

Opportunities for emissions reduction at the farm level due to implementation of carbon sequestration strategies

Scoping Study – Extensive livestock enterprises

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Abstract

Grazing enterprises occur on 56% of Australia's landmass and constitute an important source of greenhouse gas (GHG) emissions and sinks; the latter being associated with carbon (C) storage in grasslands and forests managed by the landholders. While the maintenance of vegetation C and soil organic carbon (SOC) is critical for the long-term productivity of grazing and agricultural lands, there is also potential for C sequestration strategies to provide an alternative income stream for landholders through engaging in environmental markets such as the Australian carbon credit unit (ACCU) Scheme. However, the implementation of strategies to sequester C on livestock grazing enterprises will likely have some impact on agricultural productivity and require investment of resources. Therefore, there is an urgent need for comprehensive, economic and financial analyses to better understand the trade-offs, opportunities for alternative income streams, and the most effective and efficient allocation of resources for landholders. The outcomes of such analyses should support adoption of suitable practices that facilitate attainment of net zero emission targets. The objectives of this scoping study were to firstly review the literature and identify opportunities for emissions reductions on extensive livestock production systems due to implementation of C sequestration strategies. The second objective was to conduct a bioeconomic case study for an agricultural enterprise in Queensland to assess the consequences of implementing a C sequestration strategy on C sequestration and net emissions, forage and animal production, and profitability and financial risk.

The literature review indicated that there has been a downward trend in the net GHG emissions attributed to Australian beef cattle and sheep over the recent decade, 2010/11-2019/20. A reduced CO₂ efflux from private forests has had the major contribution to this decline. However, the key vegetation ACCU Scheme method which underpinned this reduction has now closed, following considerable scrutiny due to concerns over the additionality and permanence of the C sequestered, and alternative suitable methods are not yet available. Additionally, afforestation across grazing lands can only be considered an interim measure for reducing net property emissions. This is because forest C accumulation in Australia typically peaks within 5-10 years of establishment. Furthermore, trees are generally competitive with pasture and with extensive livestock production. Consequently, strategies that increase SOC storage in grasslands may offer more potential.

However, it was identified that there is poor confidence in predicting: 1) the maximum SOC storage capacity of different soils and dynamics of change towards the saturation level; 2) the permanency of sequestered SOC, and 3) the levels of GHG emissions associated with the C sequestration strategy. Predicting the potential for SOC sequestration remains a challenge due to the diversity in climate, soil and landscape characteristics across Australian landscapes as well as variation in land use history and livestock production systems. Furthermore, detecting any changes in SOC stocks due to management interventions can be difficult due to the dominant effects of climate and soil variables in Australian environments, particularly rangelands.

The scientific literature indicated strong context dependency and biophysical limits, in addition to economic and financial trade-offs, when implementing C sequestration strategies. The strategies that showed most potential to increase SOC stocks on extensive livestock properties while minimising negative impacts to agricultural productivity and business profit included: 1) converting from cropping to permanent pasture, or 2) sowing productive legumes in existing grass pastures. These latter activities may provide C market opportunities for landholders with the proviso that there are soil and climate constraints to the quantity of SOC that can be sequestered and maintained over time.

There are few published studies available to indicate how the full range of possible C sequestration strategies may affect net paddock and/or property emissions and business profit. An increase in net C sequestration on a project area will not necessarily result in reduced net emissions. Additionally, even when net emissions can be reduced, this may not result in a positive effect on business profit. A number of recent modelling studies of sheep and beef production systems in southern Australia reported that many strategies to reduce net property GHG emissions reduced farm income, even with assumed payments for C sequestration, methane reduction or biodiversity improvements, or when applying C taxes. Regardless, maintaining or increasing SOC is beneficial for agricultural productivity. However, for primary producers to adopt C farming practices on a broad scale, it will be necessary for the economic benefits to exceed the costs to their

business. Additional analyses of net emissions and economic outcomes should therefore be conducted for promising C sequestration strategies, to enable landholders to better understand the trade-offs and opportunities for their extensive livestock businesses.

Our case study analysis assessed the impacts of converting cropland to grazed grass pasture in the Condamine region of southern Queensland as an example of a higher-productivity region of extensive livestock production in northern Australia.

Soil organic C in the 0-30 cm interval decreased in the cropping scenario by an average of 0.20 t C/ha.annum over 10 years with large increases in loss (emissions) during the long fallow period following harvest of the third crop in the rotation. However, there was an average increase in the grazed pasture scenario of 0.06 t C/ha.annum. The rate of SOC sequestration estimated for the grazed pasture scenario peaked in Year 4 and then declined over the subsequent 6 years. It was estimated that, at the low rate of C sequestration estimated for the conversion of a cropping paddock to grazed pasture in this study and the small project area of 238 ha, the total costs of an ACCU Scheme SOC sequestration project are likely to exceed the income.

Despite the C sequestration of 51.5 t CO₂-e/annum in the grazed pasture scenario, cf. a loss of 180.6 t CO₂-e/annum in the cropping scenario, the net emissions from the grazed pasture scenario were 10.3 times that of the cropping scenario, on average. The large net emissions from the grazed pasture scenario (2,975 t CO₂-e/annum) were primarily due to the large Scope 3 emissions from purchased livestock (2,734 t CO₂-e/annum) which constituted 91% of the total GHG emissions (not considering C sequestration). However, if Scope 3 emissions from purchased livestock are not included (as for property-bred livestock), the net emissions from the grazed pasture scenario (241 t CO₂-e/annum) were less than that from the cropping paddock (288 t CO₂-e/annum), due to the effects of C sequestration which counteracted the substantial contribution of enteric methane emissions.

The average of the crop rotation cycle of 4 years, generated around 1.2 times the gross margin (\$356/ha.annum) of the average annual gross margin for the grazed pasture over 10 years following establishment (\$292/ha.annum).

Combined, the case study results indicate that, even although there was a C sequestration benefit under pasture, maintaining the paddock under the given cropping sequence in the short to medium term is more profitable and produces lower net emissions than converting it to a perennial grass pasture for livestock production using purchased livestock.

It is recommended that additional case studies are conducted to produce a library of such scenarios to provide guidance to producers in their decision making.

Executive summary

Background and objectives

Grazing enterprises occur on 56% of Australia's landmass and constitute an important source of greenhouse gas (GHG) emissions and sinks; the latter being associated with carbon (C) storage in grasslands and forests managed by the landholders. While the maintenance of vegetation C and soil organic carbon (SOC) is critical for the long-term productivity of grazing and agricultural lands, there is also potential for C sequestration strategies to provide an alternative income stream for landholders through engaging in environmental markets such as the Australian carbon credit unit (ACCU) Scheme. However, the implementation of strategies to sequester C on livestock grazing enterprises will likely have some impact on agricultural productivity and require investment of resources. Therefore, there is an urgent need for appropriate economic and financial analyses to better understand the trade-offs, opportunities for alternative income streams, and the most effective and efficient allocation of resources for landholders. The outcomes of such analyses should support adoption of suitable practices that facilitate attainment of net zero emission targets. The first objective of this scoping study was to review the literature and identify opportunities for emissions reductions on extensive livestock production systems due to implementation of C sequestration strategies. The second objective was to conduct a bioeconomic case study for an agricultural enterprise in Queensland to assess the consequences of implementing a suitable strategy on C sequestration and net emissions, forage and animal production, and profitability and financial risk.

Key findings from the literature review

Opportunities for carbon sequestration on extensive livestock production systems in Australia

Evidence to support carbon sequestration opportunities on extensive livestock enterprises

Generally, the potential for C storage in vegetation and soil is highest in regions with relatively higher rainfall and lower temperatures. Furthermore, to deliver long-term C sequestration in Australian agricultural lands, it has been recommended that regions and soils should be targeted that have a relatively high silt + clay content and cation exchange capacity, and a low C saturation in the silt + clay fraction.

Overall, the review of evidence supporting C sequestration opportunities on extensive livestock enterprises found that the potential is highly context-dependent, with significant biophysical limits and economic trade-offs constraining practical application. Strategies aimed at increasing woody vegetation, including through reduced grazing pressure or fire management, show inconsistent and unpredictable outcomes and in most cases will reduce pasture biomass and livestock carrying capacity over time, negatively affecting productivity and profitability in the absence of alternative income streams such as ACCU Scheme participation.

While tree plantings can sequester substantial amounts of C, particularly in higher productivity environments, commercial plantings generally offer greater sequestration potential than environmental plantings and are more likely to deliver meaningful outcomes where site productivity is high. Income from an ACCU Scheme project and/or agroforestry may improve the feasibility of such strategies for landholders. However, their adoption remains constrained by the high cost and risk of establishment, as well as long payback periods, meaning that careful and contemporary economic analysis is essential to evaluate their viability within livestock enterprises.

In contrast, opportunities to increase SOC in grazing systems are generally more constrained and uncertain. There is limited consistent evidence that changes in grazing management or pasture rejuvenation alone lead to measurable and sustained increases in SOC, which restricts the applicability of current soil C ACCU methods in extensive systems. However, certain land use and pasture improvement strategies, particularly 1) conversion from cropping to permanent pasture and 2) the introduction of productive legumes, have demonstrated more reliable potential to increase SOC stocks, although gains remain limited by soil and climate conditions and may decline over time. Additional strategies, such as fertiliser application, soil amendments, irrigation or landscape modification, may enhance SOC under specific

conditions, but their effectiveness is variable and they are often associated with uncertain or unfavourable economic returns in extensive livestock systems.

Importantly, even where C sequestration is achieved, it does not necessarily translate to reduced net emissions or improved profitability. Many strategies involve trade-offs between environmental and production outcomes, and in some cases may reduce farm income despite delivering emissions benefits. However, as C farming practices can deliver broader ecosystem co-benefits, including improved soil function and landscape condition, this supports the case for approaches to integrated payment for ecosystem services in addition to the ACCU scheme. In summary, broad scale adoption of C sequestration strategies will depend on whether they provide net economic benefits to landholders, indicating the critical need for comprehensive economic analyses to evaluate trade-offs and inform decision-making.

The historical contribution of, and potential for, carbon sequestration to reduce net greenhouse gas emissions attributed to Australian livestock production

Reduced CO₂ efflux from private forests has had the major contribution to the downward trend in net GHG emissions attributed to Australian beef cattle and sheep over the recent decade, 2010/11-2019/20. Grasslands transitioned from a relatively minor net source of emissions to a net sink, in ca. 2015/16, due to reduction in emissions sources such as biomass burning and grassland soils. Most analyses of net zero pathways for Australia rely on C sequestration, primarily forest-based sequestration, to make a substantial contribution. However, in contrast to increases in forest area, other strategies to increase SOC sequestration in grasslands are generally not competitive with grazing and appear to offer most opportunity for further growth as a sink with least damage to agricultural productivity and profitability. Carbon stored in non-woody vegetation such as grass is treated as a neutral, short-term cycle rather than a permanent removal and therefore cannot generally be counted as a permanent sink in Australia's national GHG inventory.

The potential for carbon market opportunities to encourage future sequestration activities

Several vegetation-based methods as part of the ACCU Scheme have underpinned the reductions in Australia's beef cattle and sheep GHG accounts by incentivising sequestration in private forests through reduced forest loss. However, these key vegetation methods have now closed, following considerable scrutiny due to concerns over the additionality and permanence of C abatement credited. The closure of these key vegetation methods has left private landholders with significantly reduced opportunities to participate in the C market. The proposed 'Integrated farm and land management (ILFM) method' is still under development. This method is anticipated to combine vegetation and soil C sequestration and is intended to restore access to C market opportunities for private landholders.

Issuance of ACCUs for SOC sequestration methods has been relatively minor to date compared to issuance for vegetation projects. The total ACCUs from SOC sequestration projects constituted only 0.2% of Australia's total ACCU issuance and 0.3% of issuance from all methods applicable to grazing enterprises. The uncertain outcome of SOC sequestration projects is likely inhibiting uptake by landholders. Concerns have also been raised about the integrity of soil C ACCU Scheme methods, with the rates of SOC sequestration reported for ACCU Scheme projects being in the range 2-8 t C/ha.annum, which is an order of magnitude greater than rates reported in scientific studies (1-1.2 t C/ha.annum). Furthermore, SOC credits issued have been found to be largely attributable to above-average rainfall rather than project interventions. Moreover, these soil C gains were not sustained when rainfall returned to average, raising concerns about the additionality of the sequestration, beyond natural climatic variability. Recommendations to improve confidence in, and integrity of, the SOC ACCU Scheme methods by increasing the number of soil C measurements required are likely to decrease the financial attractiveness for landholders. It appears likely that, without changes to the methods to increase the benefits for landholders relative to the costs and risks, there will continue to be poor adoption of SOC ACCU Scheme methods.

Net emission and profitability at the farm level as a consequence of implementing carbon sequestration strategies

There are few published studies available to indicate how the full range of possible C sequestration strategies may affect net paddock and/or property emissions and business profit. An increase in net C sequestration on a project area will not necessarily result in reduced net emissions. Additionally, even when net emissions can be reduced, this may not result in a positive effect on business profit. A number of recent modelling studies of sheep and beef production systems in southern Australia reported that many strategies to reduce net property GHG emissions reduced farm income, even with

assumed payments for sequestered C, methane reduction, or biodiversity benefits, or when applying C taxes. The trade-offs between economic and environmental outcomes often resulted in those strategies that delivered the greatest SOC accrual and GHG reduction not necessarily being the most profitable. However, one of the more promising strategies for C sequestration, sowing adapted, perennial legumes into existing grass pastures, has also been found to be one of the more profitable management strategies for northern Australian extensive livestock systems. This strategy can also improve emissions intensity and, consequently, increase carrying capacity. However, if stocking rates are increased in response to the additional carrying capacity, net property-level greenhouse gas emissions will also increase.

Case study

Effect on net emissions and profit due to conversion of cropland to pasture for grazing cattle in southern Queensland

The objective of this case study analysis was to investigate a potential C sequestration strategy for its effects on both net GHG emissions and profit, for a mixed farming enterprise in northern Australia. An enterprise in the Condamine region in the western downs of southern Queensland was selected as an example of a higher-productivity region of northern Australia. The analysis assessed a paddock as part of a vertically integrated aggregation of eight properties located in southern and southwest Queensland. Due to the complex and extensive nature of this integrated business, a single paddock was selected for this scoping study. This initial, constrained case study analysis allowed development of a framework to integrate assessment of C sequestration, GHG emissions and profitability with minimum data collection load on the producer cooperators.

The implications for profitability and net emissions were assessed for the strategy of converting a 238-ha broad-acre cropping paddock to perennial grass pasture. The base scenario was a repeating 4-year, 3-crop rotation of barley – barley – sorghum. The alternative scenario was to establish perennial grass pasture used for backgrounding young heifers prior to feedlot entry. The two systems were compared as steady states to indicate the average profitability and net emissions over 10 years. The steady state approach was adopted in this analysis as it best fitted the requirements of the current GHG emissions models. This approach examines the alternative strategies once fully implemented, to determine if it is worthwhile making a change from the base, or existing strategy (in this case, the cropping rotation). If the outcome is positive for profitability and/or net emissions, then the implementation phase would be considered to determine if the change is possible and feasible from a cash-flow, financial risk, and practical management perspective.

Parameters for the scenario analysis were informed by previous, and anticipated future levels, of inputs and production from the case study paddock. The levels of production, and the production responses to the alternative management scenario, were determined by the case study cooperators, with reference to existing data sets, and published literature where available. This involved an iterative process of obtaining feedback and then applying adjustments to the models to ensure that the models were adequately structured and calibrated for the base scenario and the alternative scenario.

In this economic analysis of alternative farming systems, the transition phase between the cropping system and the perennial pasture was relatively short (< 6 months) and was ignored. Furthermore, in the current analysis, the perennial pasture was grazed by heifers either purchased or supplied from sources independent of the other activities conducted on the individual property. This allowed the paddock to be treated as a separate activity, with all livestock traded into and out of the paddock. It was therefore appropriate for the economic analysis to be undertaken as a gross margin analysis at the level of the paddock.

The gross margins were calculated using the typical gross margin approach based on the allocation of variable costs to enterprises or activities. The gross margins also included an allowance for the labour costs associated with machinery operation and livestock management, and fuel, oil, repairs and maintenance of farming plant and equipment. As the pastures have a life of more than 1 year and have establishment costs that contribute to production over several years, the establishment costs were amortised (added as an equivalent annual cost) over the expected economic life of the pasture (10 years in this case). The amortisation process included the opportunity cost of the capital applied in the pasture establishment process. Livestock capital costs were incorporated as an opportunity cost in the livestock gross margin. These approaches allowed the paddock level gross margins for cropping and grazed pasture to be compared on an annual equivalence basis. The rundown in pasture biomass production over 10 years following establishment was accounted for in the analysis.

Changes in SOC for cropping or grazed pasture in the target paddock, were estimated using the simple process-based model, SOCRATES (Soil organic carbon reserves and transformations in ecosystems). The GHG accounting framework (GAF) calculators developed by the University of Melbourne were used to calculate total GHG emissions for each paddock scenario. GHG emissions were determined as the average for the 4-year cropping rotation and as the average over 10-years for the grazed pasture scenario to match the expected life of the pasture.

Key findings from the case study

Soil organic C in the 0-30 cm interval decreased in the cropping scenario by an average of 0.20 t C/ha.annum over 10 years with large increases in loss (emissions) during the long fallow period following harvest of the third crop in the rotation. However, there was an average increase in the grazed pasture paddock of 0.06 t C/ha.annum. The rate of SOC sequestration estimated for the grazed pasture paddock peaked in Year 4 and then declined over the subsequent 6 years. It was estimated that, at the low rate of C sequestration estimated for the conversion of a cropping paddock to grazed pasture in this study and the small project area of 238 ha, the total costs of an ACCU Scheme SOC sequestration project are likely to exceed the income.

Despite the C sequestration of 51.5 t CO₂-e/annum in the grazed pasture scenario, cf. a loss of 180.6 t CO₂-e/annum in the cropping scenario, the net emissions from the grazed pasture were 10.3 times that from the cropping scenario, on average. The large net emissions from the grazed pasture scenario (2,975 t CO₂-e/annum) were primarily due to the large Scope 3 emissions from purchased livestock (2,734 t CO₂-e/annum) which constituted 91% of the total GHG emissions (not considering C sequestration). However, if Scope 3 emissions from purchased livestock are not included (as for property-bred livestock), the net emissions from the grazed pasture scenario (241 t CO₂-e/annum) were less than that from the cropping paddock (288 t CO₂-e/annum), due to the effects of C sequestration which counteracted the substantial contribution of enteric methane emissions.

Over the full crop rotation cycle of 4 years, the grain cropping system generated around 1.2 times the gross margin (\$356/ha.annum) than the average annual gross margin for the grazed pasture over 10 years following establishment (\$292/ha.annum).

Combined, the case study results indicate that, even although there was a C sequestration benefit under pasture, maintaining the paddock under the given cropping sequence in the short to medium term is more profitable and produces lower net emissions than converting it to a perennial grass pasture for livestock production using purchased livestock.

Conclusions and recommendations

The literature review presented in this report is intended to improve understanding of the opportunities for emissions reductions in extensive livestock production systems due to the implementation of C sequestration strategies. The case study analysis of converting a paddock in southern Queensland from grain cropping to grazed perennial pastures is an initial example of expected outcomes for C sequestration, net emissions and farm profit. This initial case study provides a foundation for developing a library of comparable scenarios that producers can use when making decisions, particularly where specialist support for detailed analysis is not readily available. Over time, such a resource could help translate complex modelling into more accessible and practical guidance for on-ground use. It is recommended that future work is undertaken to expand this scenario analysis to a wider range of regions, land types and sequestration strategies to test sensitivity to key assumptions such as rainfall, livestock prices and input costs and to assess integrated payment approaches that recognise co-benefits beyond C alone. Overall, effective support for landholders will require decision frameworks that jointly consider C outcomes, net emissions, enterprise profitability, financial risk and implementation feasibility.

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1. Introduction

Grazing is Australia's dominant land use, occurring on 56% of the landmass (Leslie and Mewett 2013; Bowen Butchart et al. 2025) and 86% of the total area used for agriculture (Debney and Lobry de Bruyn 2024). Grazing is conducted across a variety of climatic zones, soil and land types from rangelands to higher rainfall zones and primarily occurs on extensive beef cattle and sheep enterprises utilising native pastures. These grazing enterprises constitute an important source of greenhouse gas (GHG) emissions and sinks; the latter being associated with grasslands and forests managed by the landholders.

There is potential for carbon (C) sequestration strategies to provide an alternative income stream for landholders through engaging in environmental markets such as the Commonwealth Government's voluntary Australian carbon credit unit (ACCU) Scheme which incentivises C sequestration in private forests and in soils (CER 2026a). In addition to these financial incentives, maintaining soil organic C (SOC) is critical for long-term productivity of landscapes (Minasny et al. 2023).

It is likely that the implementation of strategies to sequester C on extensive livestock enterprises will have some impact on agricultural productivity and require investment of resources. Therefore, there is an urgent need for comprehensive, economic and financial analyses to better understand the trade-offs, opportunities for alternative income streams, and the most effective and efficient allocation of resources for landholders. The outcomes of such analyses should support adoption of suitable practices that facilitate attainment of net zero emission targets. To address these considerations, the objectives of this study were defined, and are outlined in Section 2.

2. Objectives

The objectives of this scoping study were:

1. To conduct a review of relevant literature and identify opportunities for emissions reductions on extensive livestock production systems due to implementation of C sequestration strategies.
2. To conduct a bioeconomic case study analysis for an agricultural enterprise in Queensland to assess the consequences of implementing a C sequestration strategy on:
 - C sequestration and emissions
 - Forage and animal production
 - Profitability and financial risk.

