelling in farm
1493 greenhouse gas assessment reveals site-specific dynamics and limitations of

APPENDIX C.3: Priorities for Low Emissions Agricultural Solutions Investment

- 1494 emission factor methods. *Agronomy for Sustainable Development* 46, 31.
 1495 <https://doi.org/10.1007/s13593-026-01104-y>
- 1496 Hénault, C., Bourennane, H., Ayzac, A., Ratié, C., Saby, N.P.A., Cohan, J.-P., Eglin, T., Gall, C.L.,
 1497 2019. Management of soil pH promotes nitrous oxide reduction and thus mitigates
 1498 soil emissions of this greenhouse gas. *Sci Rep* 9, 20182.
 1499 <https://doi.org/10.1038/s41598-019-56694-3>
- 1500 Hochman, Z., Garcia, J.N., Horan, H., Whish, J., Bell, L., 2021. Design of sustainable dryland
 1501 crop rotations require value judgements and efficient trade-offs. *Environ. Res. Lett.*
 1502 16, 064067. <https://doi.org/10.1088/1748-9326/ac0378>
- 1503 Janke, C., Kirkegaard, J., Hunt, J., Barton, L., Bell, L., Karunaratne, S., Macdonald, L.M., Pasut,
 1504 C., Stockmann, U., Tavakkoli, E., Vadakattu, G., Wasson, A., Farrell, M., 2025. The pros
 1505 and cons of increasing soil organic matter in dryland cropping systems. *Crop*
 1506 *Pasture Sci.* 76. <https://doi.org/10.1071/CP24257>
- 1507 Jensen, T.A., Antille, D.L., Tullberg, J.N., 2025. Improving On-farm Energy Use Efficiency by
 1508 Optimizing Machinery Operations and Management: A Review. *Agric Res* 14, 15–33.
 1509 <https://doi.org/10.1007/s40003-024-00824-5>
- 1510 Joseph, S., Cowie, A.L., Van Zwieten, L., Bolan, N., Budai, A., Buss, W., Cayuela, M.L., Graber,
 1511 E.R., Ippolito, J.A., Kuzyakov, Y., Luo, Y., Ok, Y.S., Palansooriya, K.N., Shepherd, J.,
 1512 Stephens, S., Weng, Z. (Han), Lehmann, J., 2021. How biochar works, and when it
 1513 doesn't: A review of mechanisms controlling soil and plant responses to biochar.
 1514 *GCB Bioenergy* 13, 1731–1764. <https://doi.org/10.1111/gcbb.12885>
- 1515 Kaur, N., Kieffer, C., Ren, W., Hui, D., 2023. How much is soil nitrous oxide emission reduced
 1516 with biochar application? An evaluation of meta-analyses. *GCB Bioenergy* 15, 24–37.
 1517 <https://doi.org/10.1111/gcbb.13003>
- 1518 Kharel, S., d'Abbadie, C., Abadi Ghadim, A., Gazey, C., Kingwell, R., 2024. Liming acidic soils
 1519 creates profits, land use options but often more emissions. *Crop Pasture Sci* 75,
 1520 CP24227. <https://doi.org/10.1071/CP24227>
- 1521 Kingwell, R., Fuchsbichler, A., 2011. The whole-farm benefits of controlled traffic farming:
 1522 An Australian appraisal. *Agricultural Systems* 104, 513–521.
 1523 <https://doi.org/10.1016/j.agsy.2011.04.001>
- 1524 Leon, A., Guntur V., S., Kishii, M., Matsumoto, N., Kruseman, G., 2022. An ex ante life cycle
 1525 assessment of wheat with high biological nitrification inhibition capacity. *Environ*
 1526 *Sci Pollut Res* 29, 7153–7169. <https://doi.org/10.1007/s11356-021-16132-2>
- 1527 Li, X., Zhao, R., Li, D., Wang, G., Bei, S., Ju, X., An, R., Li, L., Kuyper, T.W., Christie, P., Bender,
 1528 F.S., Veen, C., van der Heijden, M.G.A., van der Putten, W.H., Zhang, F., Butterbach-
 1529 Bahl, K., Zhang, J., 2023. Mycorrhiza-mediated recruitment of complete denitrifying
 1530 *Pseudomonas* reduces N₂O emissions from soil. *Microbiome* 11, 45.
 1531 <https://doi.org/10.1186/s40168-023-01466-5>
- 1532 Lilley, J.M., Kirkegaard, J.A., 2024. Validated simulation of a long-term cropping experiment
 1533 reveals a pathway for improved productivity. *European Journal of Agronomy* 159,
 1534 127225. <https://doi.org/10.1016/j.eja.2024.127225>
- 1535 Llewellyn, R., Ouzman, J., 2019. Chapter 2 Conservation agriculture in Australia : 30 years
 1536 on.
- 1537 Llewellyn, R.S., Brown, B., 2020. Predicting Adoption of Innovations by Farmers: What is
 1538 Different in Smallholder Agriculture? *Applied Economic Perspectives and Policy* 42,
 1539 100–112. <https://doi.org/10.1002/aep.13012>
- 1540 Macdonald, L.M., Kookana, R.S., van Zwieten, L., Singh, B.P., Singh, B., Farrell, M., 2016.
 1541 Regional Considerations for Targeted Use of Biochar in Agriculture and Remediation
 1542 in Australia, in: *Agricultural and Environmental Applications of Biochar: Advances*

