Potential for soil carbon sequestration in Northern Australian grazing lands: A review of the evidence

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The Department of Agriculture and Fisheries proudly acknowledges all First Nations peoples (Aboriginal peoples and Torres Strait Islanders) and the Traditional Owners and Custodians of the country on which we live and work. We acknowledge their continuing connection to land, waters and culture and commit to ongoing reconciliation. We pay our respect to their Elders past, present and emerging.

Objectives

The aim of this project was to review the evidence on prospects for soil carbon sequestration in northern Australia, focusing on land used for extensive beef cattle, sheep or goat production.

The report analyses published information and data under the following key content topics:

1. Soil carbon background: Defining soil carbon and soil carbon sequestration.
2. Impact of management strategies on soil carbon sequestration based on a review of regionally relevant literature and available in-field measurements and modelling studies (where supported by on-ground information), including:
   - Identification of management strategies reported to result in positive, negative or no change in long-term ('permanent') soil organic carbon storage; and
   - Exploration of possible reasons for inconsistency in estimates of potential carbon sequestration.
3. Opportunities, key requirements and impediments to participation in soil carbon crediting schemes such as the Australian Emissions Reduction Fund.
4. Measurement and monitoring requirements to validate permanent soil carbon sequestration in grazing land at paddock to property scale.
5. Risks and barriers associated with various soil carbon sequestration strategies, focusing on biophysical constraints on 'permanent' storage of carbon in northern grazing land soils.
6. Key knowledge gaps and research needs.
7. Conclusions and Recommendations

Scope and Structure

Published papers and reports (including those in the 'grey literature' were collated and reviewed for evidence on soil carbon sequestration in land under long-term grazing management or following land use and land cover conversion involving ruminant livestock production in extensive grazing regions. Emphasis was placed on Queensland and the Northern Territory studies, but information from studies in other regions are included in the review to supplement northern Australian data where they provide additional relevant insights. Based on evaluation of the most reliable evidence, a quantified assessment of soil carbon sequestration potential under this major land use is provided, knowledge and research gaps are identified, and a brief overview is given of the policy implications.

The first section of this report provides an overview of the context and current debate on soil organic carbon sequestration for soil health and climate change mitigation in Australia, including the setting of national emissions reduction targets of parties to the United Nations Framework Convention on Climate Change Paris Agreement. The second section reviews evidence for a significant increase in long-term soil carbon storage when improved livestock or pasture management is implemented in regions of northern Australia. Management strategies relevant to beef cattle, sheep and goat producers are evaluated for their potential to increase soil carbon sequestration while supporting profitable grazing enterprises.

Possible reasons for the inconsistencies in reported management-induced soil carbon change are explored, including differences in definitions relating to soil carbon or management, quality of measurement methods used to estimate permanent carbon storage, timing relative to dynamics of soil carbon cycling and storage, and challenges in monitoring sequestration in areas of high climate variability. The following three sections look, respectively, at opportunities, requirements and impediments for producers implementing strategies for soil carbon gain, measurement and monitoring challenges, and risks for achieving and maintaining increased soil carbon storage under carbon crediting scheme rules. The final section of the report identifies gaps in data and knowledge and makes recommendations for R&D to improve the evidence base needed for soil carbon sequestration policy development and livestock management decisions in northern Australian.

Beverley Henry
16 January 2023

Contents

Summary

Understanding soil carbon sequestration

Increasing the amount of organic matter in soil has long been recognised by agronomists and farmers as beneficial for soil health and plant growth. Soil organic matter (SOM), comprising plant residues, root exudates and microbial and larger soil fauna biomass, contains around 58% carbon (C) by mass. This C comes initially from atmospheric carbon dioxide (CO_2) that is taken up by leaves in photosynthesis and converted to organic molecules for plant growth and function, in turn providing energy for the soil microbial populations and larger soil fauna that feed on them. Through the processes of respiration and decomposition much of the C cycles back to the atmosphere as CO_2 in a short time (days to a few years), with only a small fraction (as little as 10% or less) of the remainder can be stored or 'sequestered' for more than a century in the soil. This fraction represents a net removal of CO_2 (a greenhouse gas, GHG) from the atmosphere.

Long-term storage of soil organic carbon (SOC) in agricultural[1] lands has increasingly become of interest as a mechanism to offset emissions of GHGs from sources such as fossil fuel combustion and contribute to global efforts to limit global warming. Targets for 'net zero' emissions by 2050 agreed by Australia and around a hundred other countries under the Paris Agreement depend on some degree of land sector C removal in vegetation and soil sequestration. However, how much mitigation can be achieved through soil carbon sequestration (SCS) is the subject of debate. Advocates for SCS, promote it as a 'win-win-win' for the environment, agricultural productivity and resilience to climate impacts, as well as enabling farmers to earn income for SOC offsets. Schemes such as the Australian government's Emissions Reduction Fund (ERF) provide a framework for land managers to receive credits which can be sold in C markets or used to reduce a farmer's net emissions (sometimes referred to as 'insetting'). Other stakeholders including some experienced soil scientists, argue that the achievable climate change mitigation through SCS has been overstated. Importantly, there is broad consensus across both sides of this debate on the value of increasing SOM for soil health, agricultural productivity and ultimately for global food security. Active research in Australia and globally seeks to improve understanding of the complex forms, functions, and dynamics of C in soil and resolve issues on the potential for SCS in different regions.

This review examines the available evidence for increasing SCS in northern Australian grasslands and woodlands using practical grazing and pasture management strategies. These land systems have had less investment in soil C research than many more intensively managed lands, and assessment of the potential for SCS is constrained by the low number of long-term grazing system studies with robust measurements of soil C stocks. The review found that reported SCS values were often difficult to compare due to inconsistencies caused by a range of factors including differences in how trials and surveys were conducted, whether 'control' or 'baseline' sites were adequate, variable methods for SOC monitoring, sampling protocols that did not account for the naturally high spatial and temporal variability in climate, soil, landscape and vegetation types across the region, and the wide range of production systems and management practices.

In evaluating the potential for management strategies to increase SCS it's important to note that surveys have revealed that, across large areas such as the grazing lands of Queensland, the amount of SOC stored (standardised for 0 – 30 cm soil layer) is largely controlled by rainfall and temperature. These climate factors are major determinants of soil moisture, which, in turn, is a strong determinant of plant growth and, consequently, organic matter (and C) available to be added

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[1] In this review *agriculture* is used in the traditional sense and is inclusive of growing crops and managing livestock for food and fibre. Where crop production is specifically referred to, cropping or cultivation are used.

to soil. A secondary determinant is soil type particularly clay content, which is a key factor in the stabilisation of SOC. In field surveys, the smaller influence of management strategies on SOC stocks may not be detected unless results have been firstly detrended for these dominant non-management drivers. Comparing treatments within a field trial usually minimises climate differences but care is needed to stratify sampling for soil type. In addition, accounting for climate variability on inter-annual to decadal time scales requires multi-decadal observations. Well-managed long-term studies in northern Australia, notably Wambiana Grazing Trial, Kidman Springs Fire Study and Brigalow Catchment Study, provide a critical resource for evaluating management strategies and for understanding the potential for SCS in regionally important land systems and climate zones. Continuation of these long-term trials and strategic investment in additional experiments in data-poor systems will help resolve knowledge gaps and inconsistencies that limit current capacity to estimate the SCS potential for different grazing management strategies relevant to northern Australian grazing systems.

Potential for soil carbon sequestration through management strategies

Evidence from published data and field study reports indicate that there is a high degree of uncertainty in the potential for SCS with adoption of many of the management strategies relevant to northern Australian grazing lands. Preliminary estimates identified some opportunities for increasing soil C but further trials are needed to better quantify SCS.

- *Livestock management* studies generally show that, relative to moderate grazing, high grazing pressure in rangeland production systems results in soils having lower SOC content. Results in northern Australia are consistent with global stocking rate trials, but better understanding is needed for grazing impacts in a variable climate and for understanding differences in SOC response across land types typical of northern Australia. Apart from the negative effect on SCS of high grazing pressure, no significant impacts on SOC were found for livestock management strategies with no evidence that SCS differed with animal type other than as a result of total grazing pressure, and no significant difference in several studies comparing rotational grazing with traditional/ continuous stocking strategies.

- *Destocking and exclosure* experiments indicated a small increase in SCS, averaging in the order of 0.04 t C ha^{-1} yr^{-1}. This strategy is unlikely to be adopted as a strategy to increase SOC except in limited non-productive parts of grazing properties. Under the 2021 ERF soil C method (Australian Government 2021, refer to Clauses 10(3) and 11(2)), destocking is not an eligible activity on production pasture land so is not a strategy that not earn ACCUs[2].

- *Pasture improvement* activities include sowing more productive grasses or incorporating nitrogen-fixing legume forages. These strategies for producing higher biomass pastures as forage have potential to result in higher SOM inputs. Estimated as a simple average, the rate of SCS for pasture improvement was 0.3 t C ha^{-1} yr^{-1}. Where baseline plant growth is constrained by N availability, N-fixation in legume-grass pastures may also provide forage and animal growth rate benefits. Research on the production and environmental benefits of planting *Leucaena* and *Desmanthus* in pastures in northern Australia is providing more

[2] ERF 2021 soil carbon method:

Clause 10(3) If a CEA includes land that is a permanent pasture, or has been used as pasture for a period of at least 2 years, the pasture must be grazed by production livestock at least once every 2 years, unless the land is de-stocked in compliance with subsection 11(2).

Clause 11(2) Land under pasture must not be de-stocked unless:

(a)the land is to be converted to a cropping system; or

(b)the de-stocking period is within the relevant drought period for the land; or

(c)the Regulator agrees in writing that exceptional circumstances exist.

consistent evidence for significant SCS potential. For legume species such as *Stylosanthes spp.* that have been widely planted over many years for pasture improvement, the 'additionality' standard under the ERF which requires an eligible activity to be 'new or materially different' will need to be tested with the CER for project registrations. However, modelling studies have indicated that productivity gains from pasture improvement strategies that increase SOC content would be very likely to provide greater income benefits for producers than participation in C markets unless offset prices become much higher than the 2022 level of around AUD30.

- *Fire management* studies indicated that small gains in SOC levels may be possible with reduced frequency and intensity of burning, but C sequestration in soil would be modest relative to that in woody biomass. It is likely a change in fire regime to increase sequestration in landscapes would lead to decreased pasture growth as tree cover increased and the production trade-off would be expected to limit the adoption of this a SCS strategy.
- *Land conversion* strategies most relevant to northern Australia involve changes between tree cover and grasslands. The results reported from land use change studies were strongly dependent on factors such as the time since conversion and baseline condition, notably whether soil was initially degraded and depleted of SOC relative to natural levels, and these factors contributed to some inconsistencies. In summary:
  - Conversion from cultivated crop production to perennial grasslands from various regions consistently show an increase in SCS with an average rate of 0.4 t C ha^{-1} yr^{-1}. This is a land use change with limited application in northern Australia.
  - Published results for SCS following conversion from forest or woodland cover to perennial grassland ranged from a decrease of 0.62 to an increase of 0.12 t C ha^{-1} yr^{-1}, with the average being a small decrease (-0.19 t C ha^{-1} yr^{-1}). This average has little meaning as the data were confounded by differences in time since conversion, measurement methods and sometimes multiple management impacts after conversion, e.g., difference in fire regimes as well as land cover change. Overall, there is insufficient reliable data to quantify potential SCS for conversion from forest to grassland cover, but the impact appears small and possibly not significant.
  - There was little evidence from global or Australian data that conversion of well-managed pasture to forest cover significantly increases SCS. Some studies showed that regeneration of woody cover through retention of regrowth on degraded land may result in increased sequestration in both soil and biomass. However, there are too few reliable data for northern Australia to predict the SCS potential across the range of conversion strategies (afforestation, reforestation, vegetation thickening, regrowth retention). Well-designed studies are needed to quantify the changes in C stocks and productivity and farm business impacts to understand full benefits and trade-offs for producers interested in conversion from grassland to tree cover.

Recommendations to improve soil carbon sequestration opportunities

1. ***Enhance the availability of reliable SOC data for SCS predictions in northern Australia***
   - *Maintain and monitor long-term studies in northern Australia:* Continue collection of high quality soil data in northern Australian studies, giving high priority to Wambiana Grazing Trial, Brigalow Catchment Study, and Kidman Springs Research Station. Sampling and analysis methods should enable quantification of SOC stock according with ERF C credit requirements. The data and time-series observations should be made available for calibration and verification of sensors and soil process models to build capacity for

predicting SCS more widely and cost-effectively than currently possible with in field sampling and analysis. This investment would improve confidence in estimates of the potential for SCS under current conditions and future climate scenarios.

- *Investigate opportunities to re-measure archived soil samples from past field studies:* Re-analysis of SOC stocks in soil samples from past field studies using up-to-date methods consistent with ERF requirements would cost-effectively expand the data available to evaluate effects of past management strategies and provide baseline data for new activities. These data would also contribute to understanding legacy effects of past management on SCS with new changes.
- *Use survey data to evaluate linkages between SOC and management across northern Australia:* Well-designed surveys of SOC stocks and site characteristics at locations representing major production systems across northern Australia have the potential to generate soil C data able to be detrended for non-management influences and enhance understanding of the potential for SCS with improved grazing and pasture management strategies.

2. ***Improve understanding of relationships between SCS, soil health and pasture production***

- *Investigate causes of variations and inconsistencies in reported SCS potential:* Preliminary analyses as part of this review indicated limited prospects for SCS with most relevant management strategies but were confounded by inconsistent findings. If the reasons for the different reported results could be clarified by re-examination of methods or supplementary data, e.g., soil type, management, production history, climate, land use/land cover information, prospective management strategies and SCS potential may be elucidated.
- *Investigate possible links between land condition variables and SOC dynamics:* While previous research has shown no clear link between indicators of land condition, such as ground cover, and total SOC stocks, further analyses on the dynamics of SOC and fractions (labile POC, stable MAOC) may establish whether, and on what timeframes, linkage may occur creating opportunities for their use as simple proxies for SCS management decisions.

3. ***Development of information materials***

- *Developing and updating an accessible SOC database:* Collate all available reliable measurement data on SOC stocks and metadata for land types and climate systems across northern grazing lands and records of management strategies. This resource would be of value to a range of stakeholders across research, policy, production, and C market industry.
- *Developing explanatory material:* The rapid expansion of SCS-related research and knowledge in areas of science and policy has raised the risk of conflicting and confusing information. Clear reference material on soil C and its role in productive landscapes and climate change mitigation would provide a valuable resource for a range of stakeholders seeking clear, factual material on SOC and opportunities for engaging in SCS activities. A series of online factsheets targeting northern Australia lands on issues such as measurement methods, ERF methods and opportunities, prospective management strategies, co-benefits and trade-offs and risks may help to address this need[3].

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[3] An example of similar regional information provided as factsheets is given by Western Australia DPIRD: https://www.agric.wa.gov.au/sites/gateway/files/Soil%20Carbon%20Measurement%20and%20Analysis%20Factsheet.pdf

1. Background

1.1 Soil carbon in context

Over recent decades, soil carbon (C) and its potential as a managed sink to remove carbon dioxide (CO_2) from the atmosphere have been increasingly discussed in the scientific literature, in the media and amongst land managers and C market stakeholders. Interest in soil organic carbon (SOC) as a climate change mitigation technology intensified after adoption of the Paris Agreement at the United Nations Framework Convention on Climate Change (UNFCCC) Conference of Parties (COP 21) in 2015 (https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement). The Paris Agreement committed 197 signatory countries to the global action to limit climate change keep warming to [preferably] no more than 1.5°C. Also at COP 21 in Paris, the French-led '4 per 1000 Initiative' (https://4p1000.org/) focused attention specifically on the combined food security and climate change benefits of increasing C storage in soil through improving soil health and offsetting greenhouse gas emissions. Interest in the use of offsets to achieve the Paris Agreement goal of 'net zero' emissions by 2050 expanded at COP 26 in 2021 at Glasgow as more countries adopted net zero targets. In November 2021, Australia also confirmed a net zero by 2050 commitment and since May 2022, the federal government has strengthened its climate change policy and actions. Globally, concerns in relation to sustainable development and food security have also raised awareness of the role of soil organic matter (and SOM) in maintaining healthy soils for functional, biodiverse ecosystems and food security for a growing human population.