3. Review of opportunities for carbon sequestration on extensive livestock production systems in Australia

3.1 Carbon sequestration in vegetation and soil

Carbon sequestration is the process of capturing and removing CO₂ (carbon dioxide) from Earth's atmosphere. Carbon can be stored in the vegetation and soil and can be categorised as either aboveground or belowground C. Aboveground C comprises that in live trees, dead trees, shrubs, coarse woody debris, grass and litter. Belowground C is found in biocrust, SOC and root C (Scharlemann *et al.* 2014).

Vegetation C is also referred to as phytomass C with C in terrestrial living plant material estimated to range from 46-59% of the dry plant mass (Scharlemann *et al.* 2014). The below ground phytomass C in root material is often estimated as being one third of the total above- and below-ground phytomass. Under national and international GHG accounting rules, living non-woody biomass is considered to have a turnover time of less than one year. Consequently, C stored in non-woody vegetation such as grass and forbs is treated as a neutral, short-term cycle rather than a permanent removal and therefore cannot generally be counted as a permanent sink in Australia's national GHG inventory (DCCEEW 2024).

Soils contain C in organic and inorganic forms with the majority of C in most soils stored as SOC in the form of soil organic matter which is comprised of decaying plant, animal, fungal and bacterial matter. Organic C losses from the soil occur largely due to heterotrophic soil respiration (e.g. by bacteria and fungi) and to a lesser extent through erosion. Soil C sequestration occurs when inputs of organic C are greater than losses. At the global level it has been estimated that about two thirds of soil C is comprised of SOC with the remainder inorganic C (Scharlemann *et al.* 2014). Worldwide, C stored in soils exceeds the amount of C stored in phytomass and the atmosphere (Scharlemann *et al.* 2014).

Inorganic C exists in soils as trapped CO₂ gas, dissolved in water or other liquids, or in solid form as carbonate minerals, often calcium carbonate (Huang *et al.* 2024). Huang *et al.* (2024) have reported that inorganic C tends to build up more in soil in arid and semi-arid environments such as Australia as there is relatively less water input to leach or remove carbonates from the soil. These authors estimated that globally, the top 2 m of soil holds about 2.3 trillion t of inorganic C which is about 5 times more C than found in all the world's terrestrial vegetation. Furthermore, it was estimated that about 1% of this inorganic C may be released over the next 30 years, with potential negative effects on plant growth and stabilisation of organic C, as well as negative effects on important ecosystem functions, Earth's waters and atmosphere. Consequently, Huang *et al.* (2024) recommend that, although the focus has been on sequestering organic C to mitigate climate change, strategies to minimise losses and increase soil inorganic C should be considered as well.

Inorganic C has accumulated in soil over vast periods of Earth's history. However, some strategies to increase organic C in soil, such as enhanced rock weathering, afforestation, and trapping organic C in soil minerals, might also increase levels of inorganic C (Huang *et al.* 2024). Additionally, adjusting irrigation and fertiliser to better match plant growth and, in some soils, incorporating organic amendments such as compost and manure to protect against acidification and improve calcium levels, can increase soil inorganic C. Regardless, the focus in this review is on sequestering organic C in soils as the Australian GHG accounting and inventory systems, and the ACCU Scheme, strictly align with the Intergovernmental Panel on Climate Change (IPCC) guidelines for national GHG inventories, which require reporting on SOC only (IPCC 2026).

The amount of organic C stored in soils is determined by the balance between the productivity of the vegetation and associated litter inputs and decomposition of the soil organic matter. Consequently, the main factors influencing SOC sequestration are precipitation and temperature, as these are the principal controls on plant growth, soil organic matter mineralisation and soil respiration (Grace *et al.* 2006). The capacity of soil to sequester organic C is also determined by soil clay content, initial SOC, bulk density, and the concentration of the organic C relative to the SOC saturation limit of

the soil (Grace *et al.* 2006). Mitchell *et al.* (2021) recommended that to deliver long-term SOC sequestration in Australian agricultural lands, regions and soils should be targeted that have a relatively high silt + clay content and cation exchange capacity (CEC), and a low C saturation in the silt + clay fraction.

Robertson *et al.* (2016) suggested from their study of 615 agricultural sites in Victoria that there was a general hierarchy of influence on SOC stock: climate > soil properties > management class > management practices. Generally, C stored in vegetation and soil are highest in regions with increased rainfall and lower temperatures (Stockmann *et al.* 2013). This is due to relatively higher vegetation growth and higher inputs to SOC as a result of increased water availability in addition to reduced turnover times and loss of SOC to decomposition caused by milder temperatures. The more temperate regions of Australia, including Tasmania and Victoria, are expected to have a greater potential for SOC sequestration than more northern regions due to a conducive climate and favourable soil types (Debney and Lobry de Bruyn 2024).

Studies have shown that changes in SOC can vary with depth, with contrasting effects in topsoil (0-30 cm) cf. subsoil (30-100 cm), (Livesley *et al.* 2021; Hu *et al.* 2024). Elledge and Thornton (2025) found that SOC stocks were steady below 1.8 m (to 4.4 m) over 36 years for three land use types within the Brigalow bioregion in central Queensland (i.e. virgin brigalow (*Acacia harpophylla*) woodland, cropping, and grazing on perennial grass pasture). Although soil sampling is typically limited to 100 cm depth, it has been demonstrated that deeper soil layers make a substantial contribution to C stocks, containing ca. 1.5 to 2 times more SOC to 3 m compared to 1 m depth (Jobbagy and Jackson 2000; Scharlemann *et al.* 2014). Elledge and Thornton (2025) reported SOC stocks for virgin brigalow woodland, cropping, or grazed buffel grass (*Cenchrus ciliaris*) pasture paddocks in the Brigalow bioregion of Queensland. These authors found that while C in the top 0.3 m of soil accounted for 56% of the SOC to 4.4 m, the 0.3 to 1.8 m depths, accounted for 30%. Additionally, a study with buffel grass pastures in the mulga lands of southern Queensland found that 19.3% of total SOC stocks were at 0.3 to 0.6 m and 19.2% at 0.6 to 1.0 m depth (Dalal *et al.* 2005).

Mitchell *et al.* (2024) reported that SOC sequestration rates in Australian scientific studies of grazing systems range from ca. 0.1 to 1.2 t C (C)/ha.annum. These were mostly reporting SOC to a depth of 30 cm. Australian grass pastures have been reported to have a rooting depth of about 2 m (Shelton and Dalzell 2007), while SOC stocks below 1.8 m appear unchanged over time (Elledge and Thornton 2025). These findings suggest that sampling below 0.3 m, and ideally to at least 1.0 m, would provide a more accurate indication of SOC stocks and changes over time, although this may be cost prohibitive for some purposes. However, a contrasting view was presented by Lam *et al.* (2013) whose meta-analysis of Australian agricultural soils indicated that the potential of improved practices to store C is limited to the surface 0-10 cm of soil and diminishes over time.

Substantial changes to SOC stocks have occurred over time due to agricultural practices, with a large proportion of the world's, including Australia's, native forests cleared to convert land to agricultural production. As reviewed by Dalal *et al.* (2021a), documented changes in SOC stocks following conversion of native forests to pastures have been variable, either increasing, decreasing or causing no change in SOC stocks. These authors reported that significant decreases were mostly found in coarse-textured rather than finer-textured soils. A long-term study in central Queensland on brigalow soils found an initial decrease in SOC stocks by 12.2% to 30 cm depth during the clearing of brigalow woodland and the pasture establishment phase (ca. 1.75 years), (Dalal *et al.* 2021a). However, this study found that there was no significant change thereafter up to 33 years mainly due to C inputs from pasture root biomass in addition to relatively low nitrogen (N) removal in animal product. These results are in line with global meta-analyses which reported a decrease in SOC stocks of ca. 10% with conversion of native forest to pasture (Don *et al.* 2011; Kopittke *et al.* 2017).

In contrast to the modest changes in SOC found for conversion to pasture, conversion of native forest to arable cropping generally leads to much larger losses of SOC. The meta-analysis by Kopittke *et al.* (2017) determined a median decrease in SOC stocks of 46% following conversion of native forest to cropping. Consistent with this finding, Dalal *et al.* (2021a) reported that SOC stocks under cropping in central Queensland brigalow lands declined by 38% to a depth of 30 cm over 26 years. This result was mainly due to insufficient root biomass inputs from crops as well as nutrient export in grain harvest.

A decrease in vegetation and soil organic C stocks on agricultural land relative to the native state indicates that there may be potential to increase vegetation C and/or SOC sequestration in agricultural systems back towards the saturation limit for that soil, through various management interventions. The extent to which this potential can be realised depends on the effectiveness of specific management strategies under different biophysical and production contexts. The following section reviews the evidence supporting different carbon sequestration strategies on extensive livestock production systems in Australia.

3.2 Evidence to support carbon sequestration opportunities on extensive livestock enterprises

Management strategies have been claimed to increase vegetation C and/or SOC on extensive livestock properties through interventions that 1) allow an increase in woody vegetation to occur, or 2) increase SOC by addressing nutrient deficiencies and enhancing pasture productivity. Some of these strategies are eligible for the ACCU Scheme under approved methods (CER 2026a).

Currently available ACCU Scheme vegetation methods relevant to extensive livestock properties, include:

- Reforestation by environmental or mallee plantings FullCAM method 2024
- Plantation forestry method
- Savanna fire management methods.

Currently available ACCU Scheme agriculture methods relevant to increasing SOC sequestration on extensive livestock properties include:

- Estimating SOC sequestration using measurement and models method.

While managers of livestock enterprises may choose to implement strategies that sequester C for other reasons, particularly if the strategy improves the profitability of their business, the ability to engage in the ACCU Scheme and earn C market income can be an incentive.

Sections 3.2.1 to 3.2.3 present the review of key C sequestration strategies relevant to extensive livestock enterprises, including increasing woody vegetation, fire management to enhance C storage and SOC sequestration in non-forested areas.

3.2.1 Increasing woody vegetation

3.2.1.1 Reduced livestock grazing pressure in woodlands to facilitate carbon sequestration through increased tree and shrub recruitment

This strategy was an accepted management change under the most important ACCU-generating vegetation method, Human-induced regeneration of a permanent even-aged native forest 1.1 (HIR), which is now closed to new projects. However, reduced livestock grazing is a potential component of grazing and land management practice change allowed under the new Integrated farm and land management (IFLM) method which is under development (ILFM Industry Taskforce 2025).

The low-productivity Mulga lands bioregion of south-west Queensland and western New South Wales have dominated the generation of ACCUs to-date through now closed ACCU Scheme vegetation projects, particularly using the HIR method, (Bowen 2025a). Witt *et al.* (2011) conducted a study using old grazing exclosures in the semi-arid mulga lands of eastern Australia and indicated that sites with exclusion of livestock grazing had potential C sequestration rates of between 0.92 and 1.1 t CO₂-e/ha.annum over a period of approximately 40 years. This was comprised of 0.73-0.91 t CO₂-e/ha.annum from above ground biomass and 0.18 t CO₂-e/ha.annum from soil C sequestration.

At a regional scale in central Queensland, Fensham *et al.* (2005) found that woody vegetation cover change between the 1940s and 1990s was largely related to extremes in rainfall relative to the long-term average, as well as stand density.

These authors found that fire and grazing had smaller or even negligible influences. However, the research of Forrester *et al.* (2025) assessing 46 existing grazing experiments distributed across Australia's rangelands, confirmed the potential for grazing management to increase woody C in specific environmental contexts. Although, the study found that responses to grazing exclusion were variable and difficult to predict, with responses ranging from moderate reductions in C stocks to large increases. Regions where grazing exclusion had little measurable impact on woody C stocks included 1) ecosystems that were naturally grassy or shrubby and don't tend to support a high density of trees, and 2) lower rainfall areas with annual precipitation of <300 mm.

The HIR ACCU Scheme method provided an economic incentive for landholders in the mulga lands to transition from livestock production to C farming, largely because the amount of profit foregone from existing livestock production was relatively low on a per unit area basis (Baumber *et al.* 2020; Bowen *et al.* 2022). However, in the absence of an alternative source of income such as an ACCU Scheme vegetation project, the complete exclusion of livestock grazing is not a feasible strategy for an agricultural business. This is also the case for a reduction in livestock grazing, rather than complete removal, because increases in woody C stocks generally reduce pasture biomass over time due to tree competition for soil water. Consequently, this has permanent negative impacts on livestock carrying capacity and production (McIvor and Gardener 1995; Jackson and Ash 1998; Burrows 2002; Scanlan 2002).

3.2.1.2 Planting trees

Establishing, converting or transitioning land to forestry plantations or, alternatively, planting native trees to store C and earn ACCUs, are identified as eligible activities relating to two current vegetation methods: Reforestation by environmental or mallee plantings FullCAM method 2024, and Plantation forestry method (CER 2026a). A modelling study of establishment and/or management of tree plantings in Australia showed that these activities can sequester significant amounts of total C, typically 0.43 – 2.87 t C/ha.annum, with soil C accounting for 14 ± 17% (Paul *et al.* 2022).

Land use change from agriculture to reforested plantings

Land use change from agriculture to reforested plantings with endemic forest species have been demonstrated to sequester substantial quantities of C. A study using paired sites in the wet tropics of Australia, determined that reforested areas accumulated ecosystem C at a rate of 7.4 t/ha.annum, with reforested areas containing, on average, 2.3 times more C than agricultural areas (233 and 102 t/ha, respectively), (Lewis *et al.* 2019). Those authors determined that C was accumulated in the living vegetation and debris pools of the rainforest plantings, but there was no evidence of accumulation of soil C. However, it took almost 50 years for C stock to reach similar levels to those observed in remnant forests, and the rate of C accumulation is expected to eventually reach plateau as the growth of the forest stand slows. The economic outcomes of pursuing such a strategy to earn ACCUs are unknown.

A modelling study by Paul *et al.* (2022) found that environmental plantings in Australia had relatively slow growth cf. commercial plantations and that this was compounded by the tendency for environmental plantings to occur in regions of lower site productivity. A further limitation is that, at present, the Reforestation by environmental or mallee plantings Full CAM method 2024, applies only to projects established in areas where Full carbon accounting model (FullCAM) data exists. Modelling studies conducted prior to the latest ACCU Scheme method development (Polglase *et al.* 2013; Evans *et al.* 2015) found that C farming from environmental plantings was a viable land use in Australia but the economic outcome was highly sensitive to variation in establishment costs. Sequestration rates would also influence the economic outcome of such activities.

Targeted tree planting and continuation of grazing

An alternative to broad-scale tree plantings and associated land-use change is a more targeted tree planting strategy on specific areas or paddocks within a farm. Planting trees in areas that are largely devoid of woody vegetation, as in south-west Victoria and Tasmania, can provide critical ecosystem services, including biodiversity and salinity management (Monckton and Mendham 2022). Additionally, trees planted in tree-less paddocks have been reported to improve pasture productivity, sheep production, and to provide animal welfare benefits through shade and shelter (Baker *et al.* 2018; Masters *et al.* 2023; Macdonald *et al.* 2025). If pasture biomass is not substantially reduced due to tree-grass competition, and the overall impact on agricultural production benefits is positive rather than negative, there may be an incentive for producers to plant trees, even without the consideration of potential ACCU Scheme income from a vegetation project. However, the economic outcome for the agricultural business would have to be carefully assessed.

Planting trees for agroforestry

Planting trees for agroforestry purposes results in long-term storage of C off-property once harvested material is converted into long-lived products such as furniture (CER 2026a). Additionally, multiple harvesting and replanting cycles over 50+ years could result in higher levels of C stocks than if trees are left unharvested (Macdonald *et al.* 2025).

A study of the softwood plantation species, *Pinus radiata*, established in a native, temperate Australian pasture, found that the plantation sequestered a significant amount of C in 16 years: net 86 t C/ha, averaging 5.4 t C/ha.annum (Guo *et al.* 2008). This was despite the loss of 14 t C/ha from the soil organic matter. The reduction in SOC in the plantation ecosystem was due to the slower turnover and decomposition of litter in the softwood plantation cf. native pasture. The relatively slow rates of C input to the soil following planting softwood species, were also reported by Paul *et al.* (2022).

Plantation forestry provides an alternative or supplemental source of income to the ACCU Scheme, as a replacement for income from agriculture. A bioeconomic 'proof-of concept' study of the potential for agroforestry in central Queensland found that the most profitable agroforestry system was to clear all existing timber and plant eucalypt strips for electrical poles (Donaghy *et al.* 2009). However, whilst complimentary grazing from Year 3 onwards provided a source of ongoing income, the business would need to support a substantial capital investment for 24 years before the timber was harvested and accumulated debts repaid. For many graziers, this extended payback period would cause cash flow challenges likely to inhibit industry participation.

3.2.2 Fire management to increase carbon stored in the landscape

Savanna fire management involves increasing the prevalence of cooler, early dry season fires with the intention of reducing large, high intensity, late dry season fires in higher rainfall areas of northern Australia (Fitch *et al.* 2022). This management strategy increases C sequestered in dead organic matter and living vegetation that would otherwise be burned in wildfires. The current ACCU Scheme includes a method associated with this strategy which allows crediting of C sequestration as well as emissions avoidance (CER 2026b). Projects are restricted to two rainfall zones in northern Australia: 600-1,000 mm annual rainfall, and >1,000 annual rainfall. A review by Henry *et al.* (2024) concluded that there was evidence of potential for a small increase in SOC stocks with a reduction in the frequency and intensity of savanna burning. However, a subsequent increase in tree biomass can result due to decreased competition from the pasture. Such an increase in tree biomass, while increasing vegetation C, can result in a productivity trade-off with livestock production.

3.2.3 Soil organic carbon sequestration in non-forested areas

3.2.3.1 Grazing management

Changes in grazing management by 'altering the stocking rate, duration or intensity of grazing (or any combination of such activities) to promote soil vegetation cover or improve soil health, or both' is identified as an eligible management activity under the 2021 Estimating SOC sequestration using measurement and models method in the ACCU Scheme (CER 2021).

However, as reviewed by Debney and Lobry de Bruyn (2024), scientific evidence for SOC sequestration associated with a change in grazing management of pastures in Australia, particularly at depth, is relatively scarce. A difficulty in interpreting results from Australian grazing trials is that the majority have not applied a fully factorial, replicated and controlled experimental design with baseline measures of SOC stocks (Debney and Lobry de Bruyn 2024). Moinet *et al.* (2023) concluded that soils under pasture are likely already close to the ceiling of SOC saturation with little potential for more sequestration. Consistent with this finding, the results of the meta-analysis of McDonald *et al.* (2023) indicated that there was no overall significant effect of grazing strategies on SOC stocks in Australian studies. A similar finding was made in the review of Debney and Lobry de Bruyn (2024), also of Australian studies. Henry *et al.* (2024) found more variability in SOC sequestration effects when focussing on Australian rangeland environments and grouping management strategies into broad categories of grazing intensity, rotational grazing (vs. continuous), and destocking (i.e. grazing excluded), although still concluded that there was limited potential overall (<0.1 t C/ha.annum).

Grazing intensity

Henry *et al.* (2024) concluded that while the impact on SOC stocks of low to moderate grazing intensity was non-significant or small in Australian rangelands (<0.1 t C/ha), preliminary evidence indicates that high grazing intensity is likely to result in a small negative effect on SOC stocks. A more recent publication reporting on a 10-year grazing management trial in central New South Wales, reported no significant effect of stocking rate on SOC stocks (Simmons *et al.* 2026). Additionally, Thornton and Elledge (2026) recently reported on a study over 10 years following a change from set stocking on buffel grass pastures in the Brigalow bioregion of central Queensland to variable stocking rates and wet season spelling (i.e. reduced grazing intensity). These authors found no significant overall change in SOC in any 0.1 m interval from 0 to 0.4 m. Soil organic C was sequestered during a wet series of years from 2010 to 2014 but subsequently lost in the dry series of years from 2015 to 2021. The same result was obtained under virgin brigalow woodland monitored over the same time period.

Rotational grazing (vs. continuous)

The review of Henry *et al.* (2024) indicated that there was no significant impact of managing the timing of grazing and rest periods in rangelands on SOC stocks. However, one experiment did indicate a non-significant decline in SOC stocks with cell grazing (one form of more intense rotational grazing strategy) cf. continuous grazing after detrending of climate effects (Allen *et al.* 2013). The more recent 10-year grazing management trial of Simmons *et al.* (2026) in central New South Wales (a temperate, high-rainfall system) measured marginally greater SOC sequestration (0.1 t C/ha.annum; 0-30 cm) in rotationally grazed treatments relative to continuously grazed treatments, likely due to the greater ground cover and pasture production. The number of paddocks in the rotation and the length of the rest period had no consistent effect on SOC sequestration. The dominant factor influencing SOC stocks in this latter experiment was the land use change from cropping to pasture 3 years prior, which caused SOC stocks to increase in all treatments (Simmons *et al.* 2026).

Destocked (grazing excluded)

The review of Henry *et al.* (2024) indicated that although results were inconsistent (ranging from -0.05 to 0.1 t C/ha.annum), an overall small positive trend in the rate of SOC sequestration was identified for destocked and/or enclosure sites cf. areas grazed by livestock.

Summary

Inconsistencies in the impact of grazing management strategies on SOC sequestration likely reflect site-specific factors such as initial SOC stocks, soil texture, climate, soil physical properties (e.g. bulk density and gravel content), fertility, plant species composition, microbial communities, soil erosion, and their interactions (Henry *et al.* 2024; Simmons *et al.* 2026). Simmons *et al.* (2026) suggested that given the lack of significant differences detected between grazing management treatments implemented in small uniform plots in research trials, detecting such differences would be considerably more difficult at a farm scale.

3.2.3.2 Converting cropland or bare fallow to pastures

Under the 2021 Estimating SOC sequestration using measurement and models method in the ACCU Scheme, an eligible management activity is 'converting cropland or bare fallow to pastures' (CER 2021).