APPENDIX C.3: Priorities for Low Emissions Agricultural Solutions Investment

- 1543 and Barriers. John Wiley & Sons, Ltd, pp. 445–474.
 1544 <https://doi.org/10.2136/sssaspecpub63.2014.0052>
- 1545 Masola, M.J., Alesso, C.A., Oggero, E., Nicolier, J.G., Antille, D.L., Imhoff, S., 2026. Controlled
 1546 traffic farming effect on soil emissions of nitrous oxide in Mollisols of Santa Fe,
 1547 Argentina. *Soil and Tillage Research* 263, 107275.
 1548 <https://doi.org/10.1016/j.still.2026.107275>
- 1549 Nasser, V., Dechow, R., Helfrich, M., Meijide, A., Rummel, P.S., Koch, H.-J., Ruser, R., Essich, L.,
 1550 Dittert, K., 2025. Evaluating N₂O emissions and carbon sequestration in temperate
 1551 croplands with cover crops: insights from field trials. *SOIL* 11, 489–506.
 1552 <https://doi.org/10.5194/soil-11-489-2025>
- 1553 Norton, R., Gourlay, C., Grace, P., 2023. Fertiliser Australia White Paper: Nitrogen Fertiliser
 1554 Use and Greenhouse Gases – An Australian Assessment. Fertilizer Australia,
 1555 Canberra, Australia.
- 1556 Officer, S.J., Phillips, F., Kearney, G., Armstrong, R., Graham, J., Partington, D., 2015. Response
 1557 of soil nitrous oxide flux to nitrogen fertiliser application and legume rotation in a
 1558 semi-arid climate, identified by smoothing spline models. *Soil Res* 53, 227–241.
 1559 <https://doi.org/10.1071/SR12049>
- 1560 Page, K.L., Allen, D.E., Dalal, R.C., Slattey, W., 2009. Processes and magnitude of CO₂, CH₄,
 1561 and N₂O fluxes from liming of Australian acidic soils: a review. *Soil Res.* 47, 747–
 1562 762. <https://doi.org/10.1071/SR09057>
- 1563 Patane, P., Landers, G., Thompson, M., Nothard, B., Norris, C.A., Olayemi, M., 2020.
 1564 Investigating losses from green and burnt cane harvesting conditions : ASSCT peer-
 1565 reviewed paper.
- 1566 Peoples, M.B., Giller, K.E., Jensen, E.S., Herridge, D.F., 2021. Quantifying country-to-global
 1567 scale nitrogen fixation for grain legumes: I. Reliance on nitrogen fixation of soybean,
 1568 groundnut and pulses. *Plant Soil* 469, 1–14. [https://doi.org/10.1007/s11104-021-](https://doi.org/10.1007/s11104-021-05167-6)
 1569 [05167-6](https://doi.org/10.1007/s11104-021-05167-6)
- 1570 Prajapati, S.K., Kumari, M., Jena, T., Ali, S.A., Singh, D.N., Yadav, S., 2025. Cereal-Legume
 1571 Integration: Association for Food Security, Soil and Environmental Sustainability, in:
 1572 Babu, S., Das, A., Rathore, S.S., Singh, Raghavendra, Singh, Rajbir (Eds.), *Ecological*