While interest remains high in the potential contribution of SOC to climate change mitigation, there is also considerable debate. Conflicting views persist amongst technical experts on how much C can be removed from the atmosphere and stored permanently, nominally for 100 years[4], in soil and which management strategies are, and will continue to be, most effective and economically viable. In part, the technical debate reflects inconsistencies in definitions, measurement methods and the challenges of quantifying relatively small long-term changes in highly variable natural systems under human management. It also relates to the fundamental complexity of SOC and its dynamics and limited number of high-quality long-term studies that have been conducted, particularly in tropical and sub-tropical regions and more arid and variable climatic zones. More clarity and better understanding are needed for meaningful policy development and for informed on-ground decisions to optimise SCS for climate change mitigation, and to increase soil health for sustainable, profitable agriculture and for healthy natural ecosystems.

1.2 What is soil carbon?

Soil C is made up of inorganic and organic C compounds. Inorganic C occurs largely as carbonate minerals and is relatively stable and not responsive to common agricultural management activities. As in most discussions of SCS in managed landscapes, the focus in this review is on organic C, which makes up around 58% of SOM and is more responsive to both human activities and non-management factors such as climate. The organic matter in soil is derived from plant material and the organisms that feed on them, and from living and dead microbial biomass and fine plant roots (Stockmann et al. 2013). The amount of C stored in soil is a function of the dynamic balance between inputs of organic matter and its loss through mineralisation.

SOM is not homogenous but exists as material with changing physical, chemical and biological

[4] Consensus amongst scientists and experts in greenhouse gas accounting is that storage for at least 100 years is required for C in soils or biomass before it can be considered to represent removal of CO_2 from the atmosphere (climate change mitigation). This review adopts the convention of referring to this as 'permanent' storage or 'carbon sequestration'.

properties as it is progressively decomposed. Decomposition transforms coarser particulate organic matter (POM, *c.* 0.5 – 2mm) recently derived from plant litter and roots, microbes and larger soil organisms to finer material (*c.* <0.5mm) that includes root exudates as well as chemically and physically transformed SOM. Root fragments, surface litter, plant residues or other material in the soil greater than 2mm in size are not considered to be SOC (Lugato et al. 2021). SOC in surface soil is dominated by the recently added particulate organic carbon (POC), much of which turns over readily returning C to the atmosphere as CO_2. Only a small fraction (often 10% or less) becomes stabilised, often protected in mineral aggregates as mineral-associated organic carbon (MAOC) some of which may be stored for centuries deep in the soil profile (Cotrufo et al. 2013; Figure 1). The stable fine SOM fraction is sometimes referred to as humus. Resistant SOC, predominantly charcoal, that is present in some soils is minimally affected by management practices and may endure deep in the soil profile for thousands of years. In northern Australian areas subject to regular burning up to 10% of C in soils may exist as this largely inert form.

In considering the potential to implement management strategies to increase SCS it is important to consider the properties of both fast and slow cycling SOC fractions and their roles in meeting production and climate change mitigation objectives. Ready decomposition and rapid cycling of the labile fraction (often accounting for 90% or more of SOM) returns C to the atmosphere as CO_2 but is essential for providing energy for microbes and larger soil organisms (Figure 1B), and for releasing nutrients, such as nitrogen (N), phosphorus (P) and sulphur (S), for plant growth. It is the small proportion of organic C inputs stablilised as the MAOC fraction that can count as SCS. In many soil analyses, only total SOC is measured although models such as RothC (used in the soil sub-model of FullCAM which is used in estimating Australia's GHG accounts) and those based on Century approximate conceptual fractions to simulate SOC dynamics (Cunningham et al. 2015).

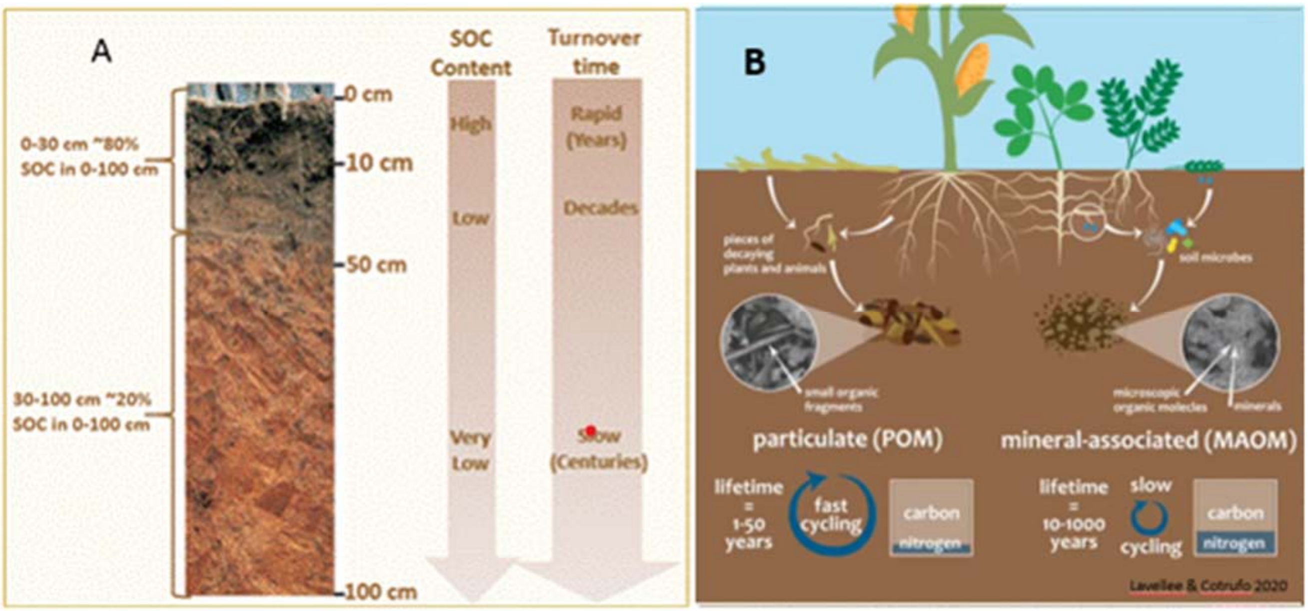


Figure 1. Forms and dynamics of SOC. SOC exists in a continuum of transformed organic matter that cycle at different rates (A), with the fine MAOC fraction that is stable for multi-decades or centuries contributing to climate change mitigation. (Credit B: Adapted from Lavellee and Cotrufo 2020).

1.3 Soil carbon sequestration

Globally, soils are estimated to contain around 1500 Pg (1500 x 10^{15} g) of C to a depth of 1 metre and 2400 Pg to 3 m depth. This is 2 to 3 times as much C as in the atmosphere and all vegetation combined (Stockmann et al. 2013, Minasny et al. 2017). Conversion of native forest and pasture to cropland has resulted in the amount of organic C stored in these soils being reduced by 42% and 59%, respectively, on average (Guo and Gifford 2002) and land management practices for food and fibre may result in continued decline in SOC stocks and negative effects on the chemical, physical and biological properties of soil important for soil health, ecosystem services and productivity (Page et al. 2020). It is widely accepted that restoring the organic matter content of soils by adopting more sustainable management practices in agricultural soils would provide multiple benefits. The technical potential for sequestration of SOC globally has been estimated at 0.4 – 0.8 Pg C yr^{-1} (Lal 2004). However, after accounting for socio-economic and practical constraints the achievable increase in storage is estimated to be much less than the biophysical potential calculated as the SOC deficit. As little as 10% of that technical potential may be realistic, and the proportion will vary by region (Sanderman et al. 2017, Henry et al. 2022).

As well as benefits for soil health and food security, increasing SCS to remove CO_2 from the atmosphere in principle provides an easier and less costly pathway to net zero emissions than the more disruptive industrial solutions (Smith et al. 2016). While hailed as an attractive climate change mitigation strategy, early enthusiasm and optimistic claims of potential SCS offsets equivalent to 20 – 35% of global anthropogenic GHG emissions (Minasny et al. 2017) have more recently been challenged. Analyses that consider realistic levels of adoption of practice change and the finite capacity of soil C sinks (Poulton et al. 2017), suggest net SCS could possibly offset only 4 – 5% of average annual global GHG emissions over the rest of the century (Henderson et al. 2022, Schlesinger and Amundson 2018). Key areas of uncertainty relate to long-term prospects for permanency of stored SOC in a warming planet with increasing frequency and intensity of extreme weather events (Roxburgh et al. 2020) and regional differences in potential SCS. The effectiveness of any management strategy implemented will depend on site-specific factors such as rainfall, temperature, soil type and past and present management. Practices proposed as more favourable for increasing SOC storage include woodland regeneration, no-till farming, cover cropping, nutrient management, organic amendment application, grazing strategies (such as avoiding over-grazing), efficient irrigation, and agroforestry, but implementation in any region depends on their suitability within a production system.

Since adoption in 2015 of the Paris Agreement the number of countries with net zero targets has grown to more than 100 countries (https://climateactiontracker.org/methodology/net-zero-targets/) and many national plans explicitly or implicitly assume that SCS will play a part. Australia's *Plan to Deliver Net Zero* by 2050 states that, to achieve this target, up to 20% of annual GHG emissions could be offset by SCS (Commonwealth of Australia 2021a). The government's *Low Emissions Technology Statement* that supports Australia's 2050 net zero target (the Net Zero Plan), assumes a contribution of 17 Mt CO2-e in 2050 but also cites CSIRO estimates of potential abatement through soil C management of 35-90 Mt CO2-e /yr (Commonwealth of Government 2021b). An even larger estimate by the private C market service provider, Agriprove (https://agriprove.io/) included in the Net Zero Plan (p. 56) is that the potential SCS across 36.58 Mha of cropping land and 28.95 Mha of grazing land (not including rangelands receiving <300 mm rainfall) could be at least 103 Mt CO_2e annually. This large range reflects current uncertainty in how much SCS is technically and practically possible. It is unclear how well the estimates take into account the low and increasingly variable rainfall that characterises much of Australia's managed land area, including extensive grazing areas. Estimating uptake by farmers should consider the technical challenges and cost of measuring small changes in SOC stock with sufficient accuracy to quantify sequestration and probable (rather than desirable) levels of adoption of SCS-positive practices, which will be constrained by socio-economic and cultural barriers, including compliance costs, opportunity costs of the practice change, and the loss of business flexibility. Permanency requirements under the ERF mean a land manager must commit to maintaining a soil C project for a minimum of 25 years and this acts as an impediment to participation (Macintosh et al. 2019, White 2022).

1.4 Soil carbon in extensive grazing lands

Two major vegetation types in Australia's northern grazing lands are rangelands and savannas. Globally, tropical savannas are an extensive, ecologically significant biome of importance for livestock production and for terrestrial C storage in biomass and soils. Rangelands also have the potential to represent a substantial C sink despite rates of SCS that are typically low per unit land area, due to the extensive area they occupy (Powlson et al. 2011). SCS is ultimately limited by the amount of photosynthetically derived organic C available for adding to the soil, and the sequestration potential in tropical and sub-tropical savannas and rangelands the sequestration potential is commonly constrained by relatively low NPP due to not having reliable soil moisture for plant growth throughout the year and often nutrient-poor soils (Janzen et al. 2022).

Estimates of SOC stocks across the Australian continent using measurement and modelling (Figure 2) show that the pattern of NPP is generally aligned with average rainfall patterns moderated by the influence of seasonally dry conditions (Duvert et al. 2020), climate variability and soil constraints (as indicated by clay content). Regular burning is also a strong influence on SOM inputs with, on average, around 20% of Australia's savanna region burnt each year (Russell-Smith et al. 2007, Russell-Smith et al. 2009). Soils hold in the order of 80% of savanna terrestrial C stocks (Dalal and Allen 2008) but predicting the potential for management to influence SCS is complex due to the dominant impacts of high variability in soil moisture and disturbance-driven dynamics that affect SOC cycling and possible long-term stabilisation. Across the northern rangelands and grazed woodlands, SOC stocks largely lie between 20 and 40 t ha^{-1} (Figure 2) which is low relative to most temperate coastal and southern temperate grazing lands where long-term average rainfall is similar but variability is lower. The high natural variability of vegetation and soil types across northern Australian landscapes, and few long-term studies with SOC monitoring result in high uncertainty in the potential SCS able to be achieved through changes in management.

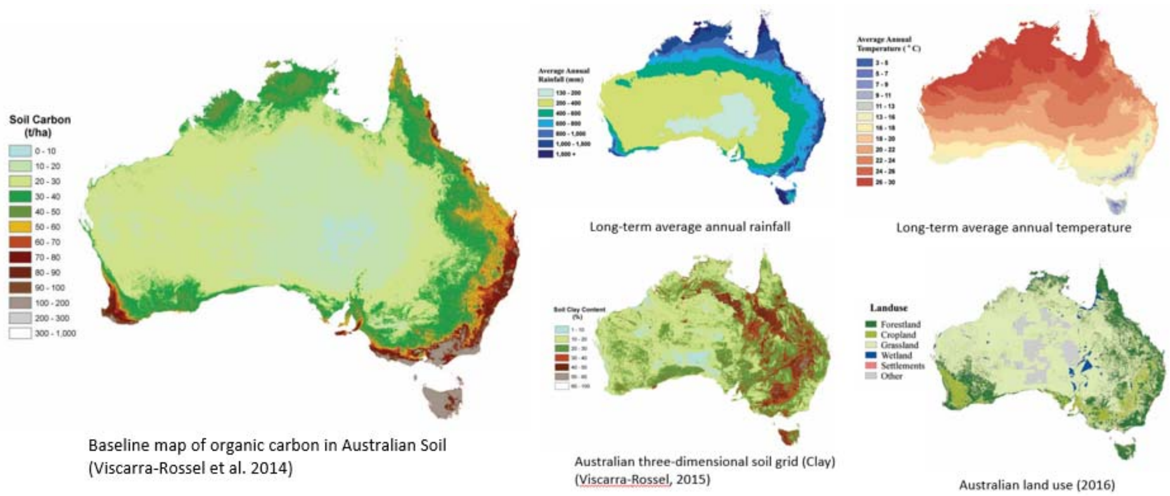
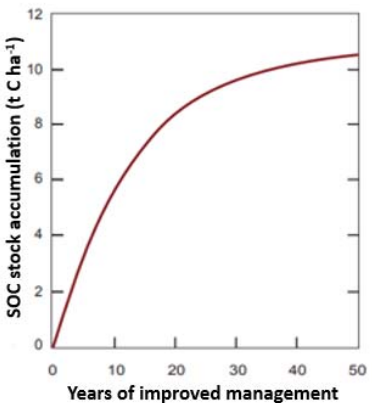


Figure 2. Soil C surface (t C ha^{-1} to a depth of 30 cm) estimate for Australia (left) is used as baseline inputs for the RothC model within FullCAM to report SOC stock change in managed lands for Australia's national GHG inventory. The four smaller maps illustrate key drivers of differences in SOC stocks: Average annual rainfall and temperature (top) which influence soil moisture and NPP, and soil clay content and land use (bottom). (Source: DISER 2021).

2. Management strategies to sequester soil carbon in grazing lands

2.1 Introduction

Under a natural undisturbed ecosystem, SOC achieves a long-term steady-state at a level determined largely by location-specific climate and soil characteristics. Grazing lands under long-term conservative management also tend to maintain an equilibrium SOC level, which may be similar to that in equivalent non-managed systems (Guo and Gifford 2002). Change in land management usually results in net loss or gain in SOC stocks relative to this steady-state baseline. The initial change can be rapid due to ready turnover of labile POC (Chan et al. 2001) but slows towards a new equilibrium level determined by the balance of SOM inputs and losses under the new management. Figure 3 illustrates this pattern of change following implementation of an improved management activity. The rate of increase in SOC stocks is relatively high over the first 5 to 10 years and then slows and approaches zero over an extended period which can typically be around 20 – 40 years but is sometimes longer. The decline in SCS over time reflects local climate and other productivity factors and also the finite capacity of soil to store C in stable forms, which is determined by properties such as clay content (Sanderman et al. 2010). In reality, the change is not smooth as shown in Figure 3 but fluctuates on shorter timescales with variations such as the quality of seasons for plant growth. For example, higher SOM inputs occur in good seasons than during drought, noting there may also be variations in management such as stocking strategy/herbivory or pasture improvement strategies. Loss of SOC stocks commonly occurs at a greater rate than restoration of C with a return to positive net inputs further complicating interpretation of SOC data at any time. These dynamics can contribute to the inconsistencies often seen in monitoring data and conclusions drawn from field trials comparing management strategies. Some studies provided too little detail relevant to the SOC changes being reported. Information such as the timing and depth of soil sampling, local seasonal conditions, clarity on baseline and changed management practice is needed to explore possible reasons for inconsistencies between studies and provide reliable predictions of regional SCS potential.