Cropping soils typically contain less SOC relative to soils under pasture in the same environment due to undergoing greater SOC decline following initial conversion from native vegetation (Kopittke *et al.* 2017). Therefore, sowing pasture in existing cropland can increase SOC stocks through increasing total stock of root C in conjunction with 1) reduced mineralisation caused by disturbance from tillage, and 2) reducing N loss through grain harvest (Dalal *et al.* 2021a; Simmons *et al.* 2026).

Globally, studies have provided evidence of positive changes in SOC stocks after conversion of cropping lands to pastures (Conant *et al.* 2001; Poeplau *et al.* 2011). Most recently, a review by Henry *et al.* (2024), identified three studies conducted in the rangelands of New South Wales (Wilson *et al.* 2011; Badgery *et al.* 2020) or southwest Queensland (Jones *et al.* 2016) with credible SOC sequestration data for conversion of cropland to pastures. These studies indicated that over 15-20 years following conversion, soils supporting perennial pastures contained more SOC than cropping soils, with an estimated SOC sequestration rate attributed to conversion of 0.06 to 0.48 t C/ha.annum (0-30 cm). However, the recent study by Thornton and Elledge (2026) reported that over 10 years following conversion of a

long-term dryland grain cropping paddock to legume ley pasture in the brigalow bioregion of central Queensland, there was no significant net change in SOC in any 0.1 m interval from 0 to 0.4 m. While SOC was sequestered during a wet series of years from 2010 to 2014, it was subsequently lost in the dry series of years from 2015 to 2021. The same result was observed under virgin brigalow woodland monitored over the same time period. Jones *et al.* (2016) reported that sites with a longer duration of cropping have demonstrated a reduced potential for SOC sequestration due to the increased soil disturbance and loss of natural soil structure that would otherwise have stabilised soil organic matter. This may have been a factor in the study of Thornton and Elledge (2026).

It is important to consider that the rates of sequestration will decrease over time as sequestration approaches equilibrium levels for a land management practice and the soil and climate of the location. For example, the high rate of SOC sequestration over 5 years following conversion of reduced tillage cropping to permanent perennial pasture in central west New South Wales: 1.2 t C/ha.annum (0-30 cm) was nearly double the predicted rate of 0.67 t C/ha.annum and expected to decline over the longer term (Badgery *et al.* 2011).

Utilising pastures in crop-pasture rotations has also been demonstrated to have positive effects on C sequestration. For example, long term field trials (13-25 years) in the low-rainfall region of the temperate Australian grain belt near Wagga Wagga found that utilising crop-pasture rotations resulted in an increase of 0.5-0.7 t C/ha.annum (0-30 cm), where the initial SOC concentrations were well below steady state levels that would be expected after long period of improved management (Chan *et al.* 2011). Additionally, as reviewed by Dalal *et al.* (2021a), shorter term studies of the introduction of a legume-based ley pasture into a cropping rotation have also been found to arrest SOC decline and sometimes to increase SOC stocks. Legume leys have an additional advantage of adding N to the soils through fixation.

3.2.3.3 Re-establishing or rejuvenating a pasture by seeding or pasture cropping

The strategy 're-establishing or rejuvenating a pasture by seeding or pasture cropping' is identified as an eligible management activity under the 2021 Estimating SOC sequestration using measurement and models method in the ACCU Scheme (CER 2021).

Replacing existing grass pastures with more productive pasture grasses would be expected to increase SOC sequestration in the short term due to higher pasture biomass production and therefore higher soil organic matter inputs (Henry *et al.* (2024). Initial soil disturbance or addition of nutrients to promote growth would result in the increased SOC sequestration in the initial years following sowing. In northern Australia, where fertiliser use on tropical pastures is uncommon, it has been well documented that productivity decline occurs over time after establishment, caused by nutrients becoming tied up in old organic matter (Peck *et al.* 2011). Additionally, as demonstrated by Badgery *et al.* (2020) and Mitchell *et al.* (2024), long term persistence of SOC stocks under pasture is uncertain given temporal changes associated with rainfall and soil nutrient availability.

As reviewed by Henry *et al.* (2024), field data to support the sowing of improved grass pastures as a reliable strategy to improve SOC sequestration rates are lacking and existing results are not promising. The study of Chan *et al.* (2010b) in higher rainfall areas of south-eastern Australia, found that gains in SOC stocks after sowing improved grass species did not persist. After a decade, SOC stocks to 30 cm were not significantly different compared to native pastures. However, a modelling study conducted by Clewett (2015) for the Condamine region of southern Queensland predicted that over 5 decades, sown grass pastures would sequester an additional 0.11 t C/ha.annum cf. native pastures, although a decline in the rate of SOC sequestration over time was predicted. It is important to note that the simulation of SOC sequestration in this latter study was not verified with field measurements. Another simulation study of a typical Merino enterprise in south-western Australia, indicated that livestock systems utilising perennial pastures may have substantially higher C sequestration compared with annual plant-based production systems, indicating that the choice of pasture is important (Thomas *et al.* 2012).

3.2.3.4 Introducing legume species in pasture systems

Under the 2021 Estimating SOC sequestration using measurement and models method in the ACCU Scheme, an eligible management activity is 'using legume species in cropping or pasture systems' (CER 2021).

Sowing legumes in grass pasture systems can increase SOC sequestration through the higher input and quality of soil organic matter resulting from N fixation. Debney and Lobry de Bruyn (2024) reviewed the effect of legumes on SOC

stocks in Australian pasture systems and identified only four published studies. All were conducted in subtropical Queensland and tropical Northern Territory environments on clay or clay loam soils with three studies assessing the tree legume leucaena (*Leucaena leucocephala*; Radrizzani *et al.* 2011; Conrad *et al.* 2017; Conrad *et al.* 2018) and the fourth, the shrubby legume Townsville stylo (*Stylosanthes humilis*; Myers 1976). The studies of leucaena indicated that leucaena-grass pastures accumulated SOC at greater rates than grass-only pastures, with one study indicating a rate of sequestration over 40 years of 0.28 t/ha.annum (0-30 cm; Conrad *et al.* 2017). On the contrary, stylo-grass pastures did not have significantly different SOC to native grass pastures (Myers 1976). In the study of Conrad *et al.* (2017), leucaena directly contributed to SOC stocks through the input of leaf litter and root turnover. However, the significant increase in SOC sequestration was primarily a consequence of the indirect contribution via N fixation, which increased soil N (36 kg N/ha.annum), and enhanced grass productivity. The density and vigour of the sown legumes will determine how much N will be added to the soil as a result of N fixation. Nutrient deficiencies such as phosphorus (P) and sulphur (S) will restrict direct legume growth and suppress the ability of the legume to fix N (Radrizzani *et al.* 2010).

The review of Henry *et al.* (2024) identified three additional papers where SOC was measured or modelled after establishing tropical and/or temperate legumes in Australia and found a consistent trend for increase in SOC stocks, with estimated sequestration rates of 0.14-0.72 t C/ha.annum (0-30 cm; Clewett 2015; Harrison *et al.* 2015; Wocheslander *et al.* 2016).

Regardless of SOC effects, addition of legumes to pasture systems have been shown to have benefits including biological N fixation, improved soil structure, erosion protection and increased biodiversity (Debney and Lobry de Bruyn 2024). Additionally, introduction of adapted, perennial legumes to pasture systems have been shown to increase livestock productivity and enterprise profitability (Bowen *et al.* 2018; Bowen and Chudleigh 2019; Bowen and Chudleigh 2021a).

3.2.3.5 Application of nutrients to the land

'Application of nutrients to the land in the form of synthetic or non-synthetic fertiliser to address a material deficiency' is an eligible management activity under the 2021 Estimating SOC sequestration using measurement and models method in the ACCU Scheme (CER 2021).

A meta-analysis of 107 long-term crop fertilisation studies around the world reported that fertilisation increased SOC compared to an unfertilised control by an average of 12.8% (Geisseler and Scow 2014). Fertilisers increase SOC under crops by supplying essential nutrients (like N, P and S) that stimulate plant growth. This allows an increase in forage biomass above ground and in the roots, which eventually breaks down and becomes incorporated into the soil as organic matter and thus SOC. A review by Howe *et al.* (2024) indicated that SOC sequestration was greatest when the N fertiliser rate was agronomically optimum in non-legume cropping systems, i.e. there was no benefit to excessive N application.

The global meta-analysis of Lu *et al.* (2011) found that SOC did not significantly change in response to N addition in grasslands. In comparison, SOC was significantly increased by 3.5% in cropping situations. It is generally considered that plant-available N may be limiting SOC accumulation in pure grass swards in Australia (Radrizzani *et al.* 2011; Dalal *et al.* 2021a; Lindenmayer *et al.* 2026). However, C:N ratio is the dominant factor that regulates N effects on microbial decomposition of litter and soil organic matter. Lu *et al.* (2011) concluded that C storage tends to decrease in response to N addition in grassland soils with high C:N ratio which is the case for many global grasslands.

The guide produced by Chan *et al.* (2010a) suggests that use of inorganic fertilisers in grazed pastures can result in C sequestration rates of 0.30 t C/ha.annum in Australian pasture lands. Addition of organic fertiliser in the form of animal manure or biosolids was expected to result in sequestration rates of 0.1 to 0.6 and 1.0 t C/ha.annum, respectively. Animal manure typically has greater C content and lower nutrient content than inorganic fertilisers (Howe *et al.* 2024). Therefore, the increase in SOC stocks from manure application are generally greater than the increase due to fertilisation alone, due to the direct addition of C to the soil. In the study of Badgery *et al.* (2011), conducted in central west New South Wales, organic amendments in the form of biosolids from Sydney Water were applied at 10 t DM/ha (4.6 t C/ha). This application was estimated to increase SOC sequestration within the range 0.6-1.0 t C/ha.annum. Howe *et al.* (2024) reported that co-application of manure with organic fertilisers can be more effective at increasing SOC than supplying them individually.

Although the application of nutrients to forages and rundown sown grass pastures can result in productivity benefits and C sequestration, the economic outcomes for livestock enterprises in northern Australia have generally been less favourable. For example, the application of N and P fertiliser to grass pastures or forages in modelled scenarios for southern and central Queensland did not significantly improve the returns of the producer in most cases (Lawrence *et al.* 2014). Estimated positive economic returns were only achieved when pastures and forages were assumed to be in good condition, relatively productive, and showed a significant assumed response in both stocking rate per hectare and cattle growth rate per head. However, the increase in price risk arising from application of fertiliser was seen as a likely impediment to adoption even under circumstances where increased gross margins were predicted. In contrast, a similar scoping study of P fertiliser application to legume-based sown pastures in southern and central Queensland indicated potential returns of 9-15% on additional funds invested when P was applied at legume establishment in grass pastures on low P soils (i.e. below the critical P requirement of the legume), (Peck *et al.* 2015). Higher returns of 12-24% appeared possible when adding P fertiliser to already established legume-grass pastures on similar soils.

3.2.3.6 Undertaking new irrigation

'Undertaking new irrigation' is an eligible management activity under the 2021 Estimating SOC sequestration using measurement and models method in the ACCU Scheme (CER 2021).

Undertaking new irrigation activities can increase SOC sequestration primarily by removing water limitations, which boosts plant biomass production. Greater plant yields and root development return more organic residue to the soil. However, irrigation also accelerates microbial respiration, frequently leading to a net loss of C rather than sequestration (Mudge *et al.* 2017). For example, studies of irrigated pastures in the temperate climate of New Zealand reported significantly less soil C than adjacent unirrigated pastures (Kelliher *et al.* 2012; Mudge *et al.* 2017). The meta-analysis of Emde *et al.* (2021) of SOC in global irrigated agricultural systems found that, overall, irrigated agriculture increased SOC stocks by 5.9% with changes in SOC varying with climate and soil depth. However, while there was an increase in sprinkler irrigated sites, there was no overall change to SOC in flood/furrow irrigated sites, and a decrease in drip irrigated sites, especially at depths below 10 cm. The greatest increases in SOC were observed on irrigated, semi-arid sites at the 0-10 cm depth (14.8%). Additionally, SOC increased in irrigated fine- and medium-textured soils but not coarse-textured soils.

3.2.3.7 Applying soil ameliorants

'Applying lime or gypsum to remediate soils' is an eligible management activity under the 2021 Estimating SOC sequestration using measurement and models method in the ACCU Scheme (CER 2021).

Acidity, and resulting aluminium toxicity, affect 14.2 million ha of agricultural land in south-western Australia alone. Both lime and gypsum can decrease the toxic effect of aluminium (Anderson *et al.* 2020). The use of lime also increases soil pH on acidic soils. Additionally, lime and gypsum can be used to suppress soil dispersion on naturally sodic and/or dispersive soils (McKenzie 2022). As lime is much less soluble than gypsum it is slower to suppress soil dispersion and achieve the desired plant biomass effects. These ameliorants can have a net positive to neutral effect on SOC sequestration primarily through removing chemical or physical growth constraints and therefore resulting in increased plant biomass inputs to the soil. However, both amendments also alter soil biological and physical properties in ways that can temporarily stimulate C losses through microbial respiration. Therefore, the impacts of lime or gypsum application on net C accumulation are heavily influenced by the existing soil nutrient levels, soil texture, management practices and timeframes (Aye *et al.* 2016).

The Australian studies of Aye *et al.* (2016) and Wang *et al.* (2016) found that the impacts of liming on SOC are strongly influenced by 1) the primary C inputs following liming and 2) the capability of the soil system to compensate for increased C mineralisation by microbes from higher pH. Therefore, to maintain and increase soil C balance and soil fertility, amelioration of soil acidity by liming should be followed by management practices that maximise biomass input and minimise soil disturbance. When lime and gypsum are applied in combination, the effects on net C sequestration rates can be additive on the condition that biomass C input and minimal soil disturbance also occur (Inagaki *et al.* 2016).

3.2.3.8 Modifying landscape or landform features to remediate the land

Under the 2021 Estimating SOC sequestration using measurement and models method in the ACCU Scheme, an eligible management activity is 'modifying landscape or landform features to remediate the land'. Such activities include practices implemented for erosion control, surface water management, drainage/flood control, or alleviating soil compaction. Examples of practices include controlled traffic farming, deep ripping and water ponding.

Read *et al.* (2012) found that rehabilitating scalded areas through water ponding in central-west New South Wales, increased SOC sequestration by up to 1.5 t C/ha.annum over the initial 5 years, before stabilising. However, long-term SOC dynamics for this strategy have not been investigated, nor has the level of any associated GHG emissions. Regardless, it is important to note that scalded areas are usually only a small proportion of a productive property.

Moravek and Hall (2014) reported on the economic outcome of mechanical interventions to remediate degraded grazing land for a field experiment conducted in the Burdekin rangelands region of Queensland. While all treatments (deep ripping, chisel ploughing and crocodile seeding) improved pasture yield and potential livestock carrying capacity, none returned a positive net present value (i.e. none produced a positive economic result) indicating that the funds invested could be better invested elsewhere. Similarly, a review by Moravek *et al.* (2017) concluded that fencing, revegetation, earth works and stock control required to rehabilitate gullies on grazing land would result in negative, nil, or very small returns. Even in circumstances where producers received grant funding to subsidise 60-70% of the capital outlay for rehabilitation projects, the finding of negative to very small returns was confirmed (Denny and Moravek 2019).

3.2.4 Summary

Overall, the review of evidence supporting C sequestration opportunities on extensive livestock enterprises found that the potential is highly context-dependent, with significant biophysical limits and economic trade-offs constraining practical application. Strategies aimed at increasing woody vegetation, including through reduced grazing pressure or fire management, show inconsistent and unpredictable outcomes and in many cases may reduce pasture biomass and livestock carrying capacity over time, negatively affecting productivity and profitability in the absence of alternative income streams such as ACCU Scheme participation. While tree plantings can sequester substantial amounts of C, particularly in higher productivity environments, commercial plantings generally offer greater sequestration potential than environmental plantings and are more likely to deliver meaningful outcomes where site productivity is high. Income from an ACCU Scheme project and/or agroforestry may improve the feasibility of such strategies for landholders. However, their adoption remains constrained by the high cost and risk of establishment, as well as long payback periods, meaning that appropriate economic analysis is essential to evaluate their viability within livestock enterprises.

In contrast to increases in vegetation C, opportunities to increase SOC in grazing systems are generally more constrained and uncertain. There is limited consistent evidence that changes in grazing management or pasture rejuvenation alone lead to measurable and sustained increases in SOC, which restricts the applicability of current soil C ACCU methods in extensive systems. However, certain land use and pasture improvement strategies, particularly 1) conversion from cropping to permanent pasture and 2) the introduction of productive legumes, have demonstrated more reliable potential to increase SOC stocks, although gains remain limited by soil and climate conditions and may decline over time.

Additional strategies, such as fertiliser application, soil amendments, irrigation or landscape modification, may enhance SOC under specific conditions, but their effectiveness is variable and they are often associated with uncertain or unfavourable economic returns in extensive livestock systems.

Importantly, even where C sequestration is achieved, it does not necessarily translate to reduced net emissions or improved profitability for a livestock enterprise. Many strategies involve trade-offs between environmental and production outcomes, and in some cases may reduce farm income despite delivering emissions benefits. However, as C farming practices can deliver broader ecosystem co-benefits, including improved soil function and landscape condition, this supports the case for approaches to integrated payment for ecosystem services in addition to the ACCU scheme. In summary, broad scale adoption of C sequestration strategies will depend on whether they provide net economic and financial benefits to landholders, indicating the critical need for comprehensive economic analyses to evaluate trade-offs and inform decision-making.

3.3 The historical contribution of carbon sequestration to net greenhouse gas emissions attributed to Australian beef cattle and sheep production

Modelling at a regional level by Bowen Butchart *et al.* (2025) indicates that GHG emissions attributed to Australian beef cattle and sheep production have trended down since 2010/11, with the net position decreasing from 148 Mt CO₂-e (carbon dioxide equivalents) to 50 Mt CO₂-e in 2019/20 (Figure 1). The analysis indicated that enteric emissions from livestock remained relatively stable over the 10-year study period (46-53 Mt CO₂-e/annum), reflecting stable trends in national herd and flock numbers. In contrast, there was a gradual decrease in C emissions from private forest and increased removals in grasslands so that by 2019/20 enteric emissions became the greatest proportional contributor to GHG emissions from beef cattle and sheep production. The downward trajectory in net emissions was primarily the result of reduced CO₂-e efflux from private forests due to declining forest loss in association with relatively stable forest gains (C accumulation associated with afforestation and with growth). Grasslands also contributed to the downward trajectory, albeit to a lesser extent, transitioning from a relatively minor net source of emissions to a net sink in ca. 2015/16 due to reduction in emissions sources such as biomass burning and grassland soils.

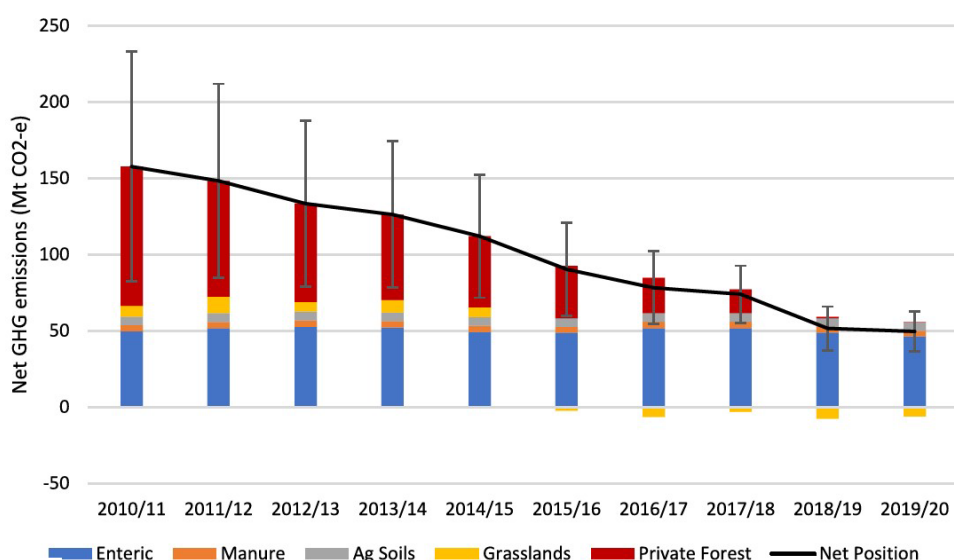


Figure 1 - Greenhouse gas (GHG) emission category contributions associated with beef cattle and sheep production over time (Bowen Butchart *et al.* (2025).

Absolute error is represented by combined emission category uncertainty.

Enteric: fermentation emissions from beef cattle pasture, beef cattle feedlot and sheep.

Manure: manure emissions from beef cattle on pastures and in feedlots, together with grazing sheep.

Agricultural soils (Ag Soils): emissions from areas classified as grazing land use including application of nitrogen fertiliser, animal waste applied to soils - lot-fed cattle, urine and faeces deposited by grazing animals, pasture residues, atmospheric nitrogen deposition – fertiliser and manure, and nitrogen leaching and run-off from fertiliser, crop residues and manure.

Grasslands: remaining grassland CO₂ sinks and sources combined (net) from pasture, grazing and fire management from areas consistently classified as grassland including sparse woody vegetation, grassland soils, controlled biomass burning; direct N₂O from nitrogen mineralisation, nitrogen leaching and run-off.

Private forest: combined (net) carbon stock gains and losses in private forests assumed to be associated with cattle and sheep operations and within the grazing landscape from aboveground biomass, belowground biomass and dead organic matter.