 1573 *Solutions to Agricultural Land Degradation*. Springer Nature, Singapore, pp. 145–
 1574 171. https://doi.org/10.1007/978-981-96-3392-0_6
- 1575 Rose, T.J., Wood, R.H., Rose, M.T., Van Zwieten, L., 2018. A re-evaluation of the agronomic
 1576 effectiveness of the nitrification inhibitors DCD and DMPP and the urease inhibitor
 1577 NBPT. *Agriculture, Ecosystems & Environment* 252, 69–73.
 1578 <https://doi.org/10.1016/j.agee.2017.10.008>
- 1579 Selzer, T., Schubert, S., 2021. Nutrient uptake of catch crops under non-limiting growth
 1580 conditions. *Journal of Plant Nutrition and Soil Science* 184, 709–722.
 1581 <https://doi.org/10.1002/jpln.202100142>
- 1582 Sevenster, M., Bell, L., Anderson, B., Jamali, H., Horan, H., Simmons, A., Cowie, A., Hochman,
 1583 Z., 2022. Australian Grains Baseline and Mitigation Assessment. Main Report. CSIRO,
 1584 Canberra.
- 1585 Sevenster, M., Burrett, B., 2025. Australian Grains GHG account 2020 (No. Version 2024).
 1586 CSIRO, Canberra, Australia.
- 1587 Teutscherova, N., Vazquez, E., Arango, J., Arevalo, A., Benito, M., Pulleman, M., 2019. Native
 1588 arbuscular mycorrhizal fungi increase the abundance of ammonia-oxidizing
 1589 bacteria, but suppress nitrous oxide emissions shortly after urea application.
 1590 *Geoderma* 338, 493–501. <https://doi.org/10.1016/j.geoderma.2018.09.023>

APPENDIX C.3: Priorities for Low Emissions Agricultural Solutions Investment

- 1591 Tullberg, J., Antille, D.L., Bluett, C., Eberhard, J., Scheer, C., 2018. Controlled traffic farming
 1592 effects on soil emissions of nitrous oxide and methane. *Soil and Tillage Research*
 1593 176, 18–25. <https://doi.org/10.1016/j.still.2017.09.014>
 1594 Umbers, A., Watson, D., 2025. GRDC Farm Practices Survey Report 2025. Grains Research
 1595 and Development Corporation (GRDC), Canberra, ACT, Australia.
 1596 Yue, K., Fornara, D.A., Heděnc, P., Wu, Q., Peng, Y., Peng, X., Ni, X., Wu, F., Peñuelas, J., 2023.
 1597 No tillage decreases GHG emissions with no crop yield tradeoff at the global scale.
 1598 *Soil and Tillage Research* 228, 105643. <https://doi.org/10.1016/j.still.2023.105643>
 1599 Zhong, L., Wang, P., Gu, Z., Song, Y., Cai, X., Yu, G., Xu, X., Kuzyakov, Y., 2025. Biochar reduces
 1600 N₂O emission from fertilized cropland soils: a meta-analysis. *Carbon Res.* 4, 31.
 1601 <https://doi.org/10.1007/s44246-025-00198-5>
 1602