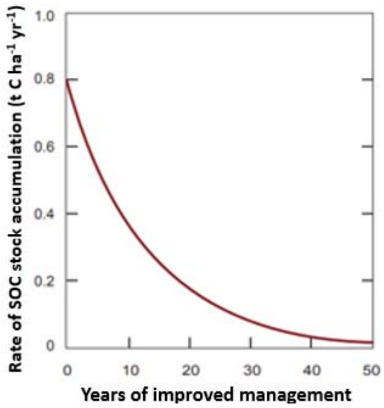


Figure 3. Illustration of the pattern of increase in SOC stocks (LH graph) and SCS (RH graph) following implementation of improved management in a landscape with baseline SOC well-below natural steady state.

Understanding reported observations of SOC stock change in response to management is also confounded by differences in sampling and analysis or other monitoring methods. A full review of SOC quantification protocols is beyond the scope of this report, but an overview is given to help explain variations in data quality and the approach taken as part of the data analysis to determine which studies could contribute sufficiently reliable evidence of management impacts on SCS. Section 4 expands on the discussion of measurement in the context of requirements and challenges for reporting SOC stock change in a grazing land project under the 2021 ERF soil C method.

Agronomic studies have traditionally estimated SOM or soil C content (%C) in the surface soil, i.e., to a depth of 5 or 10 cm, to provide guidance for improving yields. The 0 – 10 cm soil layer is where recent POC is highest and where much of the rapid cycling of the labile fraction occurs, providing nutrients for plant growth, energy for microbial processes and other physical, chemical and biological benefits for soil quality, structure and function. Decomposition of SOM in this layer returns CO_2 to the atmosphere (Figure 1). Estimates of %C in surface soil provides valuable information for on-farm decisions. However, on its own C concentration it is not sufficient to quantify sequestration which requires a calculation of mass accumulation. The change in soil C stocks can only be estimated accurately based on a statistically valid sampling protocol and repeat measurements over time of the mass of C in a known mass of soil. The minimum depth of sampling for quantifying SCS is globally accepted under UNFCCC reporting to be 30 cm and many soil scientist advocate for a depth of at least a metre (Paustian et al. 2019). SOC stock change in an equivalent soil mass requires measurement of both %C in a known volume of soil and soil bulk density (BD) to account for changes in compaction and, from repeat sampling, SCS is calculated (typically in units of t C ha^{-1} yr^{-1}).

Sampling protocol and monitoring period may contribute to inconsistencies between findings of studies on the impacts on SCS of management practices in agricultural lands. Sampling to a depth of 30 cm or more helps to ensure that more stable SOC fractions are included in the sample (Figure 1) and reduces the risk of interpreting a change in distribution of C in the soil profile as a change in the amount of C stored. Distribution is influenced by, amongst other factors, plant rooting distribution which can be changes by management strategies such as conversion of woodlands to pasture. Measurement of SCS can require detection of a small annual increase or decrease in total SOC stocks, such as a change of 1% or less, against a background of natural spatial and temporal variability. Measurement intervals of at least 5 years are suggested by many soil scientists (See reviews by Paustian et al 2019, Smith et al. 2020) to enable statistically significant cumulative SOC stock changes with affordable and practical sampling densities. Careful interpretation is needed to distinguish genuine SCS from fluctuations driven by natural climate and edaphic variability. Many early reports of SOC stock increases under conservation agriculture practices such as no-till farming are now considered to be overestimates because of errors introduced by inappropriate and short interval soil sampling protocols (Powlson et al. 2016).

In northern Australian which has one of the most variable climates in the world, the effects of seasonal rainfall or, more precisely, soil moisture available for plant growth, tend to dominate the variation in SOC stocks in grazed savannas and rangelands over decadal and shorter time periods (Allen et al. 2013, Badgery et al. 2020). This variability and the short duration (years to decadal) of many past studies confound assessment of potential SCS in northern grazing systems. Nevertheless, there is some credible regionally relevant evidence from measurement and field trial data that, within the constraints of climate and soil factors, SOC stocks may be increased through improved grazing land management practices.

As reported by others (e.g., Sanderman et al. 2010, Sanderman and Baldock 2010, Badgery et al. 2020) confidence in SCS assessment is constrained by the limited number of studies, and notably in extensive grazing lands. This review collated evidence from peer-reviewed papers and publicly available reports against criteria for the reliability of SOC stock change data from measurement and modelling studies (Table 1). Studies in sites used predominantly for extensive beef cattle, sheep and goat production were targeted. Greater weight was given to results for Queensland and Northern Territory grazing lands and to studies with clear supporting information on site description, local conditions, management systems and grazing strategies. Availability of data on baseline SOC level, period since practice implementation and soil sampling protocols and/or model parameterization was also given priority. Secondarily, credible studies from other regions containing information and data on management strategies and land types of relevance to northern Australian grazing systems were also evaluated.

Table 1. Measurement and monitoring issues that contribute to evaluating the credibility of reported data and the quality of assessments of the impacts of management strategies on soil carbon sequestration in northern Australian extensive grazing lands.

Criterion	**Requirement**	**Issues for N Australian grazing lands**
SOC stock change	Measuring SOC stock requires removal of inorganic carbon, gravel, SOM >2mm and BD measured on a standard volume of soil. Stock change requires repeat measurements.	Accurate measurement (sampling and analysis) per sample is costly. Large areas and high variability increase the number of samples required, often making statistically valid monitoring and verification unviable.
Sampling Depth	Sampling to ≥ 30 cm allowing SOC stock calculation on an Equivalent Soil Mass (ESM) basis.	Access and deep sampling in grazed woodlands/ savannas can be difficult and seasonally restricted (e.g., due to flood, fire). Published data for surface soil (0 - ≤10 cm) is not comparable with SCS data.
Permanence	SOC can be lost in poor seasons, fire, or with domestic/feral/native grazing; Permanence requires maintenance of practices for SCS [ideally for > 25 years].	Maintaining increased SOC stocks in low-input grazing lands can be impossible (e.g., in droughts when TGP can't be controlled); loss often more rapid than; permanence (25 or 100 yr) seen as a risk for business and ERF participation.
Monitoring period	Repeat measurement (e.g., 5 yearly) for at least 25 years.	Slow and variable changes)e.g., due to climate variable) are difficult to detect and interpret.
Spatial variability	Stratified random sampling or spatial estimates (using proximal or remote sensing) can reduce variance.	Differences in vegetation (trees/tussocks), topography, soil type) occur on various spatial scales and affect impacts of grazing and pasture management.
GHG emissions	C credits are net of SCS and GHG emissions due to new management activities (e.g. N_2O (sown legumes); enteric CH_4 (change in stocking rate or feed quality).	Legumes (e.g., Leucaena, Desmanthus) may increase N_2O emissions; adding stock (if better forage), increases CH_4 offsetting SOC removals; higher feed quality may reduce daily CH_4 emissions or life-time emissions.
Management history	Past management affects baseline SOC stocks and trajectory; can affect response to management.	Legacy of past management on SOM level and land condition affects response to new practices; SOC deficit affects SCS potential.
Baseline measurement	C credits may require 5 or more years management data for baseline (pre-practice change)	Record-keeping may not be available or specific for the period or location in large grazing properties where stocking varies with conditions, markets, ownership.
Modelling	Process models used to predict SCS should be fit-for-purpose (i.e., peer-reviewed and local/site parameterization). Site-specific measurements needed for calibration, validation are costly in extensive grazing lands.	Models (e.g., RothC, Century) provide credible modelling of SOC in northern grazing lands with location-specific calibration and validation data; measurements show dynamics not well-simulated in regions that are arid or have variable climate.

2.2 Factors affecting soil carbon storage in grazing land

A synthesis of global data from hundreds of grassland studies indicated that improved management (grazing strategies, fertilisation, sowing legumes, more productive grass species, irrigation, conversion from cultivation) commonly increased SOC stocks (Conant et al. 2017). The studies reported rates of SCS ranging from 0.1 to >1 t C ha^{-1} yr^{-1} with soil properties, topography, climate and past management appearing to be major determinants. Conant et al. found no significant change in SOC stocks following conversion from native vegetation to grassland, consistent with results from a meta-analysis published earlier by Guo and Gifford (2002). The large extent of land used for grazing (26% of the ice-free land surface, FAO 2012) means grazing lands have the potential to be a substantial biological C sink even at low rates of SCS per hectare (Powlson et al. 2011). Grazing lands can also be a substantial source of CO_2 emissions, with research showing long-term, high intensity grazing can result in net loss of SOC (Janzen 2006, Powlson et al. 2011).

Organic matter levels in many Australian soils are low compared to global averages and the SOC content is commonly between 1% and 5% by mass. Arid or semi-arid rangelands fall towards the lower end of this range, some having <1% SOC (Figure2) or SOC stocks to 30 cm depth of 20 – 40 t C ha^{-1} (Viscarra Rossel et al. 2014). A comprehensive review of Australian field studies by Sanderman et al. (2010) examined the impacts of improved management in grazing lands through adoption of practices such as fertilisation, liming, irrigation, or more productive grass species. The authors concluded that SCS rates of 0.1 to 0.3 t C ha^{-1} y^{-1} in the top 30cm of soil were possible (with low to medium confidence). SCS rates may be higher (possibly 0.3 to 0.6 t C ha^{-1} y^{-1}), when land is converted from cultivation to permanent pasture. Results averaged across improved and natural grasslands tend to mask the extent of regional differences. Most data available for this review were from the temperate, wetter regions of southern Australia while representation of northern and more arid regions in the data was relatively poor (Sanderman et al. 2010). SCS rates reported from different studies may be affected by a wide range of variables, including the quality of measurements, time since management change, legacy effects from previous management (i.e., baseline SOC) and complex poorly understood interactions between these and other factors (Sanderman et al. 2015, Waters et al. 2017, McKenna et al. 2022). Several studies have shown that climate and soil properties are the primary determinants of C stocks in agricultural soils, often responsible for 80% or more of the variation in SOC between sites (Rabbi et al. 2015, Badgery et al. 2021, Allen et al. 2013). Rabbi et al. (2015) found that moisture availability (or its converse, aridity) was a major influence on both total C content of soil and its stability, which is not surprising given its importance for NPP. By comparison the impacts of management were small (Figure 4). However, within the constraints of climate and soil influences, there is evidence that management practices can affect SOC.

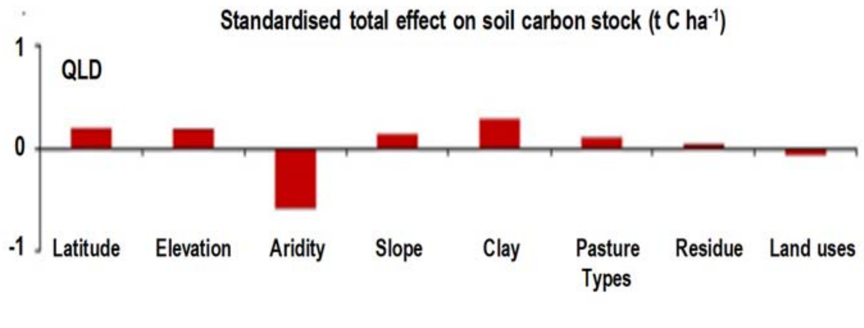


Figure 4. Standardised total effect (direct plus indirect) of variables (aridity, clay percentage, latitude, topography (i.e., slope and elevation), land use and management) on C stock in the top 0-30 cm soil. Data are for Queensland agricultural lands (Source: Rabbi et al. 2015).

2.3 Management effects on soil carbon stocks

The most reliable evidence on the extent to which various management strategies affect SCS comes from long-term paired site comparisons within the same location where differences in climate and soil properties are minimized. Across different locations, management impacts can be determined when data are detrended for the effects of non-management factors. As noted above (Figure 4), multiple studies have shown that the influence of management on sequestration is relatively small and often difficult to detect (Sanderman et al. 2010, Paustian et al. 2019). The effects of management strategies on SOC stocks must translate to an increase in the stable (MAOC) fraction if storage is to persist. While management can shift the balance of organic C inputs and mineralisation loss as CO_2 towards a net increase in SOC stocks, long-term sequestration is difficult to achieve in northern grazing lands. Generally low NPP and large inter-annual fluctuations in rainfall (McKeon et al. 2004, Liu et al. 2017) make this a challenging environment for consistent implementation of management practices that are effective in increasing (or even maintaining) SOC stocks (Janzen et al. 2022).

A number of strategies have been proposed for increasing SOC in extensive grazing systems but confidence in achievable SCS is limited by the low number of long-term studies in northern Australian with reliable measurements or validated modelling data. Relevant strategies are discussed below and the evidence for their effectiveness is evaluated.

2.3.1 Livestock management strategies

Rates of both organic matter input and loss from soils are affected by grazing via a range of mechanisms, including:

- Herbivory removes plant biomass that may otherwise be incorporated in soil;
- Trampling by stock affects litter breakdown and soil compaction;
- Dung and urine add organic C and/or nutrients;
- Overgrazing can expose soil to accelerated respiratory loss and increase risk of erosion.

Globally the effect of different grazing strategies on soil C across a range of livestock production systems are contested (Reeder and Schuman 2002, Piñeiro et al. 2010, McSherry and Ritchie 2013). One large global meta-analysis found that when SOC was normalised to a consistent soil depth, grazing had a negative effect on organic C stocks across all 83 studies considered. However, in dry environments there was an increase of 5.8 to 16.1%, and this was highest in grasslands dominated by C4 species which include many of the tropical grasses (Abdalla *et al.* 2018). In field trials, non-management influences dominate and also interact with management factors in complex ways to make the detection and attribution of any impacts on SOC content difficult. These challenges and characteristic variability contribute to a lack of consistency and clarity in reported impacts of livestock management strategies and have led to conflicting recommendations and ongoing debate on the potential for SCS.

As in global research, results from Australian studies comparing different grazing strategies have been inconsistent, variously finding a small decrease (Allen et al. 2013, Hawkins 2017), no or non-significant effect (Sanjari et al. 2008, Allen et al. 2013, Pringle et al. 2014, Pringle et al. 2016, Sanderman et al. 2015, Rabbi et al 2015, Raeisi and Raihi 2014) or an increase in soil C (Orgill et al. 2017b, Waters et al. 2017). Strategies can be broadly classed as: (1) changing grazing pressure based on either set or variable stocking rates or removing all livestock; and (2) adopting rotational or time-controlled grazing (sometimes termed holistic or cell-grazing). Differences in terminology (Box 1) and/or poorly described and monitored practices have also likely played a part in differences in data and their interpretation. Waters et al. (2019) reviewed research across Australia's 'southern' rangelands in which they included south-west and central-west Queensland rangelands, to evaluate SOC stocks as an indicator of sustainable land management. These authors concluded that without more clarity on the definitions and measurement protocols used to generate data, it was not possible to understand whether differences in total grazing pressure (TGP) management, SOC stocks, and sustainability of the systems were causally linked. Similarly, a review of data from northern Australian studies found that stored SOC (to a depth of 30 cm) appeared to be influenced by various combinations of grazing intensity, land condition and land/soil type, and that it was difficult to establish evidence for a strong link between livestock management and SOC content (Bray et al. 2010, Bray et al. 2016). This conclusion is consistent with findings from rangeland studies in other countries on the importance of the influence of complex interactions between drivers of SCS (McKenna et al. 2022). Because there are few quantitative data from trials linking livestock grazing strategies and SOC stocks in northern Australian grazing lands, this review draws on relevant data for New South Wales rangelands (*See details of studies in Table A1, Appendix A*).

Box 1: Terms used in livestock grazing strategies

The following definitions of livestock management strategies are adapted from material from Allen et al. (2013) and Business Queensland *Grazing and stocking strategies to improve production* (https://www.business.qld.gov.au/industries/farms-fishing-forestry/agriculture/grazing-pasture/improved-production/stocking-strategies).

Continuous stocking: Pastures are never or rarely spelled with grazing over most of the year; this strategy is generally used on extensive areas of land.

Rotational grazing: Stock are moved between paddocks so that a period of grazing is followed by a period of resting ('spelling') a paddock. The spelling period depends on the condition and growth of pasture and predicted growing season rainfall.

Cell or time-controlled grazing: Many small paddocks are heavily stocked for short periods, followed by a long spelling period. These forms of intensive rotational grazing are management-intensive, requiring more fencing and watering points.

Destocking: Removal of livestock grazing from a paddock (with grazing by native or feral animals still possible).

Exclosures: Exclusion of herbivores and the absence of grazing livestock.