3.4 The potential for carbon sequestration to continue to reduce net greenhouse gas emissions attributed to Australian beef cattle and sheep production

While reduced CO₂ efflux from private forests has had the major contribution to the downward trend in net GHG emissions attributed to Australian beef cattle and sheep over the recent decade, 2010/11-2019/20, it is important to note that afforestation across grazing lands can only be considered an interim measure for reducing net property emissions. Forest C accumulation in Australia typically peaks within 5-10 years of establishment, after which the rate of sequestration declines (Doran-Browne *et al.* 2016; Gowen and Bray 2016). In contrast, enteric methane emissions occur continually and in proportion to livestock numbers. If forest area was to be continually expanded over time to balance enteric methane emissions, livestock carrying capacity and production level would be negatively impacted as trees compete with grass for water and nutrients. Despite these limitations, in environments where remaining woody vegetation is limited on grazing properties, such as in south-west Victoria and Tasmania, tree plantings may provide additional benefits, including improved farm biodiversity, pasture productivity, sheep production, and animal welfare benefits through the provision of shelter and shade (Baker *et al.* 2018; Masters *et al.* 2023; Macdonald *et al.* 2025).

The difficulty in maintaining a net zero position on a grazing enterprise using only sequestration through increased woody vegetation is demonstrated by the case study of Jigsaw Farms in south-west Victoria (Macdonald *et al.* 2025). At this property, tree plantings on 17% of the area resulted in greater C sequestration in trees and soils than the equivalent GHG emissions, for only ca. 7 years before emissions again exceeded sequestration due to declining sequestration rates in trees and soils.

The capacity to continue the conversion of land to forest in Australia has been modelled by CSIRO in a net zero to 2050 scenario (CCA 2024). The Australia-wide land sink was projected to increase through to 2050 with an additional 3 million ha of land converted to forest to provide a C sink of 129 Mt CO₂-e. Despite the accepted considerable uncertainty over the ability to increase forest-based sequestration, most analyses of net zero pathways rely on this strategy to make a substantial contribution (CCA 2024; Malos *et al.* 2024; McCall *et al.* 2025; Whittle *et al.* 2025).

In contrast to increases in forest area, other strategies to increase SOC sequestration in grasslands, such as introducing legume species to grass pastures, are generally not competitive with grazing and appear to offer opportunity for further growth as a sink. Furthermore, the co-benefit of increasing SOC on soil health and productivity is well accepted, particularly for degraded soils (Minasny *et al.* 2023). Additionally, increased SOC buffers against toxins and protects soil from erosion and compaction (Debney and Lobry de Bruyn 2024). As grasslands cover >50% of the global terrestrial land area, they are estimated to contain a large proportion of the global stock of SOC (Schuman *et al.* 2002), i.e. around one third (to a depth of 1 m). Therefore, a small relative increase in grassland SOC could have a substantial positive impact on the global C sink.

However, reservations exist regarding the potential of SOC to mitigate climate change due to significant ongoing emissions of GHG from soil due to agricultural use which exceed SOC sequestration potential (Minasny *et al.* 2023). Lam *et al.* (2013) indicated that small increases (7-13%) in the C concentration in the surface layer of Australian agricultural soils may not be technically credible due to sampling errors, spatial variability and uncertainties associated with measurement and analysis. Moreover, these authors concluded that management-induced changes in C in the surface soil layer are very vulnerable to loss and that most Australian cropping soils are continuing to lose C regardless of agricultural practices designed to sequester C. Additionally, it has been identified that over the longer-term, climate change may impede sequestration and maintenance of SOC in regions where decreases in rainfall and increases in temperature are likely (Gibson *et al.* 2021; Wang *et al.* 2022; Gibson *et al.* 2023). However, Dalal *et al.* (2021b) obtained contrasting results for a subtropical soil under native woodland vegetation in Queensland, where increased SOC stocks over 33 years were associated with increases in CO₂ and temperature, while rainfall remained unchanged. Minasny *et al.* (2023) has asserted that the future global focus should be on maintaining SOC stocks and reducing losses rather than on increasing SOC. However, despite these limitations, C sequestration in vegetation and soils is expected to make a significant contribution to achieving Australia's net zero target (CCA 2024; Malos *et al.* 2024; McCall *et al.* 2025; Whittle *et al.* 2025).

3.5 The potential for carbon market opportunities to encourage future sequestration activities

Environmental markets, such as C or ecosystems service markets, provide a framework for landholders to invest in sustainable practices while gaining economic and financial benefits. Environmental markets facilitate the trade of environmental assets or ecosystems services including C credits, water rights and biodiversity offsets. The creation of C market opportunities through the ACCU Scheme has been a key strategy to encourage GHG abatement in Australia through reduction in emissions or C sequestration (CER 2026a). ACCU Scheme methods issue a C credit for every 1 t CO₂e sequestered or avoided, after adjustment for any GHG emissions associated with implementing the strategy (CER 2026a). Projects must meet the 'additionality' requirement by demonstrating that the strategy is not 'business as usual' and C sequestration projects must meet 'permanence' requirements of maintaining sequestered C for either 100 or 25 years. Selecting project sites with low existing C stocks provides greater potential to sequester C within the constraints of soil type and climate (e.g. as per Badgery *et al.* 2011). The two key C sequestration categories of ACCU Scheme methods relevant to extensive livestock producers are those that are considered vegetation-based methods and SOC sequestration methods. The past contribution, and the future potential, of these ACCU Scheme methods to encourage measurable C sequestration and net emissions reductions for extensive livestock enterprises, is reviewed below.

Vegetation-based methods

Several vegetation-based methods as part of the ACCU Scheme have underpinned the reductions in Australia's beef cattle and sheep GHG accounts by incentivising sequestration in private forests through reduced forest loss (Bowen Butchart *et al.* 2025). However, these key vegetation methods have now closed, following considerable scrutiny due to concerns over the additionality and permanence of C abatement credited (Merzian *et al.* 2021; Macintosh *et al.* 2022a; Macintosh *et al.* 2022b; Macintosh *et al.* 2024). Notably, Macintosh *et al.* (2024) identified that most projects registered under the most important ACCU-generating vegetation method, HIR, were 1) non-compliant with key regulatory requirements that are essential to project integrity and 2) have had minimal impact on woody vegetation cover in credited areas. The closure of these key vegetation methods has left private landholders with significantly reduced opportunities to participate in the C market.

The low-productivity Mulga lands bioregion of south-west Queensland and western New South Wales have dominated the generation of ACCUs to-date through vegetation projects (Bowen 2025a). Jassim *et al.* (2022) reported that up to a third of the Mulga lands bioregion (7 million ha) had transitioned from extensive grazing to C farming in less than a decade. This transition likely occurred due to the favourable ratio of C income to opportunity cost, i.e. the small amount of profit foregone per unit land area from existing livestock production (Baumber *et al.* 2020; Bowen *et al.* 2022). However, although C farming in the mulga lands has been shown to be more profitable than beef production, it was not the most profitable land use compared to rangeland meat goat production in the mulga lands near Charleville in south-west Queensland (Bowen *et al.* 2022). It is important to note that negative social impacts have been identified in rural communities where these vegetation projects are being undertaken at scale. These result from the destocking of properties, increase in landholder absenteeism, non-active land management, and inequitable distribution of benefits (wealth) within the community (Baumber *et al.* 2022; Jassim *et al.* 2022).

The proposed IFLM method is still under development but is anticipated to combine vegetation and soil C sequestration enabling crediting of C stored from managed regeneration and plantings of native forest as well as improvements to soil (Carbon Market Institute 2026; DCCEEW 2026a). The method is being designed to allow multiple activities that store C on the land to occur on a single property or project area. This method is intended to restore access to C market opportunities for private landholders while improving the environmental integrity of credited abatement. Adoption of the IFLM method by landholders will be determined by perceived benefits, costs and risks. Again, appropriate economic and financial analysis would provide valuable insights to inform landholder decision making once the details of the new method are known.

Soil organic carbon sequestration methods

Issuance of ACCUs for SOC sequestration methods has been relatively minor to date compared to issuance for vegetation projects (CER 2026a). Data downloaded from the Clean Energy Regulator (CER) on 29/11/2024, indicated that while the method 'Estimation of SOC sequestration using measurement and models 2021' had 529 project

registrations Australia-wide, only 16 had been issued with ACCUs (Bowen 2025a). Those total ACCUs constituted only 0.2% of Australia's total ACCU issuance and 0.3% of issuance from all methods applicable to grazing enterprises.

The uncertain outcome of SOC sequestration projects is likely inhibiting uptake by landholders. Henry *et al.* (2024) identified that there is poor confidence in predicting: 1) the maximum SOC storage capacity of different soils and dynamics of change towards the saturation level; 2) the permanency of sequestered SOC, and 3) the levels of GHG emissions associated with the project. Predicting the potential for SOC sequestration remains a challenge due to the diversity in climate, soil and landscape characteristics across Australian landscapes as well as variation in land use history and livestock production systems. Furthermore, detecting any changes in SOC stocks due to management interventions can be difficult due to the dominant effects of climate and soil variables in Australian environments, particularly rangelands.

Concerns have also been raised about the integrity of soil C ACCU Scheme methods, with the rates of SOC sequestration reported for ACCU Scheme projects due to the application of management strategies being in the range 2-8 t C/ha.annum, which is an order of magnitude greater than rates reported in scientific studies (1-1.2 t C/ha.annum) (Mitchell *et al.* 2024). The research of Mitchell *et al.* (2024) indicated that SOC credits issued in 2023 were largely attributable to above-average rainfall rather than project interventions. Moreover, these soil C gains were not sustained when rainfall returned to average, raising concerns about the additionality of the sequestration, beyond natural climatic variability. Badgery *et al.* (2020) documented substantial temporal changes in SOC in a low rainfall, temperate environment, where SOC stocks increased over 12 years in four different farming systems and then decreased back to starting levels over the subsequent 3 years. The authors concluded that these changes over time were likely associated with changes in soil N availability. This study indicated the risk of non-permanence in SOC sequestration projects with associated implications for landholders engaging in ACCU markets. Recommendations to increase the minimum preliminary measurement period to at least 5 years and to increase the number of soil samples required (Mitchell *et al.* 2024) as well as monitoring a reference land use in addition to the ACCU project area (Badgery *et al.* 2020) are likely to decrease the financial attractiveness of soil C methods for landholders if adopted. It appears likely that without changes to the methods to increase the benefits for landholders relative to the costs and risks, there will continue to be poor adoption of SOC ACCU Scheme methods. Net emissions and profitability as a consequence of implementing carbon sequestration strategies.

4. Net emissions and profitability as a consequence of implementing carbon sequestration strategies

4.1 Calculating net emissions

The net emissions or C position for an agricultural property is the balance of CO₂ removals from the atmosphere and GHG emissions either reduced or avoided. An increase in net C sequestration on a project area may not result in reduced net emissions in all cases. Therefore, it is important to consider the net abatement in preliminary assessments which incorporate changes in all GHG emissions resulting from the C sequestration strategy. If the impacts of the C sequestration strategy are limited to the paddock level and only change paddock emissions, then the analysis of net emissions may be limited to that level. However, when the strategy causes changes in the breeding herd or flock structures, and any other farm-level emissions, then it is critical to assess the change in paddock management at the farm level so that all the various impacts on emissions can be assessed and included.

Carbon accounting is the process used to estimate the GHG emissions and sequestration associated with an enterprise. As it is difficult and expensive to measure actual emissions on-farm, standard calculations are applied to estimate net emissions from the property, paddock, or enterprise and the C footprint (emissions intensity) of products (Eckard 2024). A C account (or audit) is equivalent to the net emissions of the business unit (t CO₂-e / business unit) and includes:

- All GHG produced which is essential to the management of business unit, including Scope 1 and 2 emissions and those Scope 3 emissions essential to the management of the property.
- The annual net change in soil and tree C, based on a 10-year rolling mean.
- Adjustments for C offsets bought or sold (note that the Science based targets initiative (SBTi) only allows purchased offsets for the intractable residual emissions (Science Based Targets Initiative 2024)).

In the calculation of net GHG emissions, Scope 1 emissions are all direct GHG emissions (CO₂, CH₄, N₂O) from within the farming enterprise. Scope 2 emissions are from electricity purchased from a fossil fuel origin onto the farm. Scope 3 emissions include all pre-farm embedded emissions associated with the purchase of products on to the farm (e.g. lime, urea, herbicides, cattle).

A C footprint or emissions intensity (t CO₂-e / t product) uses the same calculations as for a C audit except the denominator is the unit of product produced rather than the business unit (Eckard 2024). Additionally, the C footprint includes all Scope 3 emissions (pre-farm GHG and some post farm) as these are essential for the product produced. MLA-funded 'Life Cycle Assessments' conducted in 2019 indicated an average emissions intensity for beef production (from farm to processor) across the beef industry of 12.6 kg CO₂-e / kg liveweight (for the 5 years to 2015), (Wiedemann *et al.* 2019). Wiedemann and Dunn (2021) provide an expected range for emissions intensity (excluding sequestration) of 9-18 kg CO₂-e / kg liveweight gain for beef breeding, growing and finishing, and 5-9 kg CO₂-e / kg liveweight gain for beef cattle traded excluding Scope 3 livestock emissions. The Australian Government provides an estimate of Australian cattle emissions intensity expressed per animal (i.e., per head) and calculated according to FAOSTAT methodology used in international trade forums: 1.83 t CO₂-e / head (5-year average, 2017-2021), (ABARES 2024).

The net C position of the farm enterprise, or product from the farm, is therefore a summation of the GHG emissions minus the annual change in soil or tree C sequestered for that annual time-step. There are number of farm-based, GHG emissions tools available that estimate emissions for grazing properties, the most widely accepted being the GHG accounting framework (GAF) calculators (e.g., the Sheep and Beef GHG accounting framework (SB-GAF) for sheep and beef) developed by the Primary Industries Climate Challenges Centre (PICCC 2023). Carbon sequestration is not estimated using the GAF tools and must be estimated separately as part of a farm-based C audit. For an official farm C audit that complies with Australian and international C accounting standards, soil C should ideally be measured in situ, using approved protocol but a combination of measurement and modelling (e.g. using FullCAM) is acceptable using

approved models and approaches. Tree C is ideally measured directly by an accredited auditor but, as for soil C, direct measurements can be coupled with modelling using a peer-reviewed tree growth model, applicable to the Australian context (e.g. FullCAM).

4.2 The appropriate economics framework to assess trade-offs between net emissions reduction and profitability

To facilitate adoption of C sequestration and other emissions mitigation strategies, economic and financial analysis is needed to assess the trade-offs and opportunities for the landholder, and to identify any potential perverse outcomes. Strategies that increase C sequestration and/or reduce net emissions may not necessarily align with farm profitability or preferred risk outcomes, so these implications need to be understood clearly if producers are to make informed adoption decisions. Such analysis may also need to be revisited over time, as changes in policy settings and market conditions can alter the economic and financial consequences for producers.

Assessing trade-offs between net emissions reduction and profitability requires a conceptual framework that matches the scale of complexity, and whole farm implications, of the proposed change. A whole farm perspective is important because many management changes that appear beneficial at the paddock level can have different implications once their effects on the rest of the business are considered. As Malcolm *et al.* (2005) emphasised, the purpose of economic and financial analysis is to assemble the important elements of the farming system into a coherent whole, even if simplified, so that the implications of change can be assessed properly. These and other authors have stated “*the whole farm operation needs to be kept in view*” (Makeham and Malcolm 1993; Malcolm *et al.* 2005). This concept is particularly relevant when evaluating emissions reduction and C sequestration strategies because changes in one part of the farm generally alter the use of machinery, labour, feed supply, livestock herd structure, overhead costs, risk exposure and future management flexibility elsewhere in the business.

Accordingly, decisions that affect emissions are generally best assessed at the farm level. A farm-level assessment is usually needed where a proposed change alters herd or flock structure, changes the timing or mix of enterprises, requires additional machinery or infrastructure, changes labour demand, or affects whole farm overheads or capital commitment (Malcolm *et al.* 2005; Pannell 2006). In such cases, a paddock-scale comparison can misrepresent the true economic effect because it omits complementarities, substitution effects and resource constraints operating elsewhere on the farm. This point is also reflected in whole farm bioeconomic and policy-oriented modelling studies.

One framework that has been applied to whole farm bioeconomic modelling is the Agricultural Production Systems Simulator (APSIM). APSIM is a process-based model that integrates crop or pasture growth, soil water and nutrient dynamics, C sequestration and GHG emissions within a farming systems context (Keating *et al.* 2003; Holzworth *et al.* 2014). Its modular structure allows different components of the farming system to be linked, while extensions such as APSFarm incorporate economic elements, enabling the simulation of management decisions and their implications for gross margins, risk, and environmental outcomes at the whole farm level (Rodriguez *et al.* 2006). By linking biophysical processes with economic decision-making, APSIM-based frameworks can assess farm-level trade-offs between productivity, profitability and emissions under alternative management scenarios.

Integrated bioeconomic models can also explicitly account for the opportunity costs of diverting land from existing agricultural uses to sequestration activities. For example, Kragt *et al.* (2012) combined the APSIM process-based model with the Model of an Integrated Dryland Agricultural System (MIDAS), a whole farm bioeconomic model, to evaluate soil C sequestration alongside farm profitability. In this framework, APSIM simulates soil organic C dynamics under alternative crop–pasture rotations and residue-retention regimes, capturing interactions among climate, soil, and management, while MIDAS represents the farm as a steady state, profit-maximising system subject to resource and technical constraints. Linking APSIM outputs to the enterprise mixes selected in MIDAS, the study derives trade-off frontiers between profit and sequestration and thereby captures the opportunity costs associated with land-use change. A similar integrated framework was used by Thamo *et al.* (2017), in which MIDAS is coupled with the FullCAM biophysical model to estimate C sequestration from reforestation options. In this case, FullCAM provides spatially and temporally explicit C estimates that are incorporated into the economic model to evaluate how C income competes with agricultural production. Several other studies have used similar models, or extensions of them, to account for trade-offs in farming systems (Polglase *et al.* 2013; Bryan *et al.* 2014; Meier *et al.* 2020; Tan *et al.* 2025).

At a broader spatial scale, Morris *et al.* (2025) used the Spatial Agriculture, Forestry and Environment (SAFE) model to estimate aggregate land use responses. SAFE is useful for analysing how policy or market settings may influence land use change across regions or industries and therefore complements whole farm analysis by providing a broader perspective on the potential scale and distribution of adoption. However, it is not a substitute for whole farm analysis where the objective is to assess detailed within-farm trade-offs, because it is less able to represent resource competition within the farm business, interactions between alternative enterprises, and practical management constraints such as seasonal labour peaks or infrastructure limits.

In sum, this literature suggests that the appropriate analytical framework depends on the extent to which a proposed mitigation or sequestration strategy changes resource allocation, enterprise structure, and management interactions across the farm business, as well as the objective of the analysis.

The farm management economics literature also makes clear that where a proposed change is relatively simple, in the sense that it does not materially affect other aspects of the farm business, analysis can be undertaken at a narrower scale. In such cases, Malcolm *et al.* (2005) suggest that gross margin analysis may be a practical and sufficient way of assessing the change, particularly where only variable costs and returns are affected. However, as Malcolm *et al.* (2005) noted, “GMs [gross margins] are not the correct technique to use if a change in farm plan involves a change in overhead costs, as is most often the case. Then a partial budget is needed”. In this sense, the key distinction is therefore not simply between paddock and farm level analysis, but between changes that affect only variable costs and returns and those that also alter overheads, capital use, labour requirements or livestock herd structure.

Gross margin analysis estimates the contribution of an activity as the income generated minus the direct variable costs incurred in producing that income. When overhead costs remain unchanged, differences in gross margin provide a practical measure of the marginal change in whole farm profit attributable to the decision (Makeham and Malcolm 1993; Malcolm 2004a). This approach is particularly useful where the change is small in scale, can be represented as a simple substitution between activities, and does not materially alter whole farm capital investment or overhead expenses (Malcolm *et al.* 2005).

The distinction between simple and complex change is therefore critical. The farm management economics literature shows that, for relatively simple innovations, a budget for one production period in the ‘steady state’ will often suffice (Malcolm 2004b; Malcolm *et al.* 2005). In this context, steady state refers to the position once the change has been fully implemented and is operating as intended, rather than during the transition period. By contrast, where a change takes several years to reach full operation, involves substantial capital outlay, or has wider implications for the operation of the farm, a steady state partial budget is inadequate on its own. In those circumstances, the analysis should extend to whole farm budgeting, multi-year cash flow analysis and, where relevant, discounting benefits and costs over time (Malcolm *et al.* 2005; Pannell 2006). Extensive analyses conducted by Bowen and Chudleigh (2021a) and Bowen and Chudleigh (2021b) indicate that most of the risk associated with change in farm management occurs during the implementation phase and that the farm management economic approach identified by Makeham and Malcolm (1993), Malcolm *et al.* (2005) and Pannell (2006) is significantly better at identifying the costs, benefits and risks of change for farmers and land holders than the complex and difficult to parameterise biophysical models, such as APSIM, developed originally for cropping systems.

In the present scoping study, the case study analysis was limited to a single paddock and assessed in steady state because the change examined was small relative to the overall farm business and was not expected to materially affect whole farm capital use, overhead costs or the broader organisation of resources. This provided an initial, constrained example for developing the analytical framework, including integration of the economic, C sequestration and GHG emissions models, while reducing the data collection and collation load on producer cooperators. Once the framework has been established and its relevance demonstrated, more complex, whole farm analyses can be undertaken. One of the main reasons for adopting a steady state framework was that it best aligned with the requirements of the available GHG modelling tools, which are designed to evaluate systems once fully established rather than during transitional phases. The purpose of the analysis was therefore to compare alternative systems once fully implemented, in order to assess whether the change would be worthwhile. If results are favourable, the implementation phase would

then need separate examination to determine the feasibility of adopting the change, including considerations of cash flow, financial risk and management constraints.