Grazing pressure studies

Grazing pressure in grasslands and grazed woodlands interacts with soil properties and climate to moderate the amount of plant residues and total organic matter input to soil and the rate of loss with trampling and soil disturbance being significant factors. The long-term Wambiana beef cattle grazing trial in north-east Queensland has monitored the impacts of beef cattle stocking rate on land condition across different soil types since 1997. Measurements over 12 years found that SOC stocks (0 – 30 cm) under heavy stocking was, on average, 1.05 t C ha^{-1} lower than in moderately stocked land, which contained 20.3 t C ha^{-1} (Bray et al. 2014). However, results varied across the three land types identified in the Wambiana trial. The *box woodlands* land type had higher SOC in the treatment with heavy stocking (Pringle et al. 2011), noting that data given by these authors were for 0 – 10 cm only and indicative only of change in SOC stocks. Using carbon isotope analysis to distinguish organic C inputs from trees and shrubs (C3 photosynthetic pathway) from perennial tropical grasses (C4 photosynthesis), Pringle et al. hypothesised that higher surface SOC stocks in the high stocking treatment were likely due to relatively higher organic matter input from tree and shrub litter which accumulated due to reduced competition as preferential consumption by cattle depleted more palatable grasses. This difference in SOC seen at 0 – 10 cm was not measured at greater depth indicating that the increase at higher stocking rate was most likely due to inputs of recent C3 derived POM. It may, therefore, not translate to increase in the more stable MAOC fraction which normally occurs deeper in the soil profile and is indicative of persistence and sequestration. The apparent interaction between SOC, grazing intensity and vegetation communities observed at Wambiana can only be quantified in long-term data across variable seasons, highlighting the importance of this multi-decadal trial with treatments across different land types.

The challenge of measuring and interpreting the impact of grazing pressure on SCS is also seen in results from a long-term (26 year) trial at Toorak in the Mitchell Grass Downs region of western Queensland (Pringle et al. 2014). In this trial with sheep, pasture utilisation was used as an indicator of grazing pressure and measurements were taken of total organic C and total soil N to a depth of 50 cm. These data showed that when the rate of pasture utilisation was varied from 0% (Exclosure) up to 80% there was no detectable relationship between grazing pressure and total SOC stocks, the soil POC fraction or the C:N ratio. There was, however, a non-significant correspondence between higher grazing pressure and lower SOC and POC stocks and an increased C:N ratio. Not unexpectedly, above-ground biomass measurements indicated that the decrease in POC at higher grazing pressure was consistent with reduced SOM inputs resulting from high consumption rates. Aboveground biomass varied with rainfall, but a marked decline was observed when pasture utilisation rates exceeded 50%, and the authors suggest this was indicative of a decline in the proportion of deep-rooted perennial Mitchell grass at utilisation rates above 50%. A similar mechanism was proposed by Waters et al. (2015) for the relationship found between ground cover and SOC in sites in central and western NSW and by Chen et al. (2015) in grasslands in China.

The importance of the interaction of climate variables and grazing intensity has been reported in two studies in NSW in areas that had contrasting climate and productivity. The first was a paired site study in the moist, cool, fertile environment of the New England Tablelands (Young et al. 2016) which compared conservative and more intensive management over more than 20 years. In the higher intensity production system, stocking and fertilisation were maintained at twice the rates as in the lower intensity system, with stocking rate carefully matched to pasture production. Comparison of the two systems did not reveal a measurable difference in SOC stocks at either 0 – 30 cm or 0 – 50 cm depths. This was in spite of significantly higher NPP in the more intensively managed system. The second NSW study illustrates the complexity in trying to interpret studies with complex management differences and limitations in measurement data (Waters et al. 2017). The eight-year study in the semi-arid regions of the Darling Riverine Plains and Cobar Pedeplain compared effects on soil C content of managing grazing intensity by using rotational grazing (with long periods of rest) combined with the use of exclusion fencing to reduce total grazing pressure (TGP). The reported impacts cannot be interpreted in terms of SCS because soil was sampled to a depth of just 20 cm and analysed only for %C. Without corresponding BD data SOC stock change could not be calculated on an equivalent soil mass basis. The multiple variables make interpretation complex, but the study appears to show a land type effect similar to that noted in the Wambiana grazing trial discussed above (Pringle et al. 2011). Waters et al. (2017) observed that the lower TGP treatment showed a positive effect on SOC on red Lixisol soils, but the effectiveness varied with soil type and also depended on the vegetation community. Effects of grazing intensity management on SOC concentration appeared to be mediated by ground cover via increased SOM inputs and/or reduced loss through erosion, and the study indicated that in semi-arid rangelands avoiding high TGP may help lower the risk of soil C losses associated with low groundcover. The dependency of the results reported by Waters et al. on use of exclusion fencing mean that it was not possible to draw conclusion from this study on the impacts of using rotational grazing to manage grazing intensity. Rotational grazing strategies are discussed in more detail below.

In summary, while conservative management of grazing pressure and avoiding over-grazing are well-established good practice for sustainable production and ecosystem health (Holt 1997), the available evidence from studies in northern Australia do not provide strong evidence that grazing pressure management alone will also increase C sequestration in soil. This conclusion is consistent with a number of international reviews, including a recent analysis by McKenna et al (2022) that found no apparent influence at a landscape scale of livestock grazing on soil C levels (organic and inorganic forms) in semi-arid rangelands of the United States. Rather, as also concluded in this review of Australian data, they found data indicated that soil C storage is controlled by complex interactions among many factors, and it is difficult to isolate impacts of livestock grazing pressure.

Rotational grazing studies

The term 'rotational grazing' is used here as a general term to cover several variations on an approach to livestock management whereby a property is fenced into multiple paddocks and short-term higher intensity grazing of pasture is followed by longer periods of rest. Included under this heading of rotational grazing are the more intensive 'cell grazing' and 'time-control grazing' strategies that involve division into more and smaller paddocks or 'cells' (see Box 1).

In recent times, rotational grazing has become a practice associated with regenerative agriculture for the grazing sector. Advocates of the practice have sought to promote it as a strategy to improve the sustainability of grass-based pasture systems, a movement that has now been growing steadily over several decades. According to disturbance ecology theory, relative to traditional (continuous) grazing, rotational grazing can increase pasture productivity by allowing vegetation to recover after short, intense grazing periods. The increased pasture biomass during rest, and theories on the value of plant litter and residues being trampled into the soil surface by animals, have led to support for adoption of rotational grazing to increase SOC storage in grassland soils. There has been intense enthusiasm from some proponents, but the claims of significant rates of SCS plus substantial production benefits remain largely anecdotal or documented only in non-peer reviewed reports. A summary of recent internationally published reviews of these claims is presented below followed by an evaluation of any evidence for a relationship between rotational grazing strategies and SCS from peer-reviewed papers and technical reports relevant to northern Australia.

There is an overall lack of consistency in published literature on the benefits of various rotational grazing strategies for SCS and productivity (Briske et al. 2008, Briske et al. 2011, Carter et al. 2014). A global review by Hawkins (2017) using quantitative meta-analysis models to examine literature from 1972 to 2016 evaluated claims that Holistic Management (HM) (also referred to as the 'Savory method') increases production of plants and animals while also increasing SOC under all conditions in all habitats. HM is a form of intensive rotational grazing that applies adaptive (as opposed to prescriptive) management as a basis for decision-making. Hawkins (2017) concluded from the literature review that there was no difference between conventional and HM treatments in plant basal cover, plant biomass and animal weight gain responses and evidence for any increase in SCS was disputed. In a second review (Hawkins et al. 2022), seven peer-reviewed studies were reported to show that a potential for increased SCS with changed grazing management does exist but is substantially less (0.13 – 0.32 t C ha^{-1} yr^{-1}) than the 2.5 – 9 t C ha^{-1} yr^{-1} estimated by the non-peer-reviewed HM literature. Further, the meta-analysis illustrated a significant between-study heterogeneity. Positive effects tended to be associated with higher precipitation, suggesting that more arid rangelands, especially with high interannual rainfall variability, would be unlikely to benefit significantly from adoption of HM. In these environments, particularly, this questionable value raises doubt about whether the additional infrastructure costs and labour needed to practice HM could be justified.

Several Australian papers have assessed the links between rotational grazing, increased productivity, and SOC and examples are discussed below for NSW rangelands (Cowie et al. 2013, Orgill et al. 2017a), Northern Territory (Schatz et al. 2020), and Queensland grazing lands (Allen et al. 2013, Sanjari et al. 2008, Sanjari et al. 2016). In northern New South Wales, Cowie et al. (2013) found some evidence for increased SCS under rotational compared with continuous grazing, but the differences were not statistically significant. Also for NSW, Waters et al. (2017) and Orgill et al. (2017a) found that, in most sites studied, SCS was not higher under rotational grazing, even when practiced in combination with exclusion fencing to control TGP (Waters et al. 2017, see discussion above). The one exception was for ridge sites where continuously grazed and fenced sites had lower SOC stocks (0 – 30 cm depth) than rotationally grazed ridge sites with 13.3 and 21.6 t C ha^{-1}, respectively. The non-representative land type (grazed ridges) and number of uncontrolled variables in this study makes it impossible to infer from the results an impact of rotational grazing alone on SCS in NSW rangeland systems or other locations.

In a more comprehensive study in the Northern Territory, Schatz et al. (2020) compared liveweight gain and SCS when Brahman and Brahman-cross cattle grazed buffel grass (*Cenchrus ciliaris* L.) under either continuous grazing or intensive rotational grazing (IRG). They found that cattle growth rate, expressed per head or per hectare, was lower under IRG than continuous grazing, and that IRG did not result in any increase in SOC over the 5-year study period. The monitoring period for this study was too short to draw conclusions about SCS. However, the authors propose that the lower production with IRG management and the extra infrastructure and operating costs in the IRG system were barriers to adoption of this strategy in cattle-grazing operations on similar pasture systems across northern Australia. They further suggest based on the results that prospects for overcoming the IRG profitability gap through income from carbon credits were not favourable.

In a survey of 98 sites from 18 properties across Queensland, Allen et al. (2013) assessed the relationship between stocking rate and climate-detrended SOC stocks for four grazing management classes, categorized as Continuous, Rotational, Cell, and Exclosure according to the definitions in Box 1. In total, 23 explanatory variables were examined in evaluating variations in SOC stocks across sites. Overall, the influence of livestock management on SOC was unclear. Cell grazing was weakly associated with lower SOC stocks (0 – 30 cm) than Rotational, Continuous grazing and Exclosure strategies, which were not significantly different. Allen et al. (2013) found the strongest associations with climate variables, with temperature and vapour pressure deficit (VPD) explaining more than 80% of the variation in SOC stocks across the sites. Annual rainfall was also important but apparently less influential and the authors suggested that a measure of 'effective' rainfall may have had a stronger explanatory power. Once detrended for climate, total standing dry matter, soil type and dominant grass species were the next strongest influences. Allen et al. (2013) analysed SOC stocks separately in the 0 – 10 cm and 0 – 30 cm layers providing some insight into C storage and dynamics in response to the grazing strategies, highlighting the importance of considering measurement methods in planning field trials and in interpreting results. The observed trend for lower SOC with cell-grazing was seen only for analysis in 0 – 30 cm and not the 0 – 10 cm layer, implying that the surface POC fraction may be more strongly dependent on non-management factors, and this aligns with understanding of climate effects on NPP and SOM inputs and of the importance of SOC dynamics in determining SCS. It also emphasises that surface sampling cannot be relied on in assessing whether grazing management affects SCS.

In south-east Queensland, a field study (Sanjari et al. 2008) comparing the impacts on SOC of continuous and time-controlled (TC) sheep grazing strategies reported a positive, though non-significant, effect of TC compared with continuous grazing. The results appeared to show increased SOC and N in areas with favourable soil conditions compared with continuous grazing, but Sanjari et al. sampled to a depth of only 10cm. Monitoring was conducted over only 5 years so differences observed were more likely to be in the labile POC fraction than in more stable C fractions important in SCS. It is difficult to compare these TC grazing results directly with the cell grazing data of Allen et al. (2013) due to differences in measurement protocols. Neither the negative trend of SOC with cell grazing (Allen et al. 2013) nor the positive trend for TC grazing (Sanjari et al. 2008) was significantly different to the rate of SCS measured in continuous grazing 'control' treatments, and results highlight then need for more long-term studies to understand impacts on SCS.

Grazing animal species impacts

There is little published information on the interaction between grazing systems, livestock species and other factors influencing SCS. Waters et al. (2019) speculated that differences in findings on grazing intensity, floristic diversity and SCS between grazing system studies may, in part, relate to the history of grazing (including animal type) and productivity of the environment in which they have occurred. Grazing by different ruminant species (cattle, sheep or goat) may have an impact through plant diversity changes (Olff and Ritchie 1998). Toth *et al.* (2018) reported that sheep had a greater negative effect than cattle on plant taxonomic and functional diversity, while macropods appeared to have little effect (Eldridge et al. 2016). Grazing patterns also differ between species with sheep, cattle, and kangaroos able to travel 3, 6 and 8 km, respectively, from water (Fensham and Fairfax 2008).

In summary, while there may be some impact of grazing animal species on SOC stocks, differences in impact of livestock production systems and SCS rates are likely to relate more to grazing pressure than to grazing species *per se* (Figure 5).

Figure 5. Illustration of use of exclusion fencing to maintain land managed for goat production in good condition (on the right). There is a lack of data to assess the impacts on SOC of grazing by different species Image: Sheep Central 4 May 2022, under Creative Commons licence).

Summary of Livestock Management Strategies

The preliminary indication from this review is that the potential for increasing SCS from improved grazing strategies in northern Australia is constrained by climate and soil factors and the limits on what practices are feasible in extensive, low-input systems. Maintaining the sequestered C for 25 or 100 years to meet ERF permanency requirements is a particular challenge where climate variability is extreme. Therefore, while *"Altering the stocking rate, duration, or intensity of grazing to promote soil vegetation cover and/or improve soil health"* is an eligible activity under the 2021 soil C method (Australian Government 2021), based on the evidence available, prospects for livestock producers in

Australia's north receiving substantial ACCUs do not look promising. The low number of high-quality studies with reliable data in northern Australia and their limited coverage across the range of landscape, vegetation and soil types, and livestock management systems means that conclusions on the potential for SCS has low confidence. There is insufficient information to enable weighting of the results from individual trials to calculate a meaningful average for different grazing strategies. Indicative values are given in Table 2 as simple means from the literature, and review findings are summarised below.

Table 2. Summary data from published studies providing indicative estimates of the impacts of grazing management strategies on SCS. NE = Not estimable; H,M,L = High, Medium, Low confidence. See Appendix A, Table A1 for more detail on individual studies.

Grazing strategy	SCS average (Range) t C ha^{-1} yr^{-1}	Average C stock t C ha^{-1}	Period of observation Years	Confidence (H,M,L)	Number of studies (sites)
Grazing intensity	-0.02 (-0.087 – 0)	NE (20—103)	12-26	L	3
Destocking/exclosure	0.04 (0 — 0.08)	23.7 (16.6 — 32.5)	12 —57	L	3
Rotational strategies vs continuous grazing	0 (-0.01 – 0)	NE (13 — 48)	5 —15	M	6

- ***Grazing intensity*** showed no clear relationship with long-term SOC stocks in northern Australia grazing lands. High grazing intensity tends to be associated with lower SOC stocks in Australia and this is consistent with global grassland studies. This decline in SOC may be the result of lower organic matter inputs due to higher herbivory and/or greater loss due to soil exposure and disturbance at high stocking rates. Outcomes are likely to vary between locations with different vegetation and soil conditions (Pringle et al. 2011) or with different landscape characteristics such as slope (Orgill et al. 2017a).
- ***Destocking or exclosure*** studies showed impacts on SOC stocks that ranged from no significant change to a small increase, with a small average sequestration rate across the three studies with reliable measurements of 0.04 t C ha^{-1} yr^{-1}. Destocking is unlikely to be widely adopted across productive grazing lands for economic reasons, but limited opportunities may exist to destock parts of a property that are less productive or are degraded to restore soil health and ecosystem services such as biodiversity. While there may be a small increase in SCS by removing grazing, destocking of land used for grazing is not eligible to earn carbon credits under the ERF 2021 soil carbon method.
- ***Rotational grazing strategies*** have predominantly been reported in peer-reviewed technical publications to have no significant effect on SCS, and anecdotal reports of large positive impacts on SOC levels have failed to be substantiated by reliable measurements. Studies in northern Australia are limited and interpretation of some are confounded by having other management differences that interact with the rotational grazing strategy to influence SCS. Evaluation of possible reasons for inconsistencies between the small number of studies was inconclusive but results were broadly consistent with recently published global reviews showing that, relative to traditional/continuous grazing, implementing some form of rotational multi-paddock grazing did not have a significant impact on SOC stocks. The preliminary conclusion that rotational grazing strategies (including more intensive cell and time-controlled grazing) is unlikely to significantly increase SCS has low confidence. There is also some evidence that pasture yields and livestock productivity are not substantially higher under long-term rotational than for continuous grazing.

- ***Livestock species*** comparison studies were very limited, and it was not possible to distinguish between animal type and total grazing pressure impacts on SOC stocks.

2.3.2 Pasture management strategies

To increase SCS, pasture management strategies need to reduce SOM loss resulting from pasture disturbance and degradation and/or increase SOM inputs through implementation of practices that enhance plant biomass production or increase the fraction of plant residues added to soil (Janzen et al. 2022). The potential for SCS also depends on the baseline SOC and its relationship to the long-term natural steady state level characteristic of the location, climate and soil properties (e.g., silt/clay content; See Section 1). A global data synthesis of grassland management effects on SOC storage published in 2001 (Conant *et al*. 2001) is frequently cited as evidence for the potential to increase SCS using forage management strategies. This analysis estimated a global mean of 0.54 t C ha^{-1} yr^{-1} in grasslands with a range of 0.11 – 3.04 t C ha^{-1} yr^{-1}. An updated dataset more recently confirmed these positive SCS findings (Conant et al. 2017), finding a similar but slightly narrower range of SCS, 0.105 – >1 t C ha^{-1} yr^{-1}. Much of the global data collated by Conant et al. for their 2001 and 2017 analyses came from temperate, higher rainfall regions and included examples of conversion from cultivation to grassland, a management activity widely recognised as favourable for SCS. In addition, the average value for sequestration in these meta-analyses was pushed up by a few unusually high examples, masking the fact that many studies had rates well below 1 t C ha^{-1} y^{-1}. Scaling up the global mean rate of SCS to large areas of the world's grasslands for soil management indicate a large C sink, but the challenges for increasing SOC stocks in managed soils and for maintaining existing stored SOC 'permanently' are being increasingly recognised (e.g., Henderson et al. 2022, Janzen et al. 2022).

In some Australian grasslands, selected management changes have produced results for SCS consistent with the global averages estimated by Conant et al. (2017). In the grazed pastures of the long-term MASTER crop-pasture rotation trial at Book Book in southern New South Wales, liming plus fertiliser application increased SOC stocks (0 – 30 cm depth) from 34.8 to 42.6 t C ha^{-1} over 13 years, giving a sequestration rate of 0.5 to 0.7 t C ha^{-1} yr^{-1} (Chan et al. 2011). However, most studies give markedly lower estimates (Sanderman et al. 2010). For the reasons discussed above, the global mean estimated by Conant et al. (2017) cannot be assumed to apply in northern Australia, where grazing systems are characterised by highly variable climate, nutrient-poor soils, and low-input livestock production. Pastures have a range of vegetation structures – woodlands, shrublands and native or naturalised grasslands – and livestock feed quantity and quality are seasonally variable (McKeon et al. 2004). In these conditions achieving a permanent SOC stock increase is challenging.

The pasture management strategies for which there was more published evidence are those also listed by the CER as eligible under the legislated ERF 2021 soil C (Australian Government 2021), "*Re-establishing or rejuvenating a pasture by seeding or pasture cropping*" and "*Using legume species in cropping or pasture systems*", and these are reviewed below.

Pasture improvement strategies

Review of the literature on improving forage growth and quality in northern Australia found several studies discussing the importance of SOM content and/or measured the C concentration in surface soil, but not reporting SOC stock change data measured according to requirements for quantifying SCS to the standard needed for soil carbon crediting. Although participation in the ERF to gain C credits remains low due to uncertainty about direct and indirect costs, effects on farm business and what longer-term obligations mean for business and succession planning. More high-quality measurement and monitoring are expected to become available for northern Australia in the future, but for this review data had to be taken from reports or papers on pasture improvement in other regions, notably the grazing lands in New South Wales (See Appendix A, Table A2). For pasture improvement practices such as sowing high producing grasses caution is needed when extending results to warmer, more arid extensive regions in the north.

The ERF 2021 soil C measurement method (Australian Government 2021) allows the use of models to report SCS to reduce the amount of in-field sampling and help manage MRV costs. Field sampling for model calibration and verification must be conducted in each carbon estimation area at project registration and at least every 10 years (CER 2021). Badgery et al. (2020) cautioned that current models do not fully represent the temporal dynamics of SOC in low rainfall environments, and the costs associated with field sampling for the baseline and to verify SOC stock change in extensive grazing lands would remain an impediment to producers' participation in the ERF (White et al. 2022). Noting the uncertainty in modelling at this time, data from one modelling study (Clewett 2015) is included for completeness. Simulations suggested that in the Condamine region of Queensland, introducing sown grasses to native pastures could be increase SCS (0 – 30 cm) at from 0 to 0.6 t C ha^{-1} yr^{-1} over a 30-year period. Field trials are needed to verify these model results under a range of baseline and climate conditions, but the high rates simulated for the first 10 years after sowing are not inconsistent with some measurements in soils with initially low SOC levels (Badgery et al. 2020; Figure 3).

Forage legume strategies

In northern Australian regions, planting forage legumes into native and naturalised grass pastures is an increasingly common practice adopted by cattle and sheep producers to improve feed quality and quantity. Incorporating legumes in pasture can help overcome seasonal feed gaps and improve digestibility with demonstrated value for increased daily weight gain (Shelton and Dalzell 2007, Harrison et al. 2015, Conrad et al 2017) and evidence of reduction in the methane (CH_4) emissions intensity of livestock products (Harrison et al. 2015, Suybeng et al. 2019, Tomkins et al. 2019). There are also claims that the capacity of deep-rooted legumes to access moisture and nutrients lower in the soil profile gives improved drought tolerance and a capacity to preserve productive longevity more than grasses alone (Suybeng et al 2019). More recently, studies have also investigated the potential for pasture legumes to increase SOC content. Planting legumes in pastures is an eligible activity in the 2021 ERF soil C method (Australian Government 2021, CER 2021), provided it meets the additionality requirement which states that the activity must be a 'new or materially different' practice in the project area (see discussion below). The ERF method potentially allows interested northern Australian producers to apply to register a project with the aim of planting legumes in additional areas of pasture to improve productivity and potentially earn ACCUs for increasing SOC stocks. If sold, income from ACCUs may help cover the initial costs of planting.

The available evidence for SCS from incorporating prospective forage legumes in northern grazing lands is discussed below, together with an overview of requirements, obligations, and possible costs and co-benefits for voluntary participation in ERF soil C projects.

Leucaena: Incorporating the shrub legume, Leucaena, in Queensland pastures has been shown to significantly increase productivity and resilience to drought (Shelton and Dalzell 2007). It is deep-rooted (2 to 6 m), which is generally associated with higher more root residues and exudates deep in the soil profile where it is more readily stabilised for long-term storage, favouring increased persistent SOC stocks. In response to the improved soil nutrient status that results from symbiotic N_2 fixation by legumes, overall forage biomass production is higher and an increase in litter and grass root residues have been observed in both surface and deeper soil. More long-term studies are needed to better understand the dynamics of SCS accumulation (Peters et al. 2013)., but there is now a growing evidence base for positive impacts of Leucaena on SOC stocks.

Using averaged values from measurements of SOC stock change at two sites in Queensland (Radrizzani et al. 2011, and Conrad 2014), Harrison et al. (2015) estimated that Leucaena plants, at around 10 years age, sequestered an additional 0.270 ± 0.120 t C ha^{-1} yr^{-1} compared to grass pastures. Conrad et al. (2017) reported a similar sequestration rate in areas with Leucaena of 0.280 t C ha^{-1} yr^{-1} in the top 30 cm, estimated to be equivalent to an increase of 17 – 30% over 40 years. These authors also examined N dynamics under Leucaena and concluded that the increase in SCS occurred primarily due to N accretion as symbiotic N_2 fixation alleviated the low N availability that is commonly a cause of reduced yields and low SOC storage in mature grass pastures. Total soil N stocks in sites with Leucaena were 32% higher in the 0–30 cm depth compared to paired grass sites, and this is equivalent to 0.036 t N ha^{-1} yr^{-1} over 40 years (Conrad et al. 2018, Kopittke et al. 2018, Tomkins et al. 2019).

Stylosanthes: Planting *Stylosanthes spp.* in pastures has been a widely established practice over several decades. By the year 2000, approximately 1 million hectares of native pastures in Queensland were estimated to have Stylo plantings, predominantly *S. scabra* and *S. hamata*, with positive impacts on beef production reported across northern Australia. Consistent with legume incorporation in grasslands more generally, *Stylosanthes* is expected to increase biomass production and improve digestibility of forage by alleviating N deficiencies and potentially increasing SCS (Crack 1972, Myers 1976). However, results from the few published studies on *Stylosanthes* have been inconsistent, showing either no effect (Myers 1976) or an increase (Rao et al. 1994) in SOC concentration. Several reports had measurements of soil C concentration but not BD so SOC stock change could not be calculated to inform estimates of SCS potential. Another barrier to participation in the ERF is the additionality requirement for projects in the2021 soil C method. To be eligible, a project activity must be implemented that is new or materially different from what being done before project registration. This may provide a challenge for producers hoping to earn C credits from planting Stylos , a common practice in northern pastures. What qualifies as a 'materially different' activity is yet to be fully tested, so it is not clear whether planting new areas or using newly developed species of *Stylosanthes* would be an eligible practice in areas where Stylos have been widely incorporated in pastures over several decades. According to some research, the long-term viability of *Stylosanthes* plantings as a management strategy for SCS may also be constrained by concerns about acidification and nutrient depletion of soils (Noble et al. 2000).

Lucerne: A 50-year modelling study using the GRASP pasture growth model for pastures sown with the perennial temperate legume, Lucerne, suggests there are long-term SCS benefits (Clewett 2015). The simulations indicated the mean SCS would be 0.6 t C ha^{-1} yr^{-1} higher on average for the first ten years under grass-legume sown pastures compared with sown grass alone. The rate of increase in SOC stocks declined after the first decade to 0.113 t C ha^{-1} yr^{-1}, and to 0.032 t C ha^{-1} yr^{-1} on average after 20 years. Model results for pasture yield were compared to field measurements at the site, but soil C stock increases did not appear to have been validated with any in-field sampling so should be considered indicative only. Lucerne is widely used in pastures and, as for *Stylosanthes,* meeting ERF method additionality requirements will be challenging in some locations.

Desmanthus: Interest in planting *Desmanthus spp*. has grown in recent years as research and industry stakeholders have observed promising production benefits particularly in the areas of undeveloped semi-arid clay soil across northern Australia. There is active research to determine its impact on SCS but no published results for *Desmanthus* pastures were found at this time. The SOC benefits following establishment are expected to be similar to those for other pasture legume species with deep-rooting and high growth rate qualities.

Tagasaste: Tagasaste is a deep-rooted perennial legume species that has received some attention for Western Australian grazing lands. A 22-year study found that planting at 15% of a grazing land area resulted in SCS of 0.9 t C ha^{-1} yr^{-1} when soil was sampled to 200 cm (Table A2; Wocheslander et al. 2016).

Potential GHG trade-offs in legume-grass pastures: Estimates of SCS and C credits in legume-grass pastures must also account for any additional emissions from pastures of nitrous oxide (N_2O), a GHG with almost 300 times the global warming potential (GWP_{100}) as CO_2 (CER 2021, Rumpel et al. 2022). These N_2O emissions offset some of the climate change mitigation benefits of SCS and decrease the number of ACCUs that are issued for an ERF project. There is little research quantifying N_2O emissions from legume-grass pastures in northern Australia, but the low nutrient status of soils is expected to result in the fixed-N being entirely or largely used in grass growth leaving little excess to be emitted as N_2O. In a modelling study, Harrison et al. (2015) estimated that soil N_2O emissions could increase by 38% under Leucaena-grass pastures compared to grass only, but this was from a very low baseline and represents a very small absolute GHG emission and minor offset of total SCS. A much larger impact on net emissions from the grazing system would arise if the stocking rate and/or livestock throughput were increased in response to higher feed availability due to legumes in the system. Enteric CH_4 from cattle commonly accounts for over 90% of beef grazing system emissions and an increase in stocking rate could more than offset mitigation from SCS. This potential for trade-offs between climate change mitigation and production benefits can become an important consideration for red meat producers interested in participating in C farming (Henry et al. 2022, Rumpel et al. 2022). A modelling study (Harrison et al. 2015) evaluated the economic feasibility of participating in the ERF to earn C credits and found that potential income from ACCUs associated with grazing Leucaena is likely to be only a small proportion of total farm income. The study also showed that income from ACCUs would be much smaller than the expected additional income from gains in productivity due to improved live weight gain on legume-grass pastures. The modelling also showed that where total farm GHG emissions were not increased, grazing Leucaena reduced the emissions intensity of beef produced. While not yet widely recognised in price premiums, low C products may provide a market advantage for producers in the future. In an alternative scenario, if animal numbers increase to take advantage of better feed following introduction of legumes, there is expected to be a corresponding increase in GHG emissions per hectare reflecting the dominance of enteric CH_4 in ruminant livestock emissions profiles (Tomkins et al. 2019). Thus, producers may be faced with challenging decisions on whether to forfeit the opportunity for higher income from production (more stock) in order to avoid breaking SOC project contractual arrangements and foregoing C credits. Future growth in the price received for offsets may alter such decisions.

Summary of pasture management strategies

The limited reliable measurement data on SOC stock change in pasture improvement sites in northern Australia results in low confidence in estimates of the potential for increasing SCS in grazing lands. Results of trials in more temperate regions demonstrating increased SCS under practices such as pasture fertilisation or sowing high producing grasses, cannot be simply extrapolated to northern Australian grazing systems that are often moisture limited and commonly have high climate variability and less fertile soils. However, stronger research on production and GHG emissions outcomes from planting forage legumes in northern grazing lands provides higher confidence in the positive estimates of SCS. Overall published measurement and modelling studies show good prospects for increasing SOC stocks by incorporating N-fixing legumes in tropical and sub-tropical grass pastures. They also indicate that participating in ERF projects to earn C offset income could be feasible for new legume plantings provided that they meet additionality requirements. Analysis of possible economic and marketing co-benefits and trade-offs showed that complex interacting factors relating to future price of ACCUs, personal grazing enterprise goals and future climate change impacts will continue to make decisions on voluntary participation in C crediting schemes complex for producers.

The available scientific evidence on the potential SCS in Australia's northern grazing systems using pasture management strategies is summarised in Table 3 and summarized below.

Table 3. Summary data from published studies providing quantified estimates of the impacts of pasture management strategies on SCS. NR = Not reported; NE = Not estimated due to insufficient data; H,M,L = High, Medium, Low. See Appendix A, Table A2 for details of individual studies.

Pasture strategy	SCS average (Range)	Average C stock	Period of observation	Confidence (H,M,L)	Number of studies (sites)
	$t\ C\ ha^{-1}\ yr^{-1}$	$t\ C\ ha^{-1}$	Years		
Pasture improvement	NE (northern pastures) 0.31 (0–0.6) (temperate)	NR	Various	L	5
Forage legumes	0.32 (0.27–0.45)	NR	20	M	5

- ***Pasture improvement practices*** that increase forage production and quality have potential to increase SCS in some temperate regions with an average rate of increase of 0.3 t C ha^{-1} yr^{-1}. The limited trials and measurements in tropical and sub-tropical rangelands and grazed woodlands mean that the prospects for SCS over much of northern Australia using pasture improvement practices that are practical and economically feasible could not be estimated.
- ***Incorporating legumes in pasture*** in the nutrient-poor, seasonally dry northern grasslands and savannas on average increased SCS at an average rate of 0.3 t C ha^{-1} yr^{-1}. The increase has been linked to symbiotic N_2 fixation and the deep-rooted properties of legumes. Based on limited observations, the rate of SCS was highest in the first decade after establishing legume-grass pastures. The rate then slowed and was assumed to be due to approaching a new equilibrium reflecting the enhanced soil N level achieved. Calculation of the net climate change benefits of adopting legume-grass pastures must subtract new emissions of GHGs, notably N_2O from soil and enteric CH_4 (if stocking is increased to take advantage of higher forage production). Modelling studies show that in northern Australian rangelands the productivity gains possible by incorporating legumes in pastures would lead to greater financial returns than projected income from C credits.

2.3.3 Fire management strategies in grazing lands

As well as being used to control the risk of harm from intense uncontrolled wildfire, fire has been used as a strategy to manage the composition and balance of forage and woody plants in extensive grazing lands and, according to some studies, provide benefits for pasture quality and soil nutrient status. Through direct effects on plant litter and impacts on cycling of other organic material, fire management changes SOM inputs and SOC levels (Cook 1994, Richards et al. 2012a, Richards et al. 2012b). This understanding has led to experiments to explore a possible role for fire management strategies in enhancing SCS. To date there are few published data showing a clear impact of fire management on SOC stocks, but some studies in tropical savannas in Australia and Africa have indicated that a lower frequency of burning is associated with higher SOC content compared to sites with more frequent burning (Allen et al 2021, Bird et al. 2000, Hunt et al. 2012).