The change that was examined, conversion of one cropping paddock to perennial pasture for a traded cattle activity, was treated as a paddock-level substitution in which the principal changes were to variable costs, production and paddock emissions. On that basis, a gross margin framework provides an efficient and transparent means of comparing the alternative uses of that paddock, consistent with established farm management economics methods recommended for marginal changes (Makeham and Malcolm 1993; Malcolm *et al.* 2005). In the scoping study, pasture establishment costs were accounted for in the gross margin by amortising (adding as an equivalent annual cost) over the expected economic life of the pasture. However, the broader literature indicates that where C sequestration strategies alter herd structure, capital investment, labour requirements or overhead costs, assessment at the whole farm level becomes necessary to capture the full trade-offs between net emission reduction and profitability.

4.3 Results from analysis of net emissions and profitability

Few published studies have examined how the full range of possible C sequestration strategies affect net paddock and/or property emissions. An increase in net C sequestration on a project area will not necessarily result in reduced net emissions, particularly over time as the effects of the strategy diminish and C sequestration rates decline. For example, the case study of Jigsaw Farms in south-west Victoria found that tree plantings on 17% of the property resulted in greater C sequestration in trees and soils than the equivalent GHG emissions, for only ca. 7 years. After that, emissions again exceeded sequestration due to declining sequestration rates in trees and soils (Macdonald *et al.* 2025). An example of a study where net GHG emissions were apparently decreased was reported by Page *et al.* 2014, cited in Badgery *et al.* 2011, for a change from continuous cropping of wheat and canola to prime lamb production. These authors estimated the net emissions at a site in central-west New South Wales and found that SOC stocks increased while there was little change in net CO₂-e from other emissions. That is, the decrease in nitrous oxide and fuel consumption with removal of cropping was nearly equal to the subsequent increase in methane emissions from sheep. In contrast, the study of by Meier *et al.* (2020) estimated that the SOC sequestered in stocked permanent pastures was offset by emissions from livestock. Another simulation study of a typical Merino enterprise in south-western Australia, indicated that livestock systems utilising perennial pastures may have substantially higher C sequestration and lower net GHG emissions compared with annual plant-based production systems, suggesting that the choice of pasture is important (Thomas *et al.* 2012).

Even when net emissions can be reduced, this may not result in a positive effect on business profit. A number of recent modelling studies of sheep and beef production systems in southern Australia reported that many strategies to reduce net property GHG emissions reduced farm income, even with C, methane reduction, or biodiversity payments, or when applying C taxes (Bilotto *et al.* 2025; Pham-Kieu *et al.* 2025; Bhattarai *et al.* 2026; Muleke *et al.* 2026). The trade-offs between economic and environmental outcomes often resulted in those strategies that delivered the greatest SOC accrual and GHG mitigation not necessarily being the most profitable. In the study by Bhattarai *et al.* (2026), nature-based strategies to increase vegetation C and/or SOC often made more economic sense than high-tech emissions reduction options such as feed additives. In that study, when C-focussed strategies also lifted production (e.g. increasing liveweight gain or wool cut), profitability improved dramatically. Pham-Kieu *et al.* (2025) reported that, across the farming systems, mitigation options and C prices examined in their study, profit from sheep production significantly outweighed income from GHG emissions reductions. Their results also indicated that sheep production systems based on grazed pastures were unlikely to become net C sinks under current commodity and C prices. Even when C prices were increased to \$100/t CO₂-e, well above the current spot price (late April 2026) of \$37.50/t CO₂-e (CO₂RE Markets 2026), sheep profit was 5 to 12 times greater than environmental income derived from small and large farms, respectively. Several modelling studies have found that combining complementary GHG mitigation strategies could deliver more favourable economic outcomes than isolated practice changes, particularly when the interventions targeted underperforming agricultural production indicators (Bilotto *et al.* 2025; Pham-Kieu *et al.* 2025; Bhattarai *et al.* 2026).

An important point to note is that the assumed income (and/or taxes) relating to net GHG emissions and abatement in these recent modelling studies are yet to be realised in practice. In addition, there are currently limited ACCU methods applicable to extensive livestock enterprises, which constrains participation in C markets. To incentivise net emission reduction, C markets and ACCU Scheme methods need to become more relevant and accessible, including for smaller

enterprises with less capacity to absorb the overhead administration costs currently associated with ACCU Scheme projects. Additionally, the ability to aggregate projects across farms, and greater opportunities and higher payments for co-benefits associated with ecosystem services, may improve participation.

Notably, sowing adapted, perennial legumes into existing grass pastures is one of the more promising strategies for C sequestration and has also been identified as one of the more profitable management strategies for northern Australian extensive livestock systems (Bowen *et al.* 2018; Bowen and Chudleigh 2019; Bowen and Chudleigh 2021a, Bowen and Chudleigh 2021b). However, farm riskiness is also likely to increase, as is the case with any strategy that intensifies inputs to improve outputs. As demonstrated in Bowen (2025b) for a case study scenario in central Queensland, establishing sufficient leucaena-grass pastures to graze for all steers produced by the beef business from weaning until reaching feedlot entry weight, substantially increased business profit over 30 years and reduced emissions intensity by 7.6%. However, this strategy increased business risk due to large peak deficits and long payback periods (up to 8 years) and also increased total annual farm emissions by 16% at full implementation of the strategy. It should be noted that additional SOC sequestration due to planting leucaena was not estimated or included in the calculations of net emissions for this scenario.

5. Case study: Effect on profit and net emissions due to conversion of cropland to pasture for grazing cattle in southern Queensland

5.1 Introduction

Beef cattle production is the most common extensive livestock enterprise in Queensland, and northern Australia more broadly. In 2024-25 the Australian farm-gate value of the beef cattle industry was \$17.1 billion with ca. 61% of the national beef cattle herd located in northern Australia and primarily grazing extensive pastures (ABS 2026).

The Condamine region in the Western Downs of southern Queensland is an example of a productive beef producing area in northern Australia which, despite its relatively small size (1.77 million ha), supports 4.1% of total cattle numbers in northern Australia (ABS 2018; MLA 2022), (Figure 2). Beef cattle production has the largest land footprint in the region (Murray-Darling Basin Authority 2026). Due to the inherent productivity of this region, beef grazing operations often focus on backgrounding and finishing young growing cattle for market. Broadacre cropping of grains, pulses and cotton are also significant agricultural enterprises in the region (Murray-Darling Basin Authority 2026).

The objective of this case study analysis was to investigate a potential C sequestration strategy for its effects on both net GHG emissions and profitability, for a mixed farming enterprise in northern Australia. An enterprise in the Condamine region of the Western Downs of southern Queensland was selected as a representative example of a higher-productivity area within northern Australia.

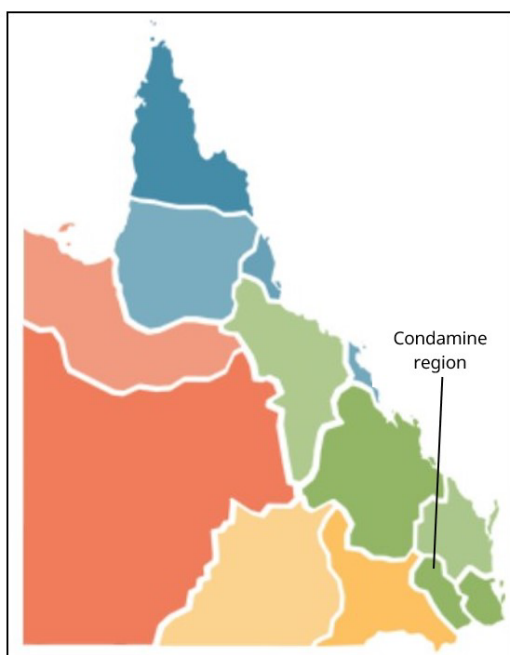


Figure 2 Natural Resource Management (NRM) regions of Queensland, showing the location of Condamine region (QWALC 2024).

5.2 Methods

5.2.1 Approach to the analysis

The analysis assessed a paddock as part of a vertically integrated aggregation of eight properties located in southern and south-west Queensland. The properties are used to conduct cattle breeding, backgrounding, feedlot-finishing, and broad-acre cropping enterprises, with some supporting a mix of enterprises. Broad-acre cropping rotations consist of cereal, legume and forage crops. Hay and silage are also produced. Additionally, the business conducts contract farming operations including in-crop spraying, planting and soil management. Due to the complex and extensive nature of this integrated business, a single paddock was selected for this scoping study to investigate the effects of implementing a potential C sequestration strategy on net GHG emissions and profit. This initial, constrained case study analysis allowed development of a framework to integrate the C sequestration, GHG and economic models and minimised the data collection load on the producer cooperators. Once the analysis framework has been established, more complex analyses can be undertaken.

The implications for profitability and net emissions were assessed for the strategy of converting a broad-acre cropping paddock with sodic soils to perennial grass pasture for a 238-ha case study paddock. The base scenario was a three-crop rotation over 4 years of barley – barley – sorghum. The alternative scenario was to establish perennial grass pasture used for backgrounding young heifers prior to feedlot entry. The two systems were compared as steady states to indicate the average profitability and net emissions over 10 years. The steady state approach was adopted in this analysis as it best fitted the requirements of the current GHG emissions models. This approach examines the alternative strategies once fully implemented to determine whether making a change from the base, or existing strategy (in this case, the cropping rotation) is worthwhile. If the outcome is positive for profitability and/or net emissions, the implementation phase would be considered to determine whether the change is viable and feasible from a cash-flow, financial risk, and practical management perspective.

The levels of production and the production responses to the alternative management scenario were determined by the case study cooperators with reference to existing data sets and published literature where available. This involved an iterative process of obtaining feedback and then applying adjustments to the models to ensure that the models were adequately structured and calibrated for the base scenario in the target paddock and for the alternative scenario. The outputs of the models therefore reflect the cooperator's expectations of what may occur over time, rather than what has actually occurred.

5.2.2 Case study paddock

The case study paddock of 238 ha is located in the Condamine region in the Western Downs of southern Queensland, approximately 40 km west of the town of Condamine. The paddock has a mix of melonhole country and red soil, likely classified as 'Poplar box and brigalow' and 'Brigalow with melonholes' land types (State of Queensland 2022). These soils are highly sodic in the deep subsoil with low to moderate total N and P. Historically, the paddock supported broad-acre cropping activities before being converted to perennial pasture in 2025.

The cooperators identified that the decision to convert the paddock from cropping to pasture was mostly due to the yield limit placed on cropping activities by the presence of sodic soils in this location and environment. The co-operators anticipated that the pasture would be a more profitable and useful component of their enterprise than maintaining the cropping rotation. Parameters for the scenario analysis were informed by previous, and anticipated future levels, of inputs and production from the case study paddock.

5.2.3 Economic analysis

5.2.3.1 Approach to economic analysis

The economic analysis was a steady state gross margin analysis of the alternative enterprises conducted in that paddock: 1) the previous cropping rotation of barley – barley – sorghum compared with 2) conversion from broad-acre cropping to perennial pasture use for backgrounding young heifer cattle prior to feedlot entry. The two systems were compared as steady states to indicate the average economic performance over the cropping rotation or the life of the pasture.

It is noted that a perennial pasture development may take time to implement, could change the financial risk of the property, require a change in capital investment, and may result in an incremental change in herd structure, performance and/or production. These factors often require the scenario analysis to be compiled in a model that considers herd structures and performance with annual time steps thereby facilitating the analysis of any change in the herd costs, incomes or management strategy over time. For example, Bowen and Chudleigh (2018) showed that it takes about a decade for the breeding herd structure of a property in central Queensland to change to accommodate a large-scale planting of leucaena. However, in the current analysis of alternative farming systems, the transition phase between the cropping system and the perennial pasture was relatively short (< 6 months) and could be ignored due to its lack of impact on the outcomes. Furthermore, in the current analysis, the perennial pasture was grazed by heifers either purchased or supplied from sources independent of the other activities conducted on the property. This allowed the paddock to be treated as a separate activity, with all livestock traded into and out of the paddock. The economic analysis could therefore be undertaken as a gross margin analysis at the level of the paddock.

The cropping and pasture scenarios were both assessed for their potential impact on paddock gross margin. As the pasture has a life of more than 1 year, and the establishment costs contribute to production over several years, the establishment costs were amortised (added as an equivalent annual cost) over the expected economic life of the pasture (10 years in this case). The amortisation process included the opportunity cost of the capital applied in the pasture establishment process. Livestock capital costs were also incorporated as an opportunity cost. These approaches allowed the paddock level gross margins for cropping and grazed pasture to be compared on an annual equivalence basis.

The gross margins were calculated using the typical gross margin approach based on the allocation of variable costs to enterprises or activities but included an allowance for the labour costs associated with machinery operation and livestock management. Additionally, the gross margins included calculation of the usual allowance of fuel, oil, repairs and maintenance (FORM) and other variable expenses associated with allocating machinery operating costs to gross margins.

The scenarios assessed in this case study involve the use of resources that have an effective life of more than one production period. For example, farming plant usually lasts for several years and can contribute to the production of many activities. Therefore, in the gross margin analysis, the operating costs of farming plant to an enterprise or activity were apportioned on an hourly, and rate of use, basis. This allowed inclusion in the gross margin of the proportional amount of operating costs of the farming plant used by each activity, improving the validity of the comparison in this case where the cropping and pasture scenarios required different amounts of machinery inputs.

Farming plant was costed in gross margins based on the FORM used on a per hour basis in the production of the output. Note that the ownership costs of the plant were not included as these costs typically do not change when one paddock on a property is converted from cropping to pasture and were therefore excluded from the analysis. For each tractor/implement or harvester combination in the enterprise or activity the following 'rule of thumb' calculations of FORM costs were made:

- Fuel. Fuel consumption (litres per hour) multiplied by the fuel cost (cents per litre net of rebates).
- Oil. Oil consumption was estimated as 10% of fuel cost.
- Repairs and maintenance. To calculate a share of repairs and maintenance for the scenario, the replacement costs of the machines were initially identified. This was either the current new value of the machine or the second-hand value if it was going to be replaced with a used machine. Secondly, the total cost of all repairs likely to be incurred over the life of the machine were identified and expressed as a percentage of the replacement value. The longer the machine was kept, the higher the percentage; for example, up to 50% or more for a tractor that is kept a long time (> 5,000 hours) and used to undertake heavy work. To calculate the hourly cost of repairs and maintenance, the replacement cost of the machine was multiplied by the percentage of the replacement cost of the machine spent on repairs over the life of the machine and divided by the hours of life of the machine. For example, if a machine costs \$10,000 and about \$3,000 is expected to be spent on repairs and maintenance over its 5-year life, then about 30% of the cost of the machine will be spent on repairs. If the machine is used for 100 hours per annum, the hourly cost of repairs and maintenance is about \$6 per hour of use.

5.2.3.2 Cropping (base scenario) gross margin

Table 1 shows the cropping rotation over a typical 4-year sequence. It is expected that two winter barley crops will be followed by a long fallow prior to a summer sorghum crop. Once the sorghum crop is harvested, there will be a long fallow before the rotation resumes with another winter barley crop. An activity gross margin was calculated for each phase of the crop rotation. Note that Activity 3 plants the sorghum crop while Activity 4 harvests the sorghum crop. The 238-ha paddock was divided into four years of cropping activities, equally, to represent the average output from the total paddock area over time. This allows comparison with the livestock gross margin in the same total paddock area. Machinery costs involved in farming operations, costs of crop treatments, expected crop yields and grain prices for each phase of the crop rotation are given in Table 2 to Table 5. The overall gross margin for the crop rotation in the 238-ha case study paddock was calculated as the sum of the Activity gross margins on 59.5-ha.

Table 1 The 4-year cropping rotation applied in the case study paddock with each year shown as an ‘activity’

Approximate start month	Crop or fallow operations in each year or activity of the cropping rotation			
-	Activity 1	Activity 2	Activity 3	Activity 4
November	summer fallow	summer fallow	long fallow	-
January				harvest sorghum
May	plant barley	plant barley	plant sorghum	long fallow
September	-	-		
October	harvest barley	harvest barley	-	

Table 2 The enterprise output and variable costs for Activity 1: summer fallow, plant barley and harvest barley (59.5 ha)

Item/treatment	Rate of application	Quantity	Price or cost per unit	Number of applications	Per hectare	Total (\$)
Enterprise output						
Revenue from barley	-	2.4 t/ha	\$340/t		\$816.00	\$48,552.00
Variable costs						
Machinery costs						
Spray rig (Fuel and Oil)	1		\$1.93/ha	3	\$5.79	\$344.51
Spray rig (Repair and Maintenance)	1		\$1.14/ha	3	\$3.42	\$203.49
Planter (Fuel and Oil)	1		\$7.91/ha	2	\$15.82	\$941.29
Planter (Repair and Maintenance)	1		\$10.22/ha	2	\$20.44	\$1216.18
Seed cost						
Barley seed	1	45 kg/ha	\$0.5/kg	1	\$22.50	\$1,339.00
Fertiliser costs						
Starter Z	1	35 kg/ha	\$1.25/kg	1	\$43.75	\$2,603.13
Urea	1	100 kg/ha	\$0.88/kg	1	\$88.00	\$5,236.00
Herbicide costs						
Balance	1	0.08 L/ha	\$110/L	1	\$8.80	\$523.60
Flame	1	0.085 L/ha	\$22.5/L	1	\$1.91	\$113.65
Paraquat	1	1.8 L/ha	\$3.65/L	1	\$6.57	\$390.92
Wetter	1	0.01 L/ha	\$7.15/L	1	\$0.07	\$4.25
Roundup	1	1.5 L/ha	\$4.65/L	1	\$6.98	\$415.00
24-D	1	0.5 L/ha	\$4.40/L	1	\$2.20	\$130.90
24-D	1	1 L/ha	\$4.40/L	1	\$4.40	\$261.80
Salve (tordon)	1	0.01 kg/ha	\$15.33/kg	1	\$0.15	\$9.12
Casual labour (machines)						
Spray rig	1		\$0.6/ha	3	\$1.80	\$107.1
Planter	1		\$3.33/ha	2	\$6.66	\$396.27
Harvesting						
Contract header	1	6ha/hr	\$319.98/hr	1	\$53.33	\$3,173.14
Fuel	1	40L/hr	\$1.75/L	9.92	\$11.67	\$694.40
Total variable costs					\$304.26	\$18,103.64

Table 3 The enterprise output and variable costs for Activity 2: summer fallow, plant barley and harvest barley (59.5 ha)

Item/treatment	Rate of application	Quantity	Price or cost per unit	Number of applications	Per hectare	Total (\$)
Enterprise output						
Revenue from barley		2.4 t/ha	\$340/t		\$816.00	\$48,552.00
Variable costs						
Machinery costs						
Spray rig (Fuel and Oil)	1		\$1.93/ha	4	\$7.72	\$459.34
Spray rig (Repair and Maintenance)	1		\$1.14/ha	4	\$4.56	\$271.32
Planter (Fuel and Oil)	1		\$7.91/ha	2	\$15.82	\$941.29
Planter (Repair and Maintenance)	1		\$10.22/ha	2	\$20.44	\$1216.18
Seed cost						
Barley seed	1	45 kg/ha	\$0.5/kg	1	\$22.50	\$1,339.00
Fertiliser costs						
Starter Z	1	35 kg/ha	\$1.25/kg	1	\$43.75	\$2,603.13
Urea	1	100 kg/ha	\$0.88/kg	1	\$88.00	\$5,236.00
Herbicide costs						
Balance	1	0.08 L/ha	\$110/L	1	\$8.80	\$523.60
Flame	1	0.085 L/ha	\$22.5/L	1	\$1.91	\$113.65
Paraquat	1	1.8 L/ha	\$3.65/L	1	\$6.57	\$390.92
Wetter	1	0.01 L/ha	\$7.15/L	1	\$0.07	\$4.25
Roundup	1	1.5 L/ha	\$4.65/L	2	\$13.95	\$830.03
24-D	1	0.5 L/ha	\$4.40/L	2	\$4.40	\$261.80
24-D	1	1 L/ha	\$4.40/L	1	\$4.40	\$261.80
Salve (tordon)	1	0.01 kg/ha	\$15.33/kg	1	\$0.15	\$9.12
Casual labour (machines)						
Spray rig	1		\$0.6/ha	4	\$2.40	\$142.80
Planter	1		\$3.33/ha	2	\$6.66	\$396.27
Harvesting						
Contract header	1	6ha/hr	\$319.98/hr	1	\$53.33	\$3,173.14
Fuel	1	40L/hr	\$1.75/L	9.92	\$11.67	\$694.40
Total variable costs					\$317.10	\$18,867.62

Table 4 The enterprise output and variable costs for Activity 3: long fallow (summer fallow and winter fallow) and plant sorghum (59.5 ha)