A long-term fire trial at Kidman Springs in the Northern Territory has twenty years data on C stocks in biomass and soils under three burning frequencies (every 2, 4 or 6 years) and two timing treatments (early and late dry season) across two pasture communities – open eucalypt savanna woodland and savanna grassland-open shrubland. The alternative fire regimes in the trial were found to have no significant, consistent effect on aboveground biomass in the open grassland/shrubland. Conversely, fire frequency and the interaction with season of burning did significantly affect aboveground C stocks in the open Eucalypt woodland site. To further investigate the impacts of fire regime, trial data were used to calibrate the Century model and simulate the response of C stocks to fire over 57-years (Hunt et al. 2012, Hunt 2014). These simulations showed lower aboveground C and lower SOC stocks with increasing fire frequency in open woodlands (Table A3). The authors concluded that opportunities to use improved fire regimes (lower frequency, less intense burning) to increase C stocks above- and below-ground do exist but are likely to be modest especially for soils. They further noted that the increase in woody density may adversely affect production and long-term trials and measurement are needed to validate the indicative modelling results and impacts on grazing productivity and profitability.

In addition to the more direct effects of fire on SOC stocks, there is evidence from an NT study at Howard Springs that, in tropical savanna woodlands, fire events interact with seasonal rainfall variations to change soil microbial decomposition processes (Livesley et al. 2011, Livesley et al. 2021). Seasonal rainfall (via its influence on soil moisture) is recognised as having a strong relationship with SOM turnover, explaining up to 70% of the variation in soil CO_2 fluxes in unburnt sites. A study in the Daly River region compared SOC stocks in savanna woodlands and in old and young sown C4 perennial grass pastures (Livesley et al. 2021). Interpretation of the impact of change in fire regime in this trial was complicated because of interactions between change in vegetation system from woodland to sown pasture and change from low intensity burning approximately every three years to about 20 years between fires after conversion to improved pasture. Over 28 years significant sequestration was found to have occurred in the area that was cleared to C4 pastures with less burning. The average SCS rate was 0.34 t C ha^{-1} yr^{-1} (0 – 30 cm) but understanding the mechanism for increased SOC stocks is complex and attribution of the SOC stock change isn't possible without further data. Nevertheless, the finding remains relevant to situations where changes involving clearing, pasture improvement, grazing management and fire management which can be a realistic improvement scenario in northern grazing regions that warrants further research. The ERF 2021 method requires a new eligible activity to be implemented in a soil C project but does not preclude additional management changes as long as all extra GHG emissions resulting from the project are accounted for (CER 2021).

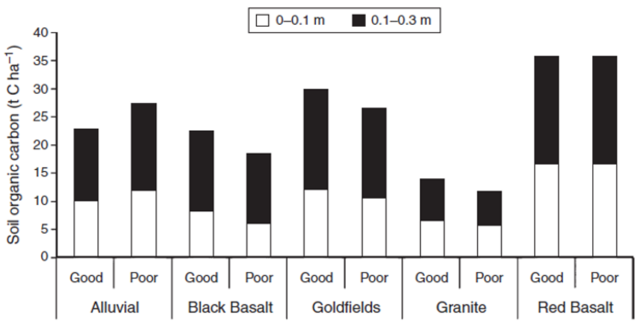
Summary for fire management strategies

Data from fire regime studies in Kidman Springs, Howard Springs, and Daly River indicate that fire management is a component of grazing land management strategies that potentially affect SCS. Quantifying the impact of fire regimes in tropical grazed savannas and grasslands can be complex due to the difficulty in attributing change when there are multiple management influences. These influences have not been well-documented in some past studies but likely contribute to inconsistencies in results. To quantify potential SCS trials and measurements are needed across all regions of northern grazing lands affected by seasonal burning, including central and southern Queensland regions. The available evidence indicates that:

- Reducing frequency and intensity of burning is associated with increased total SOC stocks, but SCS increases are likely to be modest relative to C sequestration in woody biomass.
- In tropical savannas, fire regimes favourable for SCS may be accompanied by higher woody vegetation cover and lower pasture biomass, and this trade-off with livestock production is likely to limit the adoption of fire management as a tool for generating soil C credits.

2.3.4 Managing land condition

Grazing management strategies, including improving forage production and quality, and some livestock grazing practices, have impacts on key indicators of land condition such as ground cover (and its corollary, bare ground), pasture biomass and species composition (Bray et al. 2016). Inconsistencies in the reported impacts of various management strategies on SOC stocks have led to suggestions that land condition may be a useful integrating indicator of management and non-management factors that influence SCS (Pringle et al. 2011, Pringle et al. 2014, Allen et al. 2013, Sanderman et al. 2015). This hypothesis is based on the observation that good land condition with strong pasture growth (Figure 6B) is consistent with general understanding of the role of NPP and of plant biomass and residues in SOM inputs essential to building SOC stocks. Although ground cover and vegetation status are linked to soil health and productivity and are indicative of organic matter input to soil (as discussed in Section 1), the amount of stable C stored permanently in soil depends on multiple interacting factors and varying timeframes. Some of these factors and dynamics are not readily assessed by technologies commonly used to assess land condition such as remote sensing of vegetation cover or bare ground. A survey of 329 sites across northern Australia showed a significant relationship between SOC stocks and certain land condition indicators (tree basal area, tree canopy cover, ground cover, pasture biomass and the density of perennial grass tussocks) (Bray et al. 2016). As expected, the relationship was stronger in the surface soil layer and declined down the soil profile. However, the experience from studies measuring SOC is that there is not a clear link between SOC stocks measured to a depth of 30cm and land condition rating (Figure 6; Bray et al. 2016). Analysis of size fractions: POC (<2mm to > 0.53mm) and MAOC and humified material (<0.53mm) may provide better understand SCS and its relationship to land condition indicators.



A. Sampling of paired sites with contrasting land condition classification showed no consistent relationship between condition classification and SOC stocks to 30 cm depth (Source: Bray et al. 2016).

B. Land in good condition (left) characterised by perennial grasses and good ground cover and neighbouring site in poor condition (right) with ephemeral species and surface disturbance. (Source: Bray et al. (2010), Georgetown Granite site example)

Figure 6. SOC stocks showed no consistent relationship (A) with land in good vs poor condition (B), despite indicators of good condition such as pasture biomass and ground cover being characteristic of higher organic C inputs to soil (Bray et al. 2016).

In summary, available data indicate better grazing land condition provides production and profitability benefits for livestock producers, making improved land condition a valuable enterprise goal. Good land condition is associated has higher average pasture biomass and ground cover which, in turn, provide for higher SOM inputs and lower loss from erosion and rapid mineralisation that occurs with exposure of bare ground. However, there is currently no strong evidence that land condition it is a reliable proxy for SCS (Bray et al. 2016 and papers cited therein).

2.3.6 Land conversion strategies

Cattle and sheep producers manage the tree-grass-crop balance in landscapes to optimise production benefits and sustainability. In northern Australia, the goal is commonly to manage tree-brass balance to increase pasture growth and forage biomass available for livestock consumption throughout the year and optimise the sustainable carrying capacity of their land (Burrows et al. 2002, Hall et al. 2020). Some producers are also interested in opportunities for C farming through participating in the ERF or other schemes. In the 2021 soil C method which credits sequestration in agricultural soils, *Re-establishing, and permanently maintaining, a pasture where there was previously no or limited pasture, such as on cropland or bare fallow* is an eligible activity, but the uncertainty in evidence for SCS with conversion of grassland to forest cover means this is not currently listed. A new ERF method, the 'integrated farm management' method, which is under development (November 2022) is expected to enable projects on areas with forest regeneration activities to include SCS in accounting for total sequestration ACCUs, but at this time its potential application in northern grazing lands is unknown.

As with other management strategies, SCS following land conversion presents challenges for measurement, additionality, permanence requirements for crediting SOC stock change. The effects on aboveground C biomass are usually clear in land use changes involving forest clearing or regeneration, but the lack of visible evidence of an impact on soil C (and belowground biomass) following land conversion can result in less attention in field monitoring programs and lower confidence in potential SCS following different land use changes (Henderson et al. 2021, Beillouin et al. 2022, Paul et al. 2002, Allen et al. 2013, de Bruyn et al. 2022).

Land conversion projects may not only affect SOC stocks but the socio-economic and cultural status of producers and of regions. These important considerations are not a focus of this review, but it is noted that several published analyses describe the socio-economic impacts for a farm business of certain land use changes, including the potential for large opportunity costs (Pannell and Crawford 2022, White 2022). This research provides insights into possible barriers to adoption of practices able to increase SCS. In northern grazing lands, the economic outcomes associated with soil C projects, along with policy instability and uncertainty arising from variable and complex processes and knowledge gaps for land conversion in different landscapes undoubtedly affect uptake by land managers (Henry et al. 2022). Over more than a decade, policy instability, low investment in regional R&D, and uncertainty in benefits and trade-offs have affected confidence in participating in C farming activities generally (Donaghy *et al*. 2010, Gowen and Bray 2016, White et al. 2021). More recently questions raised by experts on the integrity of some methods (including methods related to land conversion)[5] and cost:benefit of participating in ERF projects, this review evaluated evidence specifically relevant to land conversion in northern Australian.

The few studies with SOC stock change measurements provide insufficient data and coverage of landscape and management systems to give confident predictions of the impacts of various land conversions on SCS across northern region (e.g. Guo and Gifford 2002, Don et al 2011, Laganiere et al. 2010, Deng et al. 2016, Dalal *et al*. 2005, Harms et al. 2005, Bray et al. 2016). Deficiencies in design and methods contributing to results being inconsistent even for similar land use changes include:

1. *Not accounting for changes in bulk density*: Measuring BD in land conversion comparison sites is important because there is commonly a difference in soil compaction between land uses, especially for change between cropping and either permanent pasture or forest. Failure to express SOC on an equivalent soil mass basis has been shown to result in the change in SOC stocks being underestimated giving errors in stock change as high as 28% (Don et al. 2011).

[5] Update: Completion of this review has coincided with the release of a review on the integrity of ACCUs (9 January 2023), too late to include a detailed statement on findings. In summary, the review headed by Prof. Ian Chubb recommended changes to improve the ERF after concluding that the scheme was basically well-designed. The recommendations included revoking the *Avoided Deforestation* method (https://www.dcceew.gov.au/sites/default/files/documents/independent-review-accu-final-report.pdf). There remains strong unresolved criticisms of the *Human Induced Regeneration* method (https://theconversation.com/chubb-review-of-australias-carbon-credit-scheme-falls-short-and-problems-will-continue-to-fester-197401).

2. *Insufficient depth of sampling*: Adequate depth of sampling (≥ 30 cm) is critical due to changes in root depth and distribution. Marin-Spiotta et al. (2009) followed changes in SOC stocks over 80 years after re-establishment of forest on tropical grasslands in Puerto Rico using stable isotope analysis to establish a chronosequence. They observed that the loss of residual pasture-derived SOC following conversion could be completely compensated by gains in tree-derived C at depth. While surface samples showed significant losses, when soil was sampled down to 100 cm no net change in total SOC was detected.
3. *Undocumented or short 'age' of conversion* (the time since change to the new land use/land cover): Change in SCS is not linear after conversion with the pattern of change differing depending on the specific land conversion (Figure 3, Deng et al. 2016). Differences in the age of conversion is very likely to be a substantial contributing factor in inconsistencies in reported SOC change between studies.

Conversion from cropland to grassland

Conversion of cultivated cropland to permanent grassland is frequently listed as a strategy with a high potential to increase C storage in agricultural soils. It is not a land use change that is applicable across substantial areas of the northern Australian grazing lands but is included in this discussion because of its prominence in global references to effective strategies for SCS in agricultural lands. Australian studies are illustrated using New South Wales data on indicative SCS rates. There are few published relevant studies (See Appendix A, Table A3) and the only examples of measured SOC stock change found were for soil samples taken to only 15 cm depth. It is stressed that confidence in these data is low in the context of this review. The following discussion highlights some of the complexities and sources of uncertainty in studies comparing different land uses. While there are insufficient studies for as detailed an analysis for other land conversion categories of interest, it is likely that some of the measurement, interactions between drivers, and dynamics issues for conversion from cropping to grassland also apply more broadly.

Rates of SCS of 0.3 to 1.9 t ha^{-1} yr^{-1} have been reported in global studies of land conversion from cultivation to permanent pasture (Franzluebber et al. 2012, Lugato et al. 2014, Post and Kwon 2000, Soussana et al. 2004). Factors contributing to increased sequestration include reduced physical disturbance, improved soil aggregation, and increased and more consistent SOM inputs from deeper roots (biomass and exudates) following replacement of annual crops with perennial grasses. As noted above, baseline condition and time since conversion are important drivers of SCS rates. Higher SCS has generally been reported from short-term studies. Due to the 'sink saturation' effect, early rates of sequestration generally slow after the first five to ten years (Figure 3) and can decrease to a low (or zero) value after 20 or more years (Smith 2016). Unless temporal patterns of SCS are monitored, there is a strong risk that if projections of achievable SCS are based on short-term (decadal or less) measurements, they will be incorrect and overstated. Comparison between studies with measurement data from differing ages of conversion are likely to be misinterpreted as showing inconsistent sequestration potential. Franzluebbers et al. (2012) observed that after conversion of arable land to perennial pasture in Georgia and Texas the rate of SCS to a depth of 20 cm dropped by half from an initial value of 0.8 t C ha^{-1} yr^{-1} after 10 years, and to a quarter after 20 years. After 50 years, a new soil equilibrium was reached, and the rate of change was close to zero.

Interpretation of data from Australian studies is also confounded by variations in time since conversion from cultivation to permanent pasture (Luo et al. 2010) making comparison between the studies and developing representative datasets complex and results uncertain. Measurements following cropland conversion to pasture in central NSW reported sequestration of up to 0.26 t C ha^{-1} yr^{-1} over 25 years (Chan et al. 2011). In contrast, a survey of commercial paddocks in central-west NSW five years after conversion from cropping to pasture provided a markedly higher average SCS of 0.78 t C ha^{-1} yr^{-1} (0 – 30 cm) (Badgery et al. 2021). Badgery et al. stated that the high rates in their study were unlikely to be maintained in the long-term and the lower rate of Chan et al. is more consistent with an average of field studies across Australia of 0.3 – 0.6 t C ha^{-1} yr^{-1} in the top 30 cm soil after conversion of cropping land to permanent pasture (Sanderman et al. 2010).

Data quality depends on the measurement method applied and comparing studies with different quantification protocols risks confusing differences due to techniques with biophysical drivers due to site or management variations. Even for standardised measurement protocols soil C and its response to change are complex. Wilson et al. (2011) assessed SCS in north-west NSW along a soil type and land use-intensity gradient and estimated that SCS on an equivalent mass basis after conversion from cultivation to pasture could be between 0.06 and 0.15 t C ha^{-1} yr^{-1} (0 – 30cm, analysed in four increments), rates that are low compared to those reported for wetter, cooler environments. These authors noted that land-use change effects on SOC were largely restricted to the upper soil layers over their observation period. Other research showed depth effects can differ between soil types. For example, in sites across the NSW North-West Slopes and Plains region converted from conventional tillage cropping to sown perennial tropical grass pastures, Schwenke et al. (2013) found that organic C was higher only to a depth of 10 cm in Vertosol soils but down to 30 cm in Chromosols. This study also illustrated there was significant variability in SOC response between sites. Many, but not all, sites sampled showed a gain in total SOC six years after establishment of pastures. There is a clear need for better understanding of the reasons for variations in SCS within and between studies to reduce uncertainty in estimates of the potential SCS (Table 4). Where soil samples have been appropriately extracted and archived, re-analysis using standardised, well-calibrated methods may help to isolate inconsistency due to measurement to refine identification of knowledge gaps requiring investment in new trials and data collection.

Conversion from forest to grassland

Published data on the response of SCS following conversion of native forest or woodlands to grassland vary considerably. Synthesis of data from hundreds of studies on conversion of a range of native vegetation types to pasture reported a small increase in SOC (Conant et al. 2001), while an updated analysis incorporating data from 52 additional studies (Conant 2017) concluded that the earlier estimate was 'optimistic' and change in SCS was, on average, more likely low and not significant. Consistent with the work of Conant et al., a number of other global meta-analyses (Guo and Gifford 2002, Don et al. 2011, Kopittke et al. 2017) concluded that conversion of native woodland to pasture resulted in a non-significant change in SOC stocks although some pointed to a possible small (≤ 10%).

Australian studies have generally suggested no significant change or a small net loss in SOC following native woody vegetation clearing to pasture (e.g., Eclesia et al., 2012, Guo and Gifford 2002, Dalal *et al*. 2005; Harms *et al*. 2005; Marin-Spiotta *et al*. 2009; Fujisaki *et al*. 2015). In contrast, Wilson et al. (2011) reported a strong decline in SOC stocks (-22 to -38%) under pasture compared to native woodland soils in the wetter, temperate northern tablelands of New South Wales. There is likely no single factor responsible for the inconsistencies in Australian studies. Differences in the quality of measurements likely contributes, but research suggests there may be a climate influence due to the range of climatic zones and variation in NPP across the continent (Figure 2, Rabbi et al. 2015), and effects of different post-conversion management and combinations of practices (Livesley et al. 2021), which are not always adequately controlled or described in studies.

The importance of detailed meta-data and long-term monitoring for understanding the combined impacts of land conversion and land management on SOC stocks is illustrated by technical publications on the Brigalow Catchment Study in central Queensland. In this study established in 1965, collection of soil data and supporting information have been maintained for over 50 years enabling multiple analyses (Cowie et al. 2007, Thornton and Shrestha 2020). In a 2011 paper, no significant change in SOC stocks was found in sites cleared from brigalow forest to pasture (Dalal et al. 2011), consistent with several meta-analyses discussed above. However, a later analysis (Dalal et al. 2021b) showed evidence that interactions between the timing of measurements and SOC dynamics can lead to results being mis-interpreted. This detailed analysis of the full dataset revealed that when native brigalow forest was cleared to pasture there was a decrease of 12.6% (3 t C ha^{-1}) in SOC (and a 24.9% decrease in soil total nitrogen, STN) within the first 1.75 years. After this time, SOC stocks stabilised with no further change over three decades so that without the pre-clearing baseline and rapid loss being included in the dataset, it appeared that clearing had no impact. The importance of baseline information and history of clearing and reclearing was also shown in a separate study that surveyed SOC across 45 sites in the Queensland Brigalow Belt (Allen et al. 2016). These authors found the magnitude of change in SOC stocks following conversion to grassland depended on legacy effects of vegetation management, with remnant (uncleared) brigalow forest having higher soil C stocks than regrowth forest stands aged 10 to 58 years or grassland pastures.

A further confounding factor now emerging in long-term studies is the influence of increasing atmospheric CO_2 concentrations resulting from anthropogenic GHG emissions. Impacts on C sequestration in vegetation and soils of CO_2 fertilisation and possible interaction with global warming and other climate changes have long been discussed within the scientific community. Due to interacting and variable influences it has been difficult to isolate these effects in the field. Data from the Brigalow Catchment Study are some of the first field measurements to show a possible positive impact on SOC of the CO_2 fertilisation effect via increased SOM inputs (Dalal et al. 2021a).

The conclusion from this review is that the amount and quality of data available for northern Australia is insufficient to quantitatively assess the impacts of land conversion from forest cover to grassland on SCS. The discussion above regarding inconsistencies in data for conversion of forest (including woodland and savanna) to pasture and also those below for the reverse direction of land use/cover change emphasises the uncertainty in current capacity to make predictions. Several large studies indicate no significant impact on SOC on average, but there was some evidence of a small decline in SCS following conversion to grassland in some landscapes.

Conversion from grassland to forest

International studies on the restoration of forest cover in grassland have found that, as in research for other land conversion strategies, changes in SOC stocks differ with soil type, legacy effects of past grazing practices, which tree species are introduced, climate factors and ongoing land management (Rasmussen et al. 2018, Singh et al. 2018). Data from paired grassland and woody vegetation sites along rainfall gradients in south-western USA and South Africa indicated that encroachment of woody plants resulted in higher SOC stocks in lower rainfall areas. In wetter areas this relationship appeared to be reversed (Jackson et al. 2002, Mureva et al. 2018), but the threshold rainfall beyond which woody increase enhanced SCS differed between countries and/or vegetation types. The threshold mean annual precipitation (MAP) was about 400 mm in the USA but around twice as high (750 – 900 mm) in South Africa, indicating region-specific determinants of SCS. Even within a region, results have highlighted the risks of extrapolating between locations. In the Eastern Cape area of South Africa (710 – 750 mm MAP) Oleofse et al. (2016) found no significant impact on SOC at one site following conversion from grassland to forest due to black wattle encroachment, while at a second site the SOC content was still declining 50 years after encroachment. There are few long-term data and poor understanding of the reasons for inconsistency between sites and between studies. As a result, there is limited confidence in estimates of potential SCS.

In Australia, there is support for restoration of forest cover in certain grasslands through national policy (https://www.cleanenergyregulator.gov.au/ERF), state government policy (e.g. https://www.agric.wa.gov.au/carbon-farming/western-australian-carbon-farming-and-land-restoration-program, https://www.qld.gov.au/environment/climate/climate-change/land-restoration-fund) and the C market industry (https://carbonmarketinstitute.org/) for C farming and for non-carbon co-benefits that have environmental, socio-economic and/or First Nations co-benefits. Opponents, however, point to potential risks of trade-offs, including for food and fibre production and for rural communities and livelihoods if productive grazing land is converted to forests. In addition to lack of consensus on policy and community issues, there is also debate on the potential for *additional* C sequestration in landscapes restored to forest cover (Chubb et al. 2022). Theoretically SCS would increase following conversion if the grassland soil was degraded i.e., had a SOC deficit. There are few measurements to support the implicit assumption that there is a SOC deficit in grassland systems driven by grazing management which can be reversed by establishing more trees is not supported by evidence from studies showing that SOC stocks are not significantly lower in grasslands than forested areas (see references in previous section). It is likely that SOC response data will vary between sites depending on past and post-conversion management, age of conversion, tree species (e.g., leguminous vs eucalypt), and any disturbance induced by forest restoration methods, including fire management in northern savannas.

Of the reviewed Australian studies with data on SOC change following conversion of grasslands to forest cover, some had limited value for assessment of potential SCS due to poor quality measurement methods and others, with reliable data, were not relevant to conditions and grazing systems in northern Australia. As for global studies results lacked consistency. In general results from southern Australia showed a small or insignificant change in SOC stocks sometimes with an initial short term SOC loss (<5 years) following tree planting followed by recovery (Cunningham et al. 2015; Paul et al. 2002). In contrast, data collated by England et al. (2016) on SOC (0 – 30 cm) for 117 sites agricultural baselines and after mixed-species plantings in southern and eastern Australia showed that differences in total SOC stocks following reforestation were significant at 52% of sites. The mean rate of SCS was 0.57 ± 0.06 t C ha^{-1} yr^{-1}. This SCS rate is high relative to most studies (see, for example, the field data synthesis by Sanderman et al. 2010) but England et al. appeared to combine data from sites used for cropping and pasture before tree planting and to not quantify baseline SOC stocks. Reported measurements show that the increase in SOC were largely in the POC fraction and it seems probable that the high average rate of sequestration was driven by cultivated cropping sites initially depleted in SOC prior to reforestation. The study highlights the difficulty in interpreting data that combines sites with diverse management history and highlights the importance of meaningful and relevant baseline information.

Few studies with robust measurement of SOC stocks were found for northern Australia. In a survey of 45 sites across Queensland's brigalow belt comparing sites with regeneration of forest through natural regrowth and pasture land, Allen et al. (2016) found that SOC stocks in regrowth and pasture sites were similar and less than in remnant brigalow forest. Studies in southern Queensland similarly found no significant difference following reforestation. A review of available SOC stock data for reforestation sites in grazing lands in SE Queensland found no significant change in SOC stocks (Henry et al. 2015). Ghadiri et al. (2009) found no significant difference between treed and non-treed areas (or between grazed and ungrazed treed areas) in the Inglewood Shire in southern Queensland, but these data were excluded from this review's analysis because of inadequate measurement depth (0 – 10 cm) and monitoring periods (5 years). In contrast to measurement studies, unverified simulations using the RothC soil C model, indicated that establishment of *Eucalyptus grandis* on Queensland pasture land would result in a loss of 8 t C ha^{-1} over 40 years (0-30 cm) equivalent to an annual decrease of 0.2 t C ha^{-1} yr^{-1} (Paul et al. 2003).

Several studies have identified that land use history and baseline SOC levels, climate, and the forest type and species established were factors relevant to the magnitude of change following forest establishment on grasslands. These variables cannot be standardised across studies and the extensive and diverse nature of grazed ecosystems in northern Australia exacerbate the resultant inconsistencies. In land use change papers relevant to this region, conversion from grassland to woodland/forest was the most studied. Most reported no significant impact of afforestation or reforestation on SOC stocks but some found that site preparation and tree planting was associated with an initial loss of SOC followed by recovery by year five.

Results indicating that conversion of grassland to forest has no significant effect on SOC stocks appear inconsistent with the finding of a small negative change in SOC stocks following conversion in the opposite direction (forest to grassland). It should be noted that variance is high relative to the difference between mean values for SOC stocks in the small number of forest and grassland sites with measurements. It is uncertain whether more data from sites that are better controlled for age of conversion and baseline condition would establish a significant difference. Because rates of net loss and net gain in SOC after a disturbance event (such as conversion) differ, with loss generally being more rapid, the changes from forest to grassland and from grassland to forest are not expected to be symmetrical before steady state sequestration is achieved. Two further points of importance in considering conversion of pasture to forest cover are: (1) While available evidence shows significant SCS is unlikely, C sequestration in above- and below-ground biomass is potentially large; and (2) in considering the potential for sequestration through land conversion strategies, it is critical for livestock producers to also examine the economic, social and non-carbon environmental benefits and trade-offs (Chenu et al. 2019, Rumpel et al. 2020).

Summary for land conversion strategies

There have been few long-term studies in northern Australia that provide reliable measurements of SOC stock changes following land conversion between grassland and other land cover or land uses and available results show considerable inconsistency. The limited data and understanding of SOC dynamics following conversion mean there is currently a high level of uncertainty in the estimates of potential SCS. There is also poor understanding of the productivity and socio-economic impacts of land conversion in the region (Donaghy et al. 2010, Gowen and Bray 2016, White et al. 2021). Averaged values for SCS are given in Table 4 noting that, apart from the case of conversion from cultivated cropping to permanent grassland (or forest) cover where increased SCS is relatively well-documented, these estimates have a very high uncertainty as summarized below.

Table 4. Summary data from published studies providing quantified estimates of the impacts of land conversion strategies on SOC stocks. H,M,L = High, Medium, Low. See Appendix A, Table A4 for details of individual studies.

Land use strategy	SCS average (Range) t C ha^{-1} yr^{-1}	Average C stock t C ha^{-1}	Period of observation Years	Confidence (H,M,L)	Number of studies (sites)
Conversion of cropland to grassland	0.40 (0.06 – 0.78)	63 (24 – 102)	4 – 100	M	9
Conversion of forest to grassland	-0.19 (-0.62 – 0.12)	41 (27 – 55)	12 —57	L	5
Conversion of grassland to forest	0 (0 – 0/NS)	35 (35 – 36) (2 sites)	10 – 58	L	4

- ***Conversion from cropping to permanent grasslands*** consistently resulted in an increase in SCS with an indicative rate of 0.4 t C ha^{-1} yr^{-1} average across the wide range in values. Factors influencing the rate of SCS included baseline SOC stocks and time since conversion. Where loss under cropping had been greater (i.e., larger SOC deficit) a higher initial rate of sequestration could be expected. SCS generally slowed over time towards a new equilibrium reflecting more consistent SOM inputs and lower disturbance under permanent grassland.
- ***Conversion from forest or woodland to perennial grasslands*** resulted in a range in estimates of SOC stock change from significant decline to a small increase. Reported rates of SCS after conversion of forest or woodland to grassland ranged from -0.62 to 0.12 t C ha^{-1} yr^{-1}. Overall, the data showed, on average, a small decrease in SCS of, on average, -0.19 t C ha^{-1} yr^{-1} with a very high uncertainty due to the small number of studies. Factors contributing to the diverse results are thought to include baseline soil condition and SOC status, time period since conversion, quality of measurement (including depth and time interval), and location climate and soil properties, but post-conversion management appeared to be a significant influence on SCS.
- ***Conversion of grassland to forest*** may involve plantings for afforestation or reforestation, or natural regeneration or regrowth. This land use change is significant in the grazing lands of northern Australia but there have been too few measurements of SOC stock change to confidently estimate the potential SCS with conversion to forest cover. For well-managed pastures, both global data and studies in northern Australian grazing lands suggest no or non-significant change in SCS. Planting or regeneration of woody vegetation in degraded pasture lands may increase SCS but there are insufficient data to quantify the change. To support land management decisions, more research is needed on the drivers and dynamics of SOC stock changes to support estimates of SCS potential. Analyses are also recommended to determine possible environmental co-benefits to establishing trees on grazing land, and to understand any impacts on whole farm production, profitability and future business planning.

3. Requirements and impediments for soil carbon sequestration

There is broad consensus amongst soil scientists and agronomists on the value of increasing the organic matter content of soils to improve soil function and soil health, support sustainable and profitable farming, and contribute to food security and ecosystem services. There is, however, debate on the extent to which SCS can be relied on as a technology to remove CO_2 from the atmosphere and substantially contribute to offsetting fossil fuel emissions to keep global warming to no more than 1.5^{o}C and mitigate climate change. Of the 164 countries signed up to the Paris Agreement (as of October 2022), 36 explicitly included SOC in agricultural land in their new and updated Nationally Determined Contributions (NDCs) submitted prior to COP27. However, in total 107 countries included SOC or related measures in their NDCs to address mitigation or adaptation (Rose et al. 2020). Hence, despite ongoing uncertainty, SCS is increasingly part of national climate change policies, and is supported by financial market mechanisms that enable voluntary C credit trading. Australia's ERF scheme seeks to incentivise activities that contribute to meeting its international emissions reduction targets under the Paris Agreement, which (as at November 2022) are a 43% reduction on 2005 levels by 2030 and net zero emissions by 2050. These policy settings and legislated methods under the ERF set out the requirements, including eligibility, MRV and permanence obligations, are met to ensure each C offset issued represents 1 tonne CO_2e abatement and provide the framework for farmers and other land managers to be rewarded for implementing practices that increase SCS.

Australia's 2021 soil C method and requirements for participating in the ERF are complex and technically challenging, and land managers frequently require the support of specialist C service providers to register, implement and report on a project (CER 2021). In addition, there may be socio-economic, cultural and non-carbon environmental implications of a decision to change management to adopt a soil C farming strategy. These multi-faceted considerations can act as impediments to uptake and land managers and other stakeholders need clear, up-to-date information and training materials. These include information on regionally applicable practices for increasing SOM in grazing lands (Baumber et al. 2022) and understanding of production benefits or trade-offs. The description of relevant issues and impediments to the adoption of SCS management strategies in northern grazing lands and participation in C farming projects outlined below synthesise information from Australian research and analysis, including Kragt et al. (2012), White et al. (2021), Pannell and Crawford (2022).

3.1 Technical issues

(a) *Additionality requirement:* There is limited robust evidence from regionally relevant trials and field data and SOC process understanding is insufficient to provide confidence in the effectiveness of various management strategies across the range of climate, soil and production systems in northern Australia. According to the Offsets Integrity Standards legislated under the 2011 *Carbon Farming Act* (https://www.cleanenergyregulator.gov.au/DocumentAssets/Pages/Information-Paper-on-the-Offsets-Integrity-Standards.aspx) which covers the ERF methods, ACCUs can only be issued for new or materially different management activities, i.e. for practices that are *additional*[6] and not likely to occur under business-as-usual. Strategies with higher confidence for SCS increase, such as incorporating legumes in pasture, are also already more widely adopted by innovative producers, and increasingly become 'common practice' especially where they have associated productivity benefits and may fail the 'additionality' test for that site (White et al. 2021). Uncertainty regarding eligibility and, in some cases, cost-benefit ratio for implementation act as impediments for new participants in ERF projects.

(b) *Uncertain production and resource implications:* There is often little reliable information on the compatibility of practices proposed to be SCS-positive with local production systems, resource (including time) availability and the management priorities (or preferences) of livestock producers. The risk, or perception of risk, to production acts as a barrier to investing in change and voluntary participation in the ERF.