Item/treatment	Rate of application	Quantity	Price or cost per unit	Number of applications	Per hectare	Total (\$)
Variable costs						
Machinery costs						
Spray rig (Fuel and Oil)	1		\$1.93/ha	9	\$17.37	\$1,035.52
Spray rig (Repair and Maintenance)	1		\$1.14/ha	9	\$10.26	\$610.47
Planter (Fuel and Oil)	1		\$7.91/ha	2	\$15.82	\$941.29
Planter (Repair and Maintenance)	1		\$10.22/ha	2	\$20.44	\$1,216.18
Seed cost						
Sorghum seed	1	2.2 kg/ha	\$23.75/kg	1	\$52.25	\$3,108.88
Fertiliser costs						
Starter Z	1	35 kg/ha	\$1.25/kg	1	\$43.75	\$2,603.13
Urea	1	100 kg/ha	\$0.88/kg	1	\$88.00	\$5,236.00
Herbicide and insecticide treatments						
Dual gold	1	1.50 L/ha	\$15.25/L	1	\$22.88	\$1,361.36
Turbine	1	0.86 kg/ha	\$15/kg	1	\$12.90	\$767.55
Roundup	1	1.5 L/ha	\$4.65/L	3	\$20.93	\$1,245.34
24-D	1	0.5 L/ha	\$4.40/L	3	\$6.60	\$392.70
Roundup	1	1.7 L/ha	\$4.65/L	1	\$7.91	\$470.65
24-D	1	0.5 L/ha	\$4.40/L	1	\$2.20	\$130.90
Dual gold	1	0.5 L/ha	\$15.25/L	1	\$7.63	\$453.99
Atrazine	1	1 L/ha	\$11.33/L	1	\$11.33	\$674.14
Paraquat	1	1.5 L/ha	\$3.65/L	1	\$5.48	\$326.06
NPV Gemstar/Vivus	1	0.1 L/ha	\$163/L	1	\$16.30	\$969.85
Petro oil	1	1 L/ha	\$6.55/L	1	\$6.55	\$389.73
Sorghum insecticide	1	2 L/ha	\$12/L	2	\$48.00	\$2,856.00
Casual labour (machines)						
Spray rig	1		\$0.6/ha	9	\$5.40	\$321.30
Planter	1		\$3.33/ha	2	\$6.66	\$396.27
Total variable costs					\$428.61	\$25,502.23

Table 5 The enterprise output and variable costs for Activity 4: harvest sorghum, long fallow (summer - winter – summer), (59.5 ha)

Item/treatment	Rate of application	Quantity	Price or cost per unit	Number of applications	Per hectare	Total (\$)
Enterprise output						
Revenue -sorghum		3 t/ha	\$330/t		\$990.00	\$58,905.00
Variable costs						
Machinery costs						
Spray rig (Fuel and Oil)	1		\$1.93/ha	4	\$7.72	\$459.34
Spray rig (Repair and Maintenance)	1		\$1.14/ha	4	\$4.56	\$271.32
Herbicide and insecticide treatments						
Roundup	1	2.3 L/ha	\$4.65/L	1	\$10.70	\$636.65
24-D	1	1.00 L/ha	\$4.40/L	1	\$4.40	\$261.80
Salve (tordon)	1	0.01 kg/ha	\$15.33/L	1	\$0.15	\$8.99
Roundup	1	1.6 L/ha	\$4.65/L	1	\$7.44	\$442.68
24-D	1	0.7 L/ha	\$4.40/L	1	\$3.08	\$183.26
Adjuvant	1	0.06 L/ha	\$13.50/L	1	\$0.81	\$48.12
Dual gold	1	1.5 L/ha	\$15.25/L	1	\$22.88	\$1,361.36
Turbine	1	0.86 kg/ha	\$15/kg	1	\$12.90	\$767.55
Paraquat	1	1.6 L/ha	\$3.65/L	1	\$5.84	\$347.48
Adjuvant	1	0.08 L/ha	\$13.50/L	1	\$1.08	\$64.26
Casual labour (machines)						
Spray rig	1		\$0.6/ha	4	\$2.40	\$142.80
Harvesting						
Contract header	1	6 ha/hr	\$319.98/hr	1	\$53.33	\$3,173.14
Fuel	1	40 L/hr	\$1.75/L	9.92	\$11.67	\$694.37
Total variable costs					\$148.93	\$8,861.33

5.2.3.3 Livestock (alternative scenario) gross margin

The livestock activity was a heifer turnover activity that relied on the purchase of yearling heifers. The livestock were expected to be purchased in two cohorts of 350 head at an average liveweight of 315 kg/head. An average weight gain of 0.75 kg/head.day was expected over a grazing period of 90 days for the first cohort and 60 days for the second cohort (the summer/autumn period).

The costs of pasture development and the total annual forage costs are presented in Table 6 and Table 7. The pasture was established by using heavy offsets to break up the cultivated soil and applying approximately 10 t/ha of feedlot manure, one weed control spray and aerial sowing of perennial grass pasture seed. The pasture included a mixture of C₄ perennial grass species: 30% Reclaimer Rhodes grass (*Chloris gayana*), 35% Gatton panic (*Megathyrsus maximus* cv. Gatton), 25% premier digit grass (*Digitaria eriantha* cv. Premier), and 10% Bisset creeping bluegrass (*Bothriochloa insculpta* cv. Bisset).

The pasture development costs were calculated at owner rates given that the machinery required were already owned by the business which also conducted cropping activities. The exceptions were the aerial seeding and D10 offset treatments for which contract rates were applied. The expected pasture life was taken to be 10 years with an amortised establishment cost per hectare per annum calculated as \$72.91/ha.annum. The paddock was also expected to receive an annual application of a fertiliser known as Cotton sustain at a cost of \$160/ha.annum for the fertiliser and about \$6.53/ha.annum application cost.

Rundown (decline in productivity) of sown pastures typically occurs after establishment, primarily due to declining available soil N as pastures age. The cooperators identified an expected decline in pasture yields to 75% of Year 1 pasture yield by Year 10. An average pasture yield over 10 years was determined and the average livestock stocking rates calculated accordingly. As the stocking rates were adjusted down to match the declining forage biomass production over 10 years, individual animal liveweight gain was assumed to be maintained. Pastures were grazed over the summer/autumn period (November to April) and spelled (ungrazed) for 6 months over the winter/spring period (May to October).

The calculation of the costs and value of the two cohorts of heifers are presented in Table 8. Livestock were expected to be purchased and sold at \$4.40/kg liveweight. Purchase and selling costs associated with freight to and from the paddock were incurred. All inbound livestock were expected to be drenched (\$1.70/head) and inoculated with a 5-in-1 vaccine (\$0.90/head) as an induction treatment. No mortalities were expected during the grazing period. The opportunity cost of livestock capital was assessed at an interest (discount) rate of 5% calculated on the opening capital value of the livestock for the grazing period. The livestock transport cost for selling was set at \$2/km.deck and the loading rate on deck was 27 and 33 for the cohort 1 and cohort 2 of heifers, respectively. The expected transport distance was 350 km to the paddock after purchase and 200 km to sale. Table 9 presents the enterprise output, variable costs, and opportunity cost of livestock using the costs and values detailed in Table 6 to Table 8.

Table 6 Pasture development costs using owned machinery and including machinery fuel, oil, repairs and maintenance costs and labour, with the exception of aerial seeding and D10 offsets for which contract rates were used

Item/treatment	Rate of application	Quantity	Price or cost per unit	Number of applications	Per hectare	Total (\$)
Pre-planting costs						
Spray rig	1		\$3.28/ha	1	\$3.28	\$780
Roundup	1	1.8 L/ha	\$4.65/L	1	\$8.37	\$1,992
Dicamba	1	0.2 L/ha	\$1.68/L	1	\$0.34	\$80
Fluroxipyr	1	0.3 L/ha	\$16.25/L	1	\$4.88	\$1,160
Feedlot manure	1	10 t/ha	\$250.00/ha	1	\$250.00	\$59,500
Planting costs						
Pasture seed	1	5.5kg/ha	\$23.60/kg	1	\$129.80	\$30,892
Seed aerial	1		\$16.36/ha	1	\$16.36	\$3,894
D10 offsets	1		\$150/ha	1	\$150.00	\$35,700
Total direct development costs					\$563	\$133,998

As the total direct development costs of the pasture was \$563/ha, the amortised development costs for life of forage of 10 years at a 5% discount rate was \$72.91/ha.annum.

Table 7 Calculation of total forage annual growing costs

Item/treatment	Rate of application	Quantity	Price or cost per unit	Number of applications	Per hectare	Total (\$)
Post planting costs						
Cotton sustain	1	160 kg/ha	\$1.00/kg	1	\$160.00/ha	\$38,080
3-point linkage spreader	1		\$6.53/ha	1	\$6.53/ha	\$1,554
Amortised development costs	1		\$72.91/ha		\$72.91/ha	\$17,353
Total forage annual costs					\$239	\$56,988

Table 8 Calculation of expected costs and values of two cohorts of yearling heifers

Parameter	Cohort 1	Cohort 2
Parameters and costs of livestock purchased		
Date the cohort enters the paddock	1 November	1 March
Number of livestock	350	350
Purchase price (\$/kg liveweight)	\$4.20	\$4.20
Average purchase weight (kg liveweight/head)	315	315
Cost of stock per head into the paddock (\$/head)	\$1,323	\$1,323
Total cost of stock (\$)	\$463,050	\$463,050
Costs of purchasing the livestock		
Trucking (30 head/deck; 350 km), (per km)	\$2.10	\$2.10
Total freight in	\$8,575	\$8,575
Trucking cost (\$ per head)	\$24.50	\$24.50
Costs associated with livestock health and drenching (treatment)		
Drenching/head	\$1.70	\$1.70
5-in-1/head	\$0.90	\$0.90
Labour/head	\$1.50	\$1.50
Total cost (\$)	\$1,435	\$1,435
Livestock weight and value leaving the paddock		
Date leaving the paddock	30 January	30 April
Expected number of days in the paddock (days)	90	60
Expected average weight gain (kg/head.day)	0.75	0.75
Total expected gain (kg/head)	68	45
Average weight leaving the paddock (kg/head)	382.5	360
Number of head sold (0% losses)	350	350
Livestock selling price (\$/kg live weight)	\$4.20	\$4.20
Gross value (\$/head)	\$1,606.50	\$1,512.00
Gross value of cohort	\$562,275	\$529,200
Costs associated with transporting to feedlot		
Rate on deck	27	33
Total freight out (200 km at \$2 per km per deck)	\$5,185	\$4,242
Trucking cost (\$ per head)	\$14.81	\$12.12
Other costs		
Opportunity cost of livestock capital (5% interest rate for the funds invested)	\$5,709	\$3,806

Table 9 The enterprise output, variable costs and opportunity cost of livestock capital for the grazed pasture scenario with average pasture and livestock performance, and pasture establishment costs amortised, over 10 years

Parameter	Per hectare per annum	Total per annum
Livestock sales revenue	\$4,586	\$1,091,475
Livestock purchase costs	\$3,891	\$926,100
Freight in, purchase costs	\$72	\$17,150
Freight out costs	\$40	\$9,428
Treatment expenses	\$12	\$2,870
Forage growing costs	\$239	\$56,988
Total variable costs	\$4,254	\$1,012,535
Interest forgone on livestock capital	\$40	\$9,515

5.2.4 Carbon sequestration for cropping or grazed pasture in the case study paddock

Changes in SOC for cropping or grazed pasture in the target paddock were estimated using the simple, process-based model, Soil organic carbon reserves and transformations in ecosystems (SOCRATES; Grace *et al.* 2006). The change in SOC was estimated over 10 years to match the expected life of the pasture as well as the time required to demonstrate annual net change in soil and tree C according to Australian and international C accounting standards (Eckard 2024). Table 10 summarises the inputs applied in the model.

Table 10 Summary of input parameters applied in the SOCRATES model to estimate soil organic carbon changes over 10 years for cropping or grazed pasture scenarios in the case study paddock

Parameter	Inputs applied in the model
Soil and land type description	Referred to available soil test results from the property. Assumed soil was primarily 'Brigalow with Melonholes' land type (State of Queensland 2022): gilgaied, deep, grey or brown cracking clays (brown or grey vertosol). Surface: self-mulching to hard setting; medium to heavy clay. Subsoil: medium to heavy clay; sodic to strongly sodic.
Cation exchange capacity (CEC)	16.15 (average of 0-10 cm and 10-30 cm measurements, from soil test)
Initial organic C %	0.9% (0-10 cm, from soil test)
Average annual rainfall	618 mm (at Condamine; Station number 042048, 1937-2018; Bureau of Meteorology 2026)
Annual mean temperature	19.65 °C (at Miles Post Office; Station number 042023, 1908-2004, average of mean maximum 27.1 °C and mean minimum 22.2 °C; Bureau of Meteorology 2026)
Randomise rainfall and temperature	No (as average yields manually entered and not model-generated)
Continuation of cropping	
Length of rotation	4 years (barley – barley – sorghum)
Plant types selected for rotation	Barley – barley – canola ('sorghum' not an option so 'canola' selected as per advice of Peter Grace, 07/05/2026)
Stubble	'Retained' for each crop
Graze	None
Fertiliser	50.45 kg N/ha for each crop (3.85 kg N/ha from non-urea-N plus 46.6 kg N/ha from urea)
Grain yields	2,400 kg/ha for barley in Year 1 and 2; 3,000 kg/ha for sorghum. Grain yield has to be entered in the year the sorghum is planted for the model to calculate biomass yield
Conversion to a grazed pasture	
Length of rotation	10 years (planted to pasture in Year 1, with an expected life of 10 years); work-around in model to allow N application in Years 2-10 was to input pasture as 'planted' every year in the model. (Peter Grace, 10/06/2026, advised that the model applies minimal mineralisation due to planting)
Plant type selected for rotation	'Improved pasture' (Peter Grace, 07/05/2026, advised that this category represents all sown pasture types while 'grass pasture' should be used to represent native pastures)
Grazing intensity	40% utilisation of dry matter (60% retained); edited the heavy utilisation parameter in the model to reflect this utilisation rate
Fertiliser	Annual application of 'Cotton sustain' fertiliser providing 9.76 kg N/ha.annum. 137.78 kg N/ha.annum from feedlot manure applied at pasture establishment. Feedlot manure assumed to be 63.2% DM and 2.18% N (MLA 2016b). Assumed 26% of manure N is volatilised as ammonia (Bauwman <i>et al.</i> 2002); of the remaining 102 kg N/ha, 33% N available in Year 1, 30% in Year 2, 20% in Year 3, 20% Year 4, 7% Year 5 (MLA 2016a).
Pasture yields	Starting yield in Year 1: 6,407 kg DM/ha; assume 25% rundown in productivity and linear decline to 4,805 kg DM/ha in Year 10; applied average yield of 5,606 kg DM/ha.annum over 10 years. (Yields estimated using Quikintake calculator (McLennan and Poppi 2019) to estimate cattle dry matter intake for the stocking rate applied and an assumed utilisation rate of pasture of 40%)

5.2.5 Greenhouse gas emissions for cropping or grazed pasture in the case study paddock

The GHG accounting framework (GAF) calculators developed by the University of Melbourne (PICCC 2023) were used to calculate total GHG emissions for each paddock scenario. These calculators take a snapshot of emissions when the farm or paddock is in a steady state. They do not have the capacity to easily assess dynamic changes in emissions as a change in management strategy is implemented. Therefore, for the 4-year cropping rotation, GHG emissions were determined as the average for the rotation. The emissions for the grazed pasture scenario were determined as the average over a 10-year timeframe as this matches the expected life of the pasture. Therefore, emissions relating to inputs occurring only at pasture establishment were divided by 10 years. In the calculation of net emissions, C sequestration for both cropping and grazed pasture scenarios were determined as the annual average over 10 years, as this is time required to demonstrate annual net change in soil and tree C according to Australian and international C accounting standards (Eckard 2024).

G-GAF Cropping GHG Accounting Framework V11.1 was used to calculate emissions for the cropping scenario and SB-GAF Seasonal V2.6 used for the grazed pasture scenario. The manure applied to the pasture at establishment, and the generic fertiliser blend used annually, could not be accommodated within the SB-GAF Seasonal V2.6 calculator. Therefore, to ensure a consistent approach, the fertiliser emissions for both the cropping rotation and pasture scenarios were estimated using the new module under development by the ZNE Ag CRC and based on the draft 'Voluntary emissions reporting guidelines' (DCCEEW 2026b). Method 2 results were adopted when these differed from results obtained using Method 1 in the new fertiliser module as Method 2 is considered to provide more specific and representative estimates (DCCEW 2026b). The Scope 3 emissions for the fertiliser applied were calculated using the new Scope 3 emission factors for Agriculture, Fisheries and Forestry (LifeCycles 2026). The Scope 1 and 3 fertiliser emissions were added to the total emissions for each scenario within the GAF calculators. Additionally, C sequestration totals determined using the SOCRATES model (Grace *et al.* 2006) as described in Section 5.2.4, were added to the GAF calculators to allow calculation of net emissions by subtracting the average soil C sequestration over 10 years from the average annual GHG emissions. Input parameters applied to the emission calculations in this analysis are summarised in Table 11 and Table 12.

Table 11 Summary of input parameters applied in the G-GAF Cropping V11.1 calculator (PICCC 2023) with new ZNE Ag CRC fertiliser module to estimate the average greenhouse gas emissions for the 4-year cropping rotation in the case study paddock

Parameter	Inputs applied in the models			
Region	Qld			
Production system	Non-irrigated crops			
Does crop get sufficient rainfall to drain through the soil profile?	No (as per advice of Richard Eckard, 19/05/2026)			
Elevation (m)	290			
Average temperature (degrees Celsius)	19.65 (at Miles Post Office; Station number 042023, 1908-2004, average of mean maximum 27.1 °C and mean minimum 22.2 °C; Bureau of Meteorology 2026)			
Total rainfall (mm)	618 (at Condamine; Station number 042048, 1937-2018; Bureau of Meteorology 2026)			
Potential evapotranspiration (mm)	2,145 (Bioregional Assessments 2019)			
Number of frost days	35.6 (at Miles Post Office; Station number 042023, 1908-2005, mean number of days $\leq 2^{\circ}\text{C}$ Bureau of Meteorology 2026)			
Farm cropping details	Activity 1 Plant and harvest barley	Activity 2 Plant and harvest barley	Activity 3 Plant sorghum	Activity 4 Harvest sorghum
Average grain yield (t/ha)	2.4	2.4	-	3.0
Area (ha) (Each crop was allocated ¼ of the 238-ha paddock to provide an average for the 4-crop rotation over time)	59.5	59.5	59.5	59.5
Non-urea nitrogen application (kg N/ha)	3.85	3.85	3.85	-
Phosphorus application (kg P/ha)	7.63	7.63	7.63	-
Potassium application (kg K/ha)	0	0	0	-
Sulphur application (kg S/ha)	1.4	1.4	1.4	-
Zinc application (kg Zn/ha)	0.35	0.35	0.35	-
Urea application (kg urea/ha)	100	100	100	-
Annual diesel consumption (L/annum)	1,131	1,197	1,127 (includes planting but not harvesting sorghum)	658 (includes harvesting sorghum)
General herbicide/pesticide use (kg active ingredients/paddock)	60	78	311	194
Herbicide (paraquat, diquat, glyphosate) (kg active ingredients per paddock)	67	107	188	128

Table 12 Summary of input parameters applied in the SB-GAF Seasonal V2.6 calculator (PICCC 2023) and new ZNE Ag CRC fertiliser module to estimate the average greenhouse gas emissions over the 10-years expected life of the grazed pasture in the case study paddock

Parameter	Inputs applied in the model
Region	Qld
North of the Tropic of Capricorn	No
Does crop get sufficient rainfall to drain through the soil profile?	No (as per advice of Richard Eckard, 19/05/2026)
Elevation (m)	290
Average temperature (degrees Celsius)	19.65 (at Miles Post Office; Station number 042023, 1908-2004, average of mean maximum 27.1 °C and mean minimum 22.2 °C; Bureau of Meteorology 2026)
Total rainfall (mm)	618 (at Condamine; Station number 042048, 1937-2018; Bureau of Meteorology 2026)
Potential evapotranspiration (mm)	2,145 (Bioregional Assessments 2019)
Number of frost days	35.6 (at Miles Post Office; Station number 042023, 1908-2005, mean number of days $\leq 2^{\circ}\text{C}$ Bureau of Meteorology 2026)
Livestock inventory – traded heifers 1-2 years old	
Livestock numbers (head)	Q1 (Nov, Dec, Jan): 350 (Mob 1 graze paddock for 90 days from 1 Nov to 30 Jan) Q2 (Feb, Mar, Apr): 350 (Mob 2 paddock for 60 days from 1 Mar to 30 Apr)
Adjustment for days grazing	As the days grazing were less than a full quarter of 91.25 days, the number of days grazing were adjusted in the 'enteric fermentation', 'manure management', 'nitrous oxide MMS' and 'agricultural soils' calculations
Liveweight average for quarter (kg/head)	Quarter 1: 349 Quarter 2: 338
Liveweight gain (kg/head.day)	Quarter 1: 0.75 Quarter 2: 0.75
Crude protein (CP, %)	Quarter 1: 11 Quarter 2: 11
Dry matter digestibility (DMD,%)	Quarter 1: 63% Quarter 2: 63%
Purchase inventory	
Number of head purchased	700
Purchase weight (kg liveweight/head)	315
Sale inventory	
Number of head sold	700
Sale weight (kg/head)	371.25
Other sources of emissions	
Non-urea nitrogen application (kg N/ha)	9.76
Phosphorus application (kg P/ha)	19.2
Potassium application (kg K/ha)	36
Sulphur application (kg S/ha)	3.5
Zinc application (kg Zn/ha)	0.88
Feedlot manure spread prior to sowing pasture (kg/ha)	632 kg DM/ha (average over 10 years); (2.18 % nitrogen; MLA 2016)
Annual diesel consumption (L/annum)	1,196.81 (includes pasture establishment activities, averaged over 10 years)
Herbicide (paraquat, diquat, glyphosate) applied pre-planting (kg active ingredients per enterprise)	19.28 (average over 10 years)
Other herbicides/pesticides applied pre-planting (kg active ingredients per enterprise)	5.24 (average over 10 years)

5.3 Results and discussion

5.3.1 Economic analysis

Over the full crop rotation cycle of 4 years, the grain cropping system generated around 1.2 times the gross margin per hectare per annum than the average annual gross margin for the grazed pasture over 10 years following establishment (Table 13). This indicates that, under the conditions and prices assumed, maintaining the paddock under the given cropping sequence in the short to medium term is more profitable than converting it to a perennial grass pasture for livestock production.

Table 13 Gross margin comparison for the case study paddock under 1) a 4-year, 3-crop grain rotation, and 2) a grazed pasture used for turnover heifers over 10 years following establishment

Parameter	Grain cropping	Grazed pasture
Total revenue	\$156,009	\$1,091,475
Total variable costs	\$71,335	\$1,012,535
Gross margin (\$/paddock) after interest	\$84,674	\$69,425
Gross margin (\$/ha.annum) after interest	\$356	\$292

The higher gross margin per hectare found here for grain cropping vs. establishment of a grazed pasture for beef cattle production is in accord with national ABARES (2025a,b) data for 2023-2024 which indicates that grain cropping generally delivers higher rates of return (averaging ca. 15.5%) than beef production although operating with higher input costs and volatility. In our case study, the high variable costs for the grazed pasture scenario were due to the purchase of cattle to stock the paddock. The findings of our study were also consistent with the relative profitability advantage of dryland cropping over cattle production reported by Browne *et al.* (2013) for a medium-rainfall region of southern-eastern Australia. These authors reported an operating profit for wheat vs. steers of \$321 and \$217, respectively, under average rainfall and median price conditions.

The study of Kragt *et al.* (2012), applying the APSIM model to crop-livestock farms in Western Australia, found that under the commodity prices at that time, farmers would forego more than \$80 in profit for every additional t of CO₂-e stored in the soil due to longer pasture phases. As for our case study, this indicates the greater profitability of cropping cf. pastures on arable soils and the opportunity cost of a change from cropping to pasture. The opportunity cost of \$80 in the study of Kragt *et al.* (2012) is much greater than the current spot C price of \$37.50 (late April 2026; CO₂RE Markets 2026). Furthermore, the analysis of Kragt *et al.* (2012) did not account for increase in GHG emissions, including livestock methane emissions.

The analysis of Chudleigh *et al.* (2002) indicated that on more fertile soils in central Queensland cropping is significantly more profitable than livestock trading. However, on more marginal soils, where there was a 30% probability of a failed crop, the cropping gross margin was about the same on average as that for livestock trading. Furthermore, based on historical climate data, the livestock gross margin on marginal cropping soils was expected to be significantly better in about 50% of years. This indicates that risk adverse producers would be more likely to choose the livestock activity due to a lower chance of failure. We did not account for any likelihood of missed or failed crops in our case study analysis, but this understanding could have been a factor in the producer cooperator's decision to change from cropping to grazed pasture in the case study paddock. It is important to acknowledge that the gross margin outcomes from our case study are sensitive to the underlying assumptions, including prices, yields and management practices, as well as to external factors such as climate and market conditions, as reported elsewhere in the literature (Browne *et al.* 2013; Gowen and Bray 2016; Chudleigh *et al.* 2002).

5.3.2 Carbon sequestration for cropping or grazed pasture in the case study paddock

The summary of output parameters from the SOCRATES model used to estimate cumulative SOC change over 10 years of cropping or grazed pasture in the case study paddock is presented in Table 14. After 10 years, the SOC % in the 0-10 cm soil interval had decreased by 7.8% in the grain cropping paddock but increased by 2.2% in the grazed pasture paddock, from an initial SOC of 0.9%. The initial SOC % (0-10 cm) in the case study paddock after long-term grain cropping was within the range reported by Lawrence *et al.* (2022) for brigalow soils in southern and central Queensland (0.8-1.3%). In comparison, SOC % under remnant vegetation was 3.3-5.0% at paired sites on the same soils in the study of Lawrence *et al.* (2022).

Table 14 Summary of output parameters from the SOCRATES model used to estimate cumulative soil organic carbon (SOC) change over 10 years of cropping or grazed pasture in the case study paddock

Parameter	Grain cropping	Grazed pasture
SOC % (0-10 cm)	0.83% Year 10 (0.9% Year 0)	0.92% Year 10 (0.9% Year 0)
Soil C (t CO ₂ -e/ha.annum; 0-30 cm)	-0.7589 t CO ₂ -e/ha.annum	0.2165 t CO ₂ -e/ha.annum
Soil C (t C/ha.annum; 0-30 cm)	-0.20 t C/ha.annum	0.06 t C/ha.annum

The decline SOC under cropping is consistent with reports by others, including for brigalow soils in southern and central Queensland with a decline of 48% (0-10 cm) reported over 28 years by Dalal *et al.* (2021a) and 60-70% over ≥ 20 years by Lawrence *et al.* (2022). This decline occurs due to insufficient C inputs from root biomass and N export in the grain harvest, exceeding the level required to maintain SOM at steady state. Lawrence *et al.* (2022) has also suggested that fallowing to store moisture plays a role in SOC loss as microbes continue to decompose organic matter in the absence of replenishment by plants.

Soil C in the 0-30 cm interval decreased in cropping paddock by an average of 0.20 t C/ha.annum over 10 years with large increases in loss (emissions) during the long fallow following harvest of sorghum crops (Figure 3). However, there was an average increase in the grazed pasture paddock of 0.06 t C/ha.annum (Figure 4). As indicated in Figure 5, the rate of SOC sequestration estimated for the grazed pasture paddock peaked in Year 4 and then declined over the subsequent 6 years. This decline in rate of SOC sequestration was associated with the assumed linear decline in pasture biomass production over time after establishment and demonstrates the importance of biomass inputs for SOC. Nitrogen availability also decreased over time due to manure fertiliser release rates declining from 33% to 0 over Years 1 to 6, although annual mineral application of 9.76 kg N/ha continued.

The average rate of C sequestration estimated for our case study grazed pasture paddock over 10 years after conversion from cropping (0.06 t C/ha.annum) was at the lower end of the range reported in the review of Henry *et al.* (2024), (0.06-0.48 t C/ha.annum, 0-30 cm) but greater than the nil result reported by Thornton and Elledge (2026) over 10 years following conversion of a long-term dryland grain cropping paddock to a legume ley pasture on similar brigalow soils. However, Lawrence *et al.* (2022) reported much greater C sequestration rates of 0.3 to 1.0 t C/ha.annum over at 10-40 years after converting long-term (24-50 years) cropping paddocks to pasture at southern Queensland sites. Lawrence *et al.* (2022) found that those sown pasture sites in southern Queensland showing very little increase in C stocks were those with an absence of legumes. Legumes increase pasture biomass production due to fixing N. Although N fertiliser was applied in the case study sites, the total annual N available decreased over 10 years, with the N release rate from manure application at pasture establishment assumed to decline to 0 by Year 6. Sowing an adapted perennial legume with the grass pasture may support increased C sequestration due to more constant inputs of N.

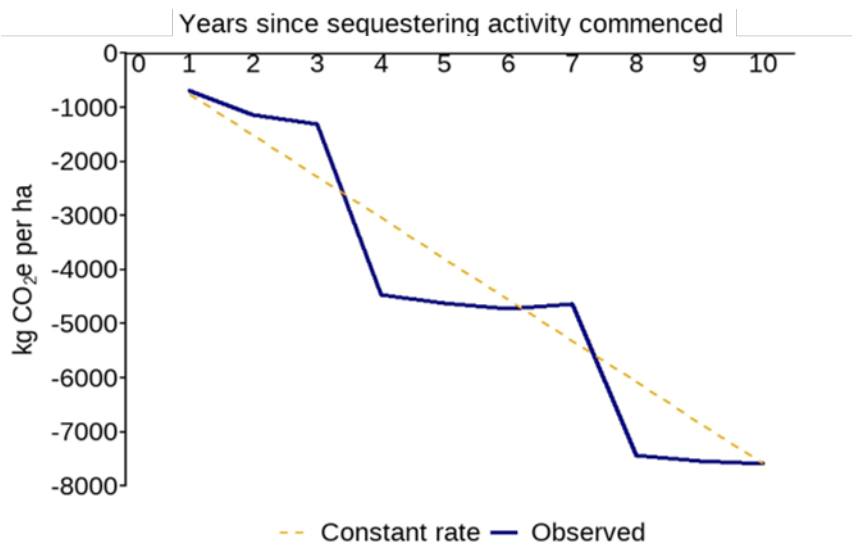


Figure 3 Cumulative soil carbon loss (kg CO₂-e/ha) in the cropping paddock over 10 years

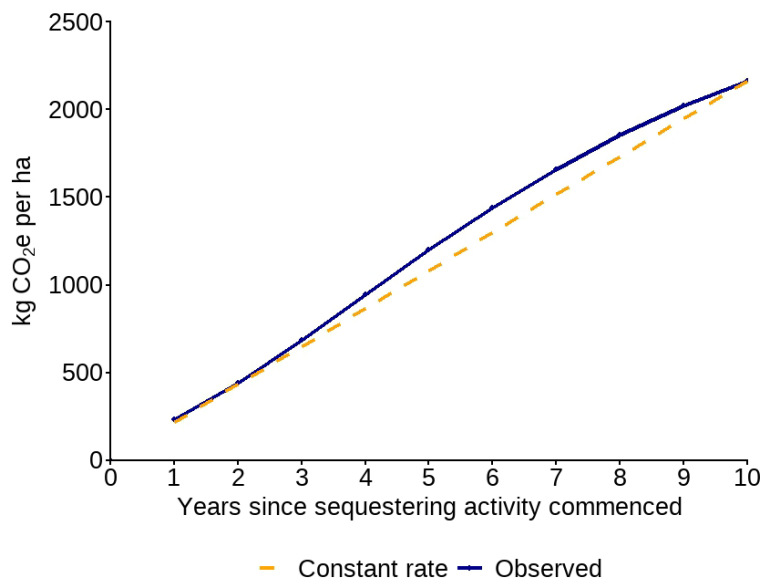


Figure 4 Cumulative soil carbon sequestration (kg CO₂-e/ha) in the grazed pasture paddock over 10 years following conversion from cropping

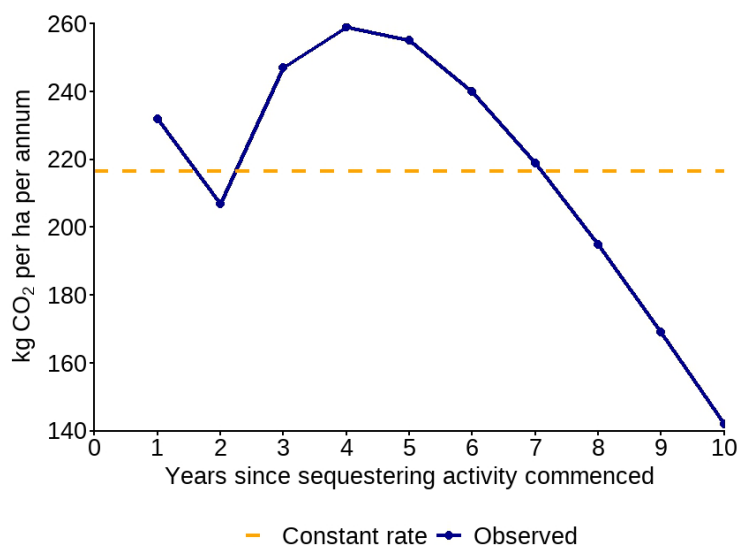


Figure 5 Annual rate of soil carbon sequestration (kg CO₂-e/ha.annum) in the grazed pasture paddock over 10 years following conversion from cropping

The grazed pasture in our case study paddock was fertilised annually with a low level of mineral N fertiliser (9.76 kg N/ha) and with organic fertiliser in the form of feedlot manure at establishment (101.95 kg N/ha remaining after assumed loss of 26% as ammonia (Bauwman *et al.* 2002)). The C:N ratio of similar brigalow soils in central Queensland under pasture, were found to be in the range of 12.8-13.5 in the soil intervals from 0-10 cm to 0-30 cm (Dalal *et al.* 2021a). If a similar C:N ratio is present in the soils in the grazed pasture paddock in this case study, it is likely that the SOC accumulation may have benefited from the N application. However, regardless of the anticipated pasture productivity and SOC response, previous economic analyses for southern and central Queensland have indicated that fertilising grass pastures with N is unlikely to be profitable for the landholder (Lawrence *et al.* 2014).

The assumption for this analysis was that, in the absence of better data, a linear decline in biomass yield occurred over 10 years to 75% of the initial yield, due to pasture rundown. Rundown (decline in productivity) of sown pastures typically occurs after establishment, primarily due to declining available soil N as pastures age, so that by 10 years after sowing the pasture yield can fall to 50% of initial yields (Peck *et al.* 2011; Dalal *et al.* 2021a). An annual application of between 50 to 100 kg N/ha has been recommended to prevent pasture rundown (Lawrence *et al.* 2014). After subtracting an assumed N loss from manure fertiliser of 26% due to ammonia volatilisation (as per Bauwman *et al.* 2002), the annual available N application to the pasture from manure and mineral fertiliser declined from 43.4 kg N/ha in Year 1 to 9.76 kg N/ha from Years 6 to 10. Therefore, it is possible that the decline in pasture yield of 25% over 10 years expected by the cooperator was optimistic. Additionally, it is likely that the decline in pasture yield did not occur linearly due to the N availability being weighted towards the initial years following establishment. This would affect the annual rate of soil C sequestration over time shown in Figure 5 but would have had minimal effect on the overall average C sequestration rate of 0.06 t C/ha.annum.

In our analysis of C sequestration, any direct inputs of organic C from the feedlot manure was not able to be accounted for using the simple SOCRATES model. The review of Howe *et al.* (2024) found that the increase in SOC due to animal manure application is typically greater than the increase due to mineral fertilisation alone, and this was attributed to the direct C input from the manure. However, in contrast, the study of Lawrence *et al.* (2022) reported that SOC showed no benefit over mineral fertilisers at the commercially used rates of feedlot manure on cropland. They concluded that this was likely due to the expected rapid breakdown of labile C in manures. A study by Tatzber *et al.* (2009) found that only 30% of C from organic amendment remained in soil after 5 years.

At the low rate of C sequestration estimated for the conversion of a cropping paddock to grazed pasture in this study (0.06 t C/ha.annum) and the small project area of 238 ha, there is unlikely to be any value in an ACCU Scheme SOC sequestration project. Assuming that re-establishment of pasture occurs in 10 years cycles and that the average

sequestration rate of 0.06 t C/ha.annum can therefore be maintained over the life of a 25-year ACCU Scheme project, the total C sequestered would be equivalent to 1,288 t CO₂e for 238 ha. With 25% of credits withheld (20% permanence period discount plus 5% risk of reversal discount) the remaining credits would be 966 t CO₂e. Assuming a spot price of \$37.50 (late April 2026; CO₂RE Markets 2026) this equates to a gross income of \$36,230 over 25 years. However, the total costs of the SOC sequestration project for a 25-year period are estimated to be in the range of \$124,730 to \$233,690 (following the approach of Zeil-Rolfe (2025)), which is substantially greater than the estimated gross income for estimated for the ACCU Scheme project. This rough estimation of costs and benefits of an ACCU Scheme project does not account for the costs of converting the cropland to pasture in our study or the opportunity cost of changing to a less profitable enterprise. Furthermore, given the decline in the annual rate of soil C sequestration over time, it is likely that the average rate of C sequestration over 25 years would be substantially less than 0.06 t C/ha.annum estimated here over 10 years.

Our finding from the current case study, that an ACCU Scheme project based on C sequestration from conversion of cropland to grazed pasture was not likely to be economically viable, is also supported by the analysis of Lam *et al.* (2013) based on a meta-analysis of results from Australian studies and C prices up to \$23/t CO₂-e. This latter study did not account for costs associated with the pasture establishment, compliance and auditing costs, and did not account for an increase in GHG emissions from livestock from net emissions. Additionally, Zeil-Rolfe (2025) determined that, for a SOC sequestration project on 433 ha in central Queensland, SOC sequestration rates would have to be at least 1.43 t CO₂-e/ha.annum with low project costs (i.e. \$190,055) in order to pay back the costs of the ACCU Scheme project. Therefore, it can be inferred that the project is likely to generate income in excess of costs only at the upper end of the SOC sequestration range reported by Henry *et al.* (2024) for converting a cropping paddock to pasture (i.e. 0.48 t C/ha.annum, equivalent to 1.78 t CO₂-e/ha.annum). However, the investment and opportunity costs associated with changing to a potentially less profitable enterprise would also need to be accounted for.

5.3.3 Net greenhouse gas emissions for cropping or grazed pasture in the case study paddock

Table 15 summarises the net GHG emissions for the cropping and grazed pasture scenarios in the case study paddock. Despite the C sequestration of 51.5 t CO₂-e/annum in the grazed pasture scenario, cf. a loss of 180.6 t CO₂-e/annum in the cropping scenario, the net emissions from the grazed pasture were 10.3 times that from the cropping scenario, on average. The large net emissions from the grazed pasture scenario (2,975 t CO₂-e/annum) were primarily due to the large Scope 3 emissions from purchased livestock (2,734 t CO₂-e/annum) which constituted 91% of the total GHG emissions (not considering C sequestration), (Figure 6). However, if Scope 3 emissions from purchased livestock are not included (as for property-bred livestock), the net emissions from the grazed pasture scenario (241 t CO₂-e/annum) were less than that from the cropping paddock (288 t CO₂-e/annum), due to the effects of C sequestration which counteracted the substantial contribution of enteric methane emissions. While total Scope 3 emissions for the grazed pasture scenario constituted 92% of total emissions (not considering C sequestration), Scope 3 emissions for the cropping scenario contributed 54% of total emissions (Figure 7).

In contrast to our study, Meier *et al.* (2020) found in an APSIM modelling exercise for three contrasting Australian sites including one near Chinchilla Queensland (with similar climate and soils to the case study site), that soil C gains under continuous livestock grazing were often negated by livestock methane and nitrous oxide emissions, such that net on-farm GHG emissions from pasture-based systems were similar to, or higher than, those from cropping. In our study, when Scope 3 emissions from purchased livestock were ignored, the net emissions in the grazed pasture scenario were 84% of those from the cropping scenario.

Our emissions intensity estimate for the cropping rotation excluding sequestration (0.23 t CO₂-e/t grain) was less than that reported for the entire Australian grains sector for the financial year 2020-2021 by Sevenster and Burrett (2025): 0.31 t CO₂-e/t excluding C sequestration. However, the emissions intensity estimate from our cropping scenario when including soil C sequestration (0.62 t CO₂-e/t grain) was much greater than the comparable estimate of Sevenster and Burrett (2025): 0.19 kg CO₂-e/t grain. It is of note that that these national figures indicate substantial net soil C removals occurred in croplands, which was the opposite of that found in our study where 180.6 t CO₂-e/annum were lost from the soil in the case study paddock on average over 10 years.

The emissions intensity estimate, excluding sequestration, for the grazed pasture paddock in our case study (11.6 kg CO₂-e/kg LW) was lower than the average for beef production across the beef industry of 12.6 kg CO₂-e/kg LW determined by Wiedemann *et al.* (2019) for the 5 years to 2015. When sequestration and Scope 3 emissions from purchased livestock were excluded, the emissions intensity of 1.12 kg CO₂-e/kg LW in our study, was lower than the range of 5-9 kg CO₂-e/kg LW provided by Wiedemann and Dunn (2021) for similar criteria.

Table 15 Summary of average net greenhouse gas emissions for the grain cropping and grazed pasture scenarios in the case study paddock

Parameter	Grain cropping total (t CO ₂ -e/paddock)	Grazed pasture total (t CO ₂ -e/paddock)
Scope 1 emissions (on-farm)		
CO ₂ – Fuel	11.1	3.23
CO ₂ – inorganic fertiliser	13.1	0
CH ₄ – Fuel	0.009	0
CH ₄ – Enteric	0	217.9
CH ₄ – Manure management	0	11.68
N ₂ O – Fertiliser inorganic	14.8 (Method 2)	1.74
N ₂ O – Fertiliser organic (feedlot manure)	0	6.83
N ₂ O – Urine and dung	0	9.91
N ₂ O – Atmospheric deposition	0	0.52
N ₂ O – Crop residues	10.1	0
N ₂ O – Leaching and runoff	0	0
N ₂ O – Fuel	0.1	0.02
Scope 1 – total	49	252
Scope 3 emissions (pre-farm)		
Fertiliser - inorganic	27.0	38.74
Herbicides/pesticides	28.2	0.73
Fuel	2.7	0.80
Purchased livestock	0	2,734
Scope 3 – total	58	2,774
C sequestration emissions from soil (average annual over 10 years)	180.62	-51.53
Net paddock emissions (t CO ₂ -e/paddock)	288	2,975
Emissions intensity excluding sequestration (t CO ₂ -e/t crop)	0.23 t CO ₂ -e/t crop	11.6 kg CO ₂ -e/kg LW
Emissions intensity including sequestration(t CO ₂ -e/t crop)	0.62 t CO ₂ -e/t crop	11.4 kg CO ₂ -e/kg LW

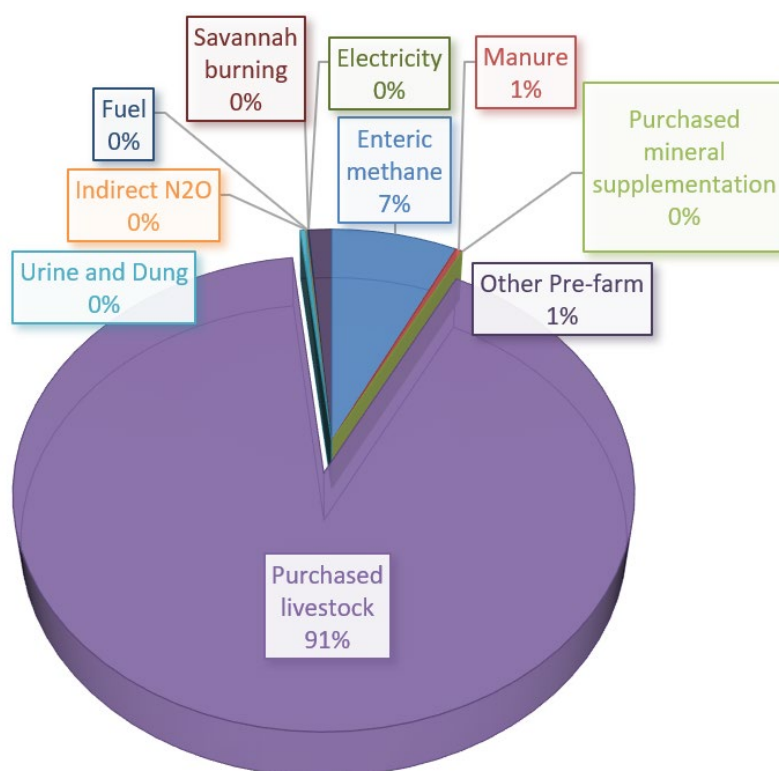


Figure 6 Percentage contribution of each emission source (except C sequestration) for the grazed pasture scenario in the case study paddock

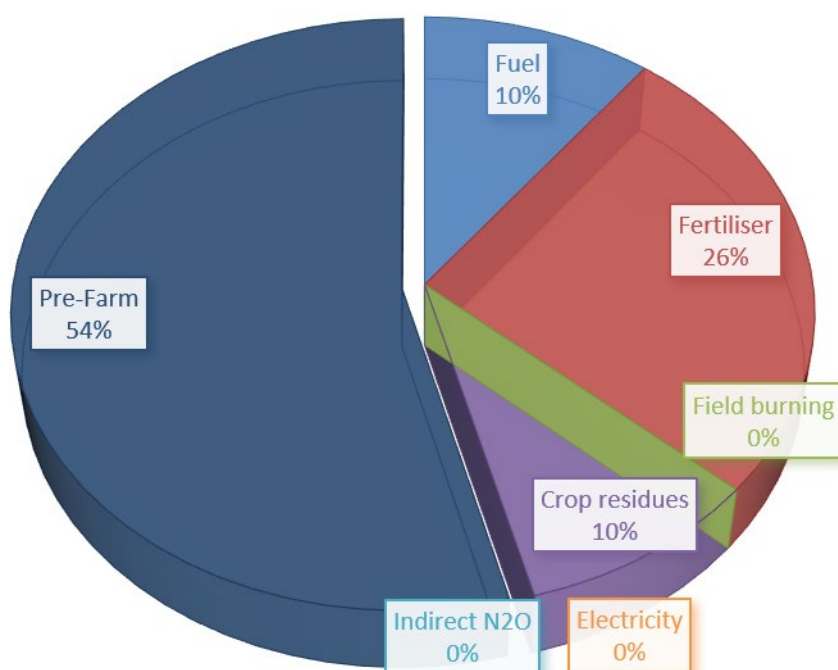


Figure 7 Percentage contribution of each emission source (except C sequestration) for the cropping scenario in the case study paddock

6. General discussion

The present study has demonstrated the application of C sequestration, emissions and economic analysis to understand the consequences of converting cropland to pasture for grazing cattle in southern Queensland, as an example of a C sequestration strategy. The study demonstrated that higher levels of C sequestration do not necessarily lead to reduced net emissions or to improved profits, indicating the trade-offs that can occur when implementing GHG mitigation strategies. This finding is in accord with others who have indicated that those strategies delivering the greatest SOC accrual and/or GHG mitigation are not necessarily the most profitable (Bilotto *et al.* 2025, Pham-Kieu *et al.* 2025, Bhattarai *et al.* 2026 and Muleke *et al.* 2026).

While the grazed pasture scenario in our case study resulted in an average soil C sequestration of 0.06 t C/ha.annum (compared to a loss of 0.20 t C/ha.annum for the grain cropping scenario), net emissions were 10.3 times that of grain cropping scenario, and the paddock gross margin for grazed pasture was 82% of the cropping rotation. Under the assumptions in this case study, the landholder would be better off, in terms of profit and net emissions, to retain the paddock as cropland rather than converting it to perennial grass pasture. However, if the primary goal is to sequester C, then the grazed pasture scenario appears capable of arresting the decline in soil C seen under long-term cropping with small annual gains possible over 10 years following pasture establishment.

The importance of biomass growth and productivity, and therefore litter inputs, to SOC sequestration (Grace *et al.* 2006) were clearly shown in the case study analysis where the rate of SOC sequestration in the grazed pasture declined rapidly over years 4 to 10. This decline was associated with the assumed linear reduction in pasture biomass growth due to pasture rundown after establishment under a moderately heavy pasture utilisation rate of 40% of annual pasture biomass growth. An alternative to re-sowing the grass pasture every 10 years to increase pasture yields (and SOC sequestration) by increasing nutrient mineralisation and plant available nutrients through soil disturbance, may be to establish adapted pasture legumes in the grass pasture sward. However, there are currently very few suitable legumes for this sub-tropical region with cold winters (Peck *et al.* 2022)

Pasture legumes have been identified as the best long-term option to increase the productivity from rundown sown grass pastures through their ability to biologically fix atmospheric N (Peck *et al.* 2011). Additionally, establishing pasture legumes is one of the more promising strategies for SOC sequestration (Debney and Lobry de Bruyn 2024; Henry *et al.* 2024). They have also been found to be one of the more profitable management strategies for north Australian extensive livestock systems, although concurrently increasing farm riskiness (Bowen *et al.* 2018; Bowen and Chudleigh 2019; Bowen and Chudleigh 2021a, Bowen and Chudleigh 2021b). Therefore, it is likely that the SOC sequestration under grazed pasture in the case study paddock could have been further increased, along with profit, if an adapted pasture legume could be identified and sown, during the conversion from cropping, in addition to the perennial C₄ grass species.

Desmanthus species such as *Desmanthus virgatus* and hybrids have been shown to be highly persistent and well-adapted to brigalow clay soils including highly alkaline and sodic conditions (Peck *et al.* 2022). Additionally, *Caatinga stylo* (*Caatinga seabrana* var. *Unica*) thrives on heavy clays and has some cold tolerance (Peck *et al.* 2022). These introduced legume species may be suitable for sowing in the soil type and climate near Condamine where the case study paddock was located, but this would have to be tested. As demonstrated by Bowen (2026b), establishing pasture legumes in a grass-only pasture generally is likely to increase the carrying capacity of the paddock and therefore increase net emissions along with profit. However, emissions intensity would be expected to decrease due to the improved diet quality and livestock growth rates on legume-grass pastures relative to grass-only pastures.

The poor estimated outcome in our case study analysis from engaging in a soil C ACCU Scheme project on the grazed pasture paddock, is in accord with the results of Zeil-Rolfe (2025). Lam *et al.* (2013) concluded that C sequestration in Australian agricultural soils as a means of offsetting a significant part of the national GHG emissions is technically limited and economically nonviable under present market conditions. This was because of (1) the technical uncertainty in measuring small soil C changes, (2) the difficulty and cost of stabilising any gain in soil C over time, and (3) the uneconomic nature of associated ACCU Scheme projects based on realistic C sequestration rates.

The relatively simple example strategy examined in the case study analysis in this report proved complex and time consuming to analyse. In this instance, six separate models were required to analyse SOC sequestration, emissions and gross margins for cropping and grazed pasture scenarios, with each requiring detailed and robust data. Given the complexity and time required to produce a useful estimate of the net emissions and the economic outcome of implementing a new strategy, it can be concluded that individual primary producers are unlikely to undertake such a detailed analysis themselves. Consultants or other industry professionals who can undertake detailed and integrated analysis of economic, financial, risk, and GHG implications for a change in farm management strategy will be required to provide an understanding of the trade-offs and opportunities from implementing GHG mitigation strategies such as C sequestration strategies.

7. Conclusions and recommendations

The literature review presented in this report is intended to improve understanding of the opportunities for emissions reductions in extensive livestock production systems due to the implementation of C sequestration strategies. The case study analysis of converting a paddock in southern Queensland from grain cropping to grazed perennial grass pastures provides an example of expected outcomes for SOC sequestration, net emissions and farm profit.

Overall, the findings from both the literature review and the case study indicate that the potential for C sequestration strategies to contribute to net zero goals in extensive livestock systems is highly context dependent and constrained by important biophysical, economic and methodological factors. Many of the sequestration strategies identified can increase C in vegetation or soils, but they may not reduce net emissions or improve landholder profitability. These trade-offs, along with uncertainty about the permanence and measurement of C gains, limit their appeal to landholders, unless they are supported by alternative income or ecosystem service payments.

The case study clearly demonstrated these trade-offs. Conversion of the cropping paddock to grazed perennial grass pasture resulted in a modest increase in SOC and a C sequestration benefit relative to the cropping scenario. The grazed pasture scenario generated a lower gross margin than the cropping scenario on an annual equivalent basis, and when Scope 3 emissions from purchased livestock were included, the pasture scenario also produced substantially higher net emissions. These findings suggest that, under the assumptions applied in this analysis, retaining the paddock in the existing cropping sequence is more favourable in the short to medium term in terms of both profitability and net emissions.

The results of the case study are based on a range of assumptions relating to prices, production levels, input costs, emissions factors, C sequestration rates and model structure. Outcomes may differ under alternative assumptions, in different regions, for different enterprise structures, or under future changes in C market settings, climate, commodity prices or input costs. Accordingly, the case study should be interpreted as an example of how these analyses can inform decision-making, rather than as a conclusion that can be generalised across production systems.

This initial case study provides a foundation for developing a library of comparable scenarios that producers can use when making decisions, particularly where specialist support for detailed analysis is not readily available. Over time, such a resource could help translate complex modelling into more accessible and practical guidance for on-ground use. In many cases, approaches like these may prove more valuable to producers and advisers than highly complex decision support tools, especially when they are easier to apply in real world decision making.

It is recommended that future work is undertaken to expand this scenario analysis to a wider range of regions, land types and sequestration strategies to test sensitivity to key assumptions such as rainfall, livestock prices and input costs and to assess integrated payment approaches that recognise co-benefits beyond C alone. Overall, effective support for landholders will require decision frameworks that jointly consider C outcomes, net emissions, enterprise profitability, financial risk and implementation feasibility.

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9. Glossary of terms and abbreviations

Table 16 Glossary of relevant terms and abbreviations

Abbreviation/Term	Definition
ACCU	Australian Carbon Credit Unit. An ACCU is a unit issued to a person by the Clean Energy Regulator. Each ACCU issued represents one tonne of carbon dioxide equivalent (t CO ₂ -e) net abatement (through either emissions reductions or carbon sequestration) achieved by an eligible offset project. ACCUs may be sold to generate income, either to the Australian Government through a carbon abatement contract or to companies and other private buyers in the secondary market.
ACCU Scheme	Australian Carbon Credit Unit Scheme, formerly known as the Emissions reduction fund (ERF). The Scheme provides incentives for a range of organisations and individuals to adopt new practices and technologies to reduce their emissions or store carbon.
APSIM	Agriculture Production Systems Simulator. A widely used process-based modelling framework that integrates crop or forage growth, soil water and nutrient dynamics, and greenhouse gas emissions with a farming systems context.
C	Carbon
CO ₂	Carbon dioxide
C ₄ grass	Commonly referred to as a warm-season, summer active, or tropical grass because they are adapted to sub-tropical, tropical, hot and/or dry conditions. These grasses use a specialised, highly efficient photosynthetic pathway to capture CO ₂ and convert it into energy which makes the plants more able to withstand heat stress than temperate, C ₃ grass species.
Carbon account / audit	Equivalent to a net emissions calculation (NE = t CO ₂ -e / business unit) and includes: (1) all GHG produced within the boundary of the farm enterprise, (2) Annual changes in soil and tree carbon, and (3) Adjustments for carbon offsets bought or sold (note, SBTi only allows purchased offsets for the intractable residual emissions).
Carbon accounting	The process used to quantify greenhouse gas (GHG) emissions from an enterprise.
Carbon footprint	Equivalent to an emissions intensity calculation (EI = t CO ₂ -e / t product). The process of quantifying GHG emissions emitted directly or indirectly by an individual, company or product (i.e. the sum of Scope 1, 2 and 3 emissions). A carbon footprint is more commonly used for products (i.e. beef) than enterprises, but it can be applied at either scale. Several standards exist to define a carbon footprint, such as ISO 14067.
Carbon neutrality	The sum of GHG emissions is completely offset by equivalent carbon sequestration. This may be achieved within an enterprise or by purchasing carbon credits.
Carbon sequestration	The process whereby carbon dioxide is removed from the atmosphere and stored in carbon sinks such as soil and vegetation.
Carbon sink	A reservoir that absorbs carbon dioxide from the atmosphere. Natural carbon sinks include, plants, soils and the ocean.
Carbon stocks	Soil carbon stocks usually refer only to organic carbon (soil organic carbon or soil organic carbon). This represents the carbon stored in living and decaying organic matter, such as plants, microbes, and humus.
CEC	Cation exchange capacity
CER	Clean Energy Regulator. The CER was established by the <i>Clean Energy Regulator Act 2011</i> and is a non-corporate Commonwealth entity which administers schemes legislated by the Australian Government for measuring, managing, reducing or offsetting Australia's carbon emissions.
CH ₄	Methane
CP	Crude protein

Abbreviation/Term	Definition
CO ₂ -e	Carbon dioxide equivalent. A unit used to compare emissions from different GHGs based on their global warming potential (GWP) over a specified time period, typically 100 years (GWP ₁₀₀)
CRC	Co-operative Research Centre
DM	Dry matter. DM is determined by oven drying feed or faecal material in an oven until constant weight is reached (i.e., all moisture is removed).
DMD	Dry matter digestibility. The proportion of feed an animal digests in the stomachs. DMD is calculated as the intake of DM minus the amount of DM in the corresponding faeces, expressed as a proportion of the intake (or as a percentage).
DMI	Dry matter intake. The quantity (weight) of feed that an animal ingests.
Discounting	The process of adjusting expected future costs and benefits to values at a common point in time (typically the present) to account for the time preference of money. With discounting, a stream of funds occurring at different time periods in the future is reduced to a single figure by summing their present value equivalents to arrive at a net present value (NPV). Note that discounting is not carried out to account for inflation. Discounting would still be applicable in periods of nil inflation.
Discount rate	The interest rate used to determine the present value of a future value by discounting. This helps determine if the future cash flows from a project or investment will be worth more than the capital outlay needed to fund the project or investment in the present.
Economic analysis	Economic analysis usually focusses on profit as the true measure of economic performance or how efficiently resources are applied. The calculation of profit includes non-cash items like opportunity costs, unpaid labour, depreciation and change in the value of livestock or crop inventory. NPV and amortised NPV are both measures of profit.
EI	Emissions Intensity. Emissions intensity values are based on the net emissions relative to the output (e.g. per kg beef, sheep meat or greasy wool). Emissions intensity values allow for comparison and benchmarking between farms of different sizes. They are the standard unit for a carbon footprint.
Enteric methane	Methane produced through enteric fermentation where plant material is broken down in the rumen. Enteric methane is the by-product of this process and is expelled by the animal through belching.
ESG	Environmental, Social and Governance. A holistic framework that measures the sustainable and ethical behaviour of a business. Australia introduced mandatory ESG reporting requirements for large businesses, commencing 1 January 2025. The legislation requires large Australian corporations and asset managers to make mandatory climate-related financial disclosures in their annual reports at the end of each financial year.
FAOSTAT	Food and agriculture organisation corporate statistical database. The world's largest database of food and agriculture statistics, operated by the United Nations.
FORM	The annual fuel, oil, repairs and maintenance allowance for the activity being assessed in the analysis
FullCAM	Full Carbon Accounting Model. A calculation tool for modelling Australia's greenhouse gas emissions from the land sector. FullCAM is used in Australia's National Greenhouse Gas Accounts for the land use, land use change and forestry sectors. Results from modelling are used to produce the annual totals for Australia's National Inventory Reports. FullCAM is also used to generate abatement estimates for methods under the ACCU Scheme.
GAF	Greenhouse gas accounting framework. Refers to a suite of industry-specific calculators developed by the Primary Industries Climate Challenges Centre (PICCC), University of Melbourne and used to measure, predict and track on-farm GHG emissions and C sequestration.
GHG	Greenhouse gas. These are gases that absorb and emit radiant energy and that are reported under the National Greenhouse and Energy Reporting scheme. GHGs include carbon dioxide (CO ₂), methane (CH ₄), nitrous oxide (N ₂ O), sulphur hexafluoride (SF ₆) and specified kinds of hydro fluorocarbons and perfluorocarbons. GHG emissions are measured as tonnes of carbon dioxide equivalence (CO ₂ -e).

Abbreviation/Term	Definition
Gilgai	An undulating terrain characterised by alternating shallow hollows, depressions, and mounds. This distinct landform is created by the cyclical shrinking and swelling of heavy clay soils during alternate dry and wet weather conditions.
GWP	Global warming potential. A measure of cumulative radiative forcing, which aims to quantify the long-term contribution of a greenhouse gas to global warming. Each GHG has a specified GWP value, and this is relative to a specified time period (typically 100 years, but values are also available for 20-year and 500-year time horizons). The 100-year time horizon is abbreviated as GWP ₁₀₀ .
Gross margin	The gross income received from an activity less the variable costs incurred. Can be sufficient to assess a change in farm management where only variable costs and returns are affected. However, if a management change involves a change in overhead costs, a more complete economic analysis is usually required in the form of a marginal analysis that considers the effect of alternative strategies at the property or business level.
HIR method	Human-induced regeneration of a permanent even-aged native forest 1.1 An ACCU scheme vegetation method which has now closed to new projects.
IFLM method	Integrated farm and land management method. A new ACCU Scheme method under development and anticipated to combine vegetation and soil C sequestration.
IPCC	Intergovernmental panel on climate change. An intergovernmental body of the United Nations. Its objective is to provide policy-makers with regular scientific assessments on climate change, its implications and potential future risks, as well as to propose adaptation and mitigation options.
LW	Liveweight
LWG	Liveweight gain
Marginal	Extra or added. Principle of marginality in economics emphasises the importance of evaluating the changes for extra effects, not the average level of performance.
MIDAS	Model of an Integrated Dryland Agricultural System. A bioeconomic computer model used to optimise mixed crop-livestock farming. It uses mathematical linear programming to analyse the biological and financial components of a farm, identifying management strategies that maximise whole farm profits subject to resource and environmental constraints.
n/a	Not applicable
N	Nitrogen
N ₂ O	Nitrous oxide
Net profit	This is the reward to the farmers own capital. Net profit equals operating profit less the returns to outside capital. The returns to lenders of fixed capital (interest, rent, leases) are deducted from Operating profit in the calculation of Net profit. It is available to the owner of the business to pay taxes or to provide living expenses (consumption) or it can be used to reduce debt. Net profit minus income tax minus personal consumption (above operators allowance if it has already been deducted from operating profit) = change in equity.
Net zero	Calculated as zero t CO ₂ -e / denominator, where the denominator is either the business enterprise or the product.
NGGI	National GHG inventory. The NGGI accounts for and estimates Australia's GHG emissions.
NIR	National inventory report. The annual report released by the Australian Government with results from the NGGI and the methods used to determine those emissions.
NPV	Net present value. Refers to the net returns (income minus costs) over the life of an investment, expressed in present day terms. A discounted cash-flow allows future cash-flows (costs and income) to be discounted back to an NPV so that investments over varying time periods can be compared. The investment with the highest NPV is usually preferred. NPV is calculated at a rate of return (usually 5-7%) which is taken as the real opportunity cost of funds to the producer.
NRM region	Natural resource management region. NRM regions across Australia are based on catchments or bioregions. The boundaries of NRM regions are managed by the

Abbreviation/Term	Definition
	Australian Government and used for statistical reporting and allocation and reporting of environmental investment programs.
P	Phosphorus
PDS	Producer demonstration site
Peak deficit	This is an estimate of the peak deficit in cash flow caused by the implementation of the management strategy. It assumes interest is paid on the deficit and is compounded for each additional year that the deficit continues into the investment period. It is a rough estimate of the impact of the investment on the overdraft if funds for the development are not borrowed but sourced from the cash flow of the business.
QDPI	Queensland Department of Primary Industries
S	Sulphur
SAFE	Spatial Agriculture, Forestry and Environment (SAFE) model. Used to estimate aggregate land-use responses. SAFE is useful for analysing how policy or market settings may influence land-use change across regions or industries,
Safe carrying capacity	A safe carrying capacity for a property is defined as a strategic, i.e., long-term (e.g., 20-30 years) estimate of livestock numbers that can be carried without any decrease in pasture condition and without accelerated soil erosion.
Safe stocking rate	A safe stocking rate is a short-term, tactical (seasonal or annual) stocking rate based on seasonal forage budgeting principles and safe utilisation rates of pasture. A safe stocking rate may be higher or lower than the long-term safe carrying capacity due to seasonal variability in rainfall.
SB-GAF	Sheep and beef GHG accounting framework tool which can be used to generate a carbon account. Developed by the University of Melbourne to align with the National Greenhouse Gas Inventory to predict the magnitude and sources of GHGs emitted from a farm and a product at the farm gate.
SBTi	Science based targets initiative. A corporate climate action organisation.
Scope 1 emissions	Direct GHG emissions from sources that are owned or controlled by a company.
Scope 2 emissions	GHG emissions from the generation of purchased electricity consumed by a company.
Scope 3 emissions	GHG emissions that are the consequence of the activities of the company but occur from sources not owned or controlled by the company. Examples include emissions from purchased supplements, and use of services. These emissions can relate to the supply chain prior to the business (i.e. purchased cattle) or after the business in the supply chain (i.e. meat processing).
SOC	Soil organic carbon
SOCRATES	Soil organic carbon reserves and transformations in ecosystems. A simple, process-based model for estimating soil carbon change.
ZNE Ag CRC	Zero Net Emissions Agriculture Cooperative Research Centre

10. Acknowledgements

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