(c) *Risks for the permanency of stored SOC:* Based on research over the past two or more decades, there is significant uncertainty in whether gains in SOC stocks achieved through new management strategies will be maintained during climate change induced increases in droughts, heat waves and other extreme weather events (Roxburgh et al. 2020). This risk of reversal of SCS cannot be ignored in ERF sequestration projects due to the *permanence*[1,2] obligation. In Australia's naturally variable climate, maintaining soil condition and soil health in northern grazing lands has always been challenging (McKeon et al. 2004), and there is now strong evidence that the risk of loss of SOC is growing (Roxburgh et al. 2020, Pannell and Crawford 2022). While there are provisions in the ERF to help manage the risk of loss of sequestered C (e.g., the 'risk of reversal' buffer and allowing a project to continue with a

[6] These requirements are set out in the six legislated *Offsets Integrity Standards* of the Carbon Farming Initiative Act 2011 (https://www.cleanenergyregulator.gov.au/DocumentAssets/Pages/Information-Paper-on-the-Offsets-Integrity-Standards.aspx)

'pause' in further crediting until the loss has been made good), practical and financial continuity can be difficult to manage in the real world where rates of loss of SOC are commonly greater than rates of gain (Badgery et al. 2021).

(d) *Measurement costs:* Currently, monitoring SOC stocks in a sequestration project is costly and resource intensive if done to the level of accuracy required to optimise ACCU issuance. This reflects the need to detect small change in SOC against a much larger background stock and the level of spatial and temporal variability in agricultural soils. Anecdotally, estimates of the cost of soil sampling and analysis vary from as high as $100 to as low as $30 per hectare, depending on the size of the Carbon Estimation Area (CEA) and sampling strategy (White et al. 2021). Under the ERF accounting for C credits must be *measurable*[1] and *conservative*[1] (See Section 4) and must also quantify and net out material *GHG emissions*[1] (e.g., CO_2 from additional fuel use, N_2O increase due to legume use, CH_4 if livestock numbers increase) resulting from implementation of new SCS practices. This requirement adds to MRV costs and in some cases could substantially detract from potential C farming income. A modelling study in southern Australian (Victorian) sites grazed by sheep, indicated that sequestration in SOC-depleted soils could more than offset CH_4 and manure N_2O related livestock GHG emissions (Meyer et al. 2016). These simulations have not been verified over time and appear to represent non-typical site, climate and soil characteristics unlikely to be widely applicable and specifically not in northern grazing lands.

3.2 Farm business issues

(a) *Permanency period obligations:* Under the ERF sequestration methods are required to maintain project activities for 25 or 100 years to meet *permanency obligations*[1,2] and this can be a serious impediment to participation. Producers have expressed concern that the obligation restricts management flexibility and options for future decision making, and potentially impacts succession planning or property development or sale (Macintosh et al. 2019).

(b) *Non-carbon co-benefits:* Of all land sector climate change mitigation activities, SCS is often promoted as most likely to provide co-benefits for farmers in terms of both productivity gains and enhanced ecosystem services such as soil water availability and increased biodiversity. Understanding of these co-benefits is still evolving, and the lack of clarity in less-studied regions such as northern Australia affects the confidence of land managers in positive outcomes. Conversely growing recognition at all levels of government of the value of environmental co-benefits for sustainability and resilience and of cultural co-benefits for communities, has led to direct financial opportunities (additional to C credits) through government legislation such as Queensland's Land Restoration Fund (LRF) (https://www.qld.gov.au/environment/climate/climate-change/land-restoration-fund).

(c) *Possible costs and potential trade-offs:* As well as co-benefits there may be significant costs and trade-offs for land managers who choose to participate in C farming (Rumpel et al. 2022). In schemes such as the ERF, costs are associated with initial transaction and infrastructure requirements for implementation of projects. There may also be foregone production income, e.g., by allowing additional pasture biomass to be added to the soil to enhance SOM rather than increasing utilisation with more stock (Harrison et al. 2015). Trade-offs can also involve allocation decisions when water supply is limited (Rumpel et al. 2022). The extent to which costs and trade-offs act as a barrier to SCS projects will vary between management systems.

(c) *Delay in return on investment in SCS activities:* For registered ERF projects (or other C farming schemes), the time between investment in SCS projects and the first issuance of C credits is often five or more years. This delay before an opportunity for any financial return from ACCUs has been identified as an impediment to participation in the ERF (Macintosh et al. 2019). In low-productivity landscapes such as semi-arid grazing lands the delay may be longer as SCS is generally slower than in more mesic regions. While the ERF introduced provisions for forward payment arrangements and shared risk of non-delivery of contracted credits, the high initial costs for baseline measurements remains a barrier for northern producers wanting a new income stream (White et al. 2021).

(d) *Technical and contractual complexity:* Surveys have shown that the detailed technical requirements and challenges of ERF methods act as a disincentive for participation in the scheme (Macintosh et al. 2019, Harrison et al. 2021). The complexity of contracts and MRV mean that farmers need to engage C farming service providers. Many extensive livestock producers maintain conservative value systems, place importance on personal independence and have a high regard for autonomy. This tends to make engagement on the 'new' area of C farming challenging, not least because of the time needed to build sufficient trust to accept advice on adopting new management strategies for SCS from 'outside' of traditional agricultural industry specialists (Macintosh et al. 2019, Henry et al. 2022).

3.3 Policy design issues

(a) *Low participation in soil C farming projects:* In general, global participation in policy frameworks that aim to incentivise adoption of SCS-positive management has been low (Henry et al. 2022). ERF soil C methods have enabled voluntary participation in SOC projects in grazing lands since 2015 but, to date (November 2022), only one project (in Gippsland, Victoria) has received credits. No projects have progressed to reporting in northern grazing lands. Full understanding of the policy, economic or technical barriers to participation is hampered by public access being limited to general information on projects. Data on specific project locations and activities that could enable analysis of real or perceived impediments and risks disclosed by livestock producers to the CER are held in confidence.

(b) *Policy to ensure integrity of C credits:* While the Australian Government plans to use SCS to source 17% of the abatement required to reach its 2050 net zero target and interim emissions reduction commitments (Commonwealth of Australia 2021a, Commonwealth of Australia 2021b), there is still more to be done in ensuring the policy settings are effective. Thamo and Pannell (2016) caution that the substantial transaction costs in frameworks and procedures for earning offsets, although an impediment to participation, must continue to rigorously meet integrity standards and that compromises in policy design intended to make sequestration attractive and reduce currently substantial transaction costs risk rendering it highly inefficient as a policy and valueless for real emissions reduction and real climate action.

(c) *Dependency of ACCU price on policy signals:* The low price for ACCUs relative to credits in some comparable international schemes has likely dampened interest in participation in the ERF. A contributing factor in the limited demand for credits (and consequently lower price) has been the lack of clear policy direction over the past decade. Following passage of the new Climate Change Bills in 2022, raising Australia's 2030 emissions target to 43% reduction on 2005 levels there is expected to be an increased demand for ACCUs. Broad participation in SOC projects depends on stakeholders across government and industry having confidence in the quality of ACCUs both domestically and internationally, and processes of review and revision of ERF governance and practice are seeking to ensure ACCUs have high integrity (Chubb et al. 2022).

4. Measurement

Net change in SOC stocks following adoption of new land management practices can be slow, particularly in areas such as northern Australia where climate is variable and NPP is relatively low, making accurate measurement of SCS challenging and costly. The annual increase in SOC stocks can be 1% or less of the original stored SOC and is often inconsistent across small spatial scales due to variations in soil properties and vegetation. Temporal fluctuations in magnitude and direction of change adds to the difficulty in detecting sequestration over time intervals less than several years, with 5 to 10 years commonly considered a feasible period (Paustian et al. 2019). Current best-practice methods remain in-field sampling and laboratory analysis using dry combustion methods, and the number of samples or measurements needed to detect a significant difference increases with variations and with the inverse of rate of change (Paustian et al. 2019). On extensive grazing lands costs can be prohibitive (White 2022) and while alternative more cost-effective and less time-consuming technologies such as remote sensing and modelling are showing promise, they are not yet sufficiently accurate and reliable to be routine for quantifying SOC stock change to the standards required for C crediting without verification using in-field sampling. The 2021 ERF method (Australian Government 2021) allows for use of spectrometric methods or a combination of modelling and measurement, but verification continues to rely on field sampling and analysis of C concentration and bulk density. Reporting of measurements of soil C content from past studies as evidence of SCS when they do not meet the protocols for quantifying sequestration required under methods such as the ERF (Australian Government 2021) is a factor in the inconsistencies in results for impacts of management strategies on SCS (Sanderman et al. 2010, Paustian et al. 2016, Paustian et al. 2019, Smith et al. 2020).

A full review of SOC measurement methods and technologies is beyond the scope of this paper but can be found in several references including those cited above (e.g., McKenzie et al. 2008, Paustian et al. 2019, Smith et al. 2020). The brief overview below focusses on those aspects of SCS quantification most relevant to understanding the reliability of evidence on potential SCS from studies in northern Australian grazing lands.

4.1 Overview of measurement requirements

The most accurate data on SCS have traditionally been based on the following steps to determine organic C concentration (SOC %) and bulk density (BD) using a sampling protocol that takes into account natural variance and allows repeat estimates of SOC stocks in an equivalent soil mass (See Box 2). the steps required are generally (Don et al. 2007):

- Repeat collection of soil cores to a specified depth of at least 30 cm, using stratified random sampling; typically the period between sampling in rangelands is 5 – 10 years;
- Sieve to remove gravel and other material >2 mm;
- Where present, remove inorganic C;
- BD measurement; and
- Laboratory dry combustion (Leco) analysis.

Adjusting SOC concentration for BD to express SOC on an equivalent mass basis enables calculation of SOC stocks in units of mass of C per hectare (t C ha^{-1}) and the rate of SCS for the measurement interval as t C ha^{-1} yr^{-1} (Box 2).

A C credit (such as the ACCU) is issued for each tonne of CO_2 equivalent units sequestered (1 t C = 3.67 t CO2), after deducting material amounts of emissions of GHG (as CO_2 equivalents using GWP_{100} factors) arising from the project. The details of sampling, analysis and accounting are given in the ERF soil carbon methods (Australian Government 2015, Australian Government 2021). While other measurement or measurement-model technologies are allowed under the 2021 SOC method, calibration and validation of current and emerging alternatives such as proximal sensing (spectrometry using mid infra-red or near infra-red), remote sensing and models analysis still rely on field sampling with laboratory analysis for calibration and verification. Investment is being made globally and in Australia to develop techniques to scale up results with sufficient accuracy to enable financially viable projects in large areas such as rangelands (Smith et al. 2020).

Box 2: ***Requirements for accurate measurement of soil carbon sequestration***

Points that can lead to more accurate measurement and more consistent reporting of SCS:

- Soil sampling for calculation of SOC stocks and stock change is more complex and more labour-intensive than collecting samples for estimating soil C content (%) and nutrient analysis for agronomic decisions (CER 2021). It requires volumetric soil samples (and estimates of bulk density), random sample location and repeat sampling to determine change over time. Sampling depth of at least 30 cm is needed to ensure SOC stock change rather than a redistribution within the soil profile is being estimated.
- Soil samples must be dried and processed (crushed, sieved, ground) to ensure representative analysis results. Sieving is essential to remove organic matter >2mm and gravel.
- Following sample preparation, analysis is carried out to determine total C concentration with the most accurate method being laboratory automated dry combustion (commonly using a Leco instrument). For soils containing inorganic C, acidification enables determination of organic C.
- Spectroscopic methods (lab- and field-based) offer the potential for more rapid, cheaper analyses but usually require extensive calibration, without which accuracy is significantly reduced.
- Modelled approaches, satellite data and flux measurement with eddy covariance techniques are being increasingly trialed, but as yet aren't sufficiently reliable and trusted for routine acceptance.
- In addition to measuring SOC stock changes (ideally over several decades), accurate estimation of C offsets and climate change mitigation, require any increases in GHG emissions (CO_2, N_2O and CH_4) resulting from the management change implemented to increase SCS must be accounted for (Chenu et al. 2019). Examples of sources that could arise in grazing lands include CO_2 from diesel use, N_2O from fertilizer, manure or planted legumes and CH_4 from ruminant livestock (Refer to Section 2.3.

4.2 Measuring soil carbon in northern grazing lands

In rangelands large property areas theoretically provide ruminant livestock producers with a major opportunity for substantial SCS even at low rates per hectare. As summarised above in Section 3, however, the expense of measurement added to transaction and implementation costs generally makes projects in extensive grazing regions financially unattractive. The ERF 2015 soil C method (Australian Government 2015) offers a 'default' factor estimation of SCS that overcomes high measurement costs but the area covered by these factors does not include much of the northern grazing region. In addition, C service providers and prospective participants in the scheme consider the estimates to be too conservative and no projects have been registered under this method.

For producers seeking to better manage measurement costs, optimal frequency and density of sampling are key considerations. Less frequent sampling results in a longer wait for issuance of ACCUs and delays the possibility of earning income from C offsets. However, in northern grazed landscapes, repeat sampling after an interval of less than five years is unlikely to be cost-effective due to the low rate of SCS expected in this region. Sampling density is a key determinant of total measurement cost, with optimal number of samples dependent on spatial variability. An evaluation of sampling density relative to variance reported from an experiment in grassland sites (Don et al.

2007) found that for a sample size of 20 the minimum detectable difference (MDD) for Arenosl and Vertisol soils was 1.2 and 2.8 t C ha^{-1}, respectively. A more costly sample size of 100 samples was required to reduce the MDD to 0.4 and 0.8 t C ha^{-1}, respectively. This is still higher than the annual rates of SCS in the order of 0.1 t C ha^{-1} or less commonly observed in rangelands (Sanderman et al. 2010), indicating that the large number of samples (and high cost) required to accurately quantify SOC stock change with an acceptable level of variance across extensive, spatially variable areas of northern rangelands. Cost is therefore likely to remain prohibitive until alternative, less costly estimation methods such as remote sensing or modelling become available and acceptable in GHG emissions accounting frameworks and in C market mechanisms. The 'hybrid' approach allowed for in the 2021 ERF method requires with less intensive sampling and analysis than the measurement only method, but still requires in-field sampling calibration and verification data over project areas. The approach requires half of the CEAs in a project to be appropriately sampled in the first 5 years of the crediting period (25 years), and then the other half sampled in the subsequent 5 years, and then 10% of the CEAs sampled per year for the remaining 15 years of crediting. With current sampling costs estimated at around AUD$30 per ha and a carbon credit price of ~A$28 (July 2022), the economic viability remains doubtful for rangelands (Box 2).

Quantification of C offsets that represent an increase in SCS due to a change in management practice relies on having good baseline data for SOC stocks before implementing the change and, preferably 'control' (without management change) sites. Much of the early data from Australian SOC studies assessing the impact of management strategies have significant uncertainty due to reliance on chronosequences or paired sites to estimate rates of change. Whether some of these studies represent accurate comparisons of SOC with and without the new management strategy is unverifiable (Badgery et al., 2014). The approaches assume that SOC stocks were the same before implementation of the management strategy and that soil properties and climate across the sites being compared were not significantly different. In most cases it is not possible to validate these assumptions (Sanderman et al. 2010, Wiesmeier et al., 2019), and confidence in results are further limited by limited or no information on historic management and whether initial SOC stocks were in steady state. The dynamics of SOC at commencement of the time of implementation of a new strategy to enhance SCS will affect the rate of change. For example, a practice change may result in a slowing of the rate of decline rather than a net increase in stored SOC (Sanderman and Baldock, 2010). Very few sites are supported by a genuine dynamic baseline that represents the 'without management change' situation.

The importance of careful measurement in understanding the long-term dynamics of SOC and response to management were illustrated in a 16-year study of temporal change in SOC stocks in agricultural land at Condobolin in NSW (Badgery et al. 2020). Total SOC stocks under perennial pasture increased over the first 12 years (to 2012), predominantly in the POC fraction, but these gains were almost completely lost again by 2016. The authors concluded that the primary factor controlling the temporal pattern of gain and subsequent reversal was not management for permanent pasture but due to rainfall and/or N limitation. This study indicates the risk in assuming that decadal increase in SOC is a measure of 'permanent' SCS and highlights the importance of monitoring SOC in reference land to provide a real baseline. Without this dynamic measure, it is not possible to distinguish the net C sequestration attributable to the management as opposed to the natural variability.

Understanding soil processes and soil C cycling has multiple applications but establishing and maintaining long-term trials requires consistent research investment which has rarely occurred, as illustrated for Australia in Figure 7.

Australian Government investment in 2021 in a 20-year National Soil Strategy (https://www.agriculture.gov.au/sites/default/files/documents/national-soil-strategy.pdf) together with continued investment in the ERF/Climate Solutions Fund (CSF) aim to help address uncertainty in SCS as well as foster good practice for soil health. Part of the investment is to drive more rapid development of technologies and MRV platforms for more accurate and cost-effective measurement methods for SOC to understand sequestration potential. Past research has resulted in a large number of soil sampling sites across Australia and a large number of archived soil samples in storage. An acceleration of innovation in new cost-effective techniques through current investment may eventually allow strategic re-analysis of archived samples from previously funded research programs in Queensland (Figure 7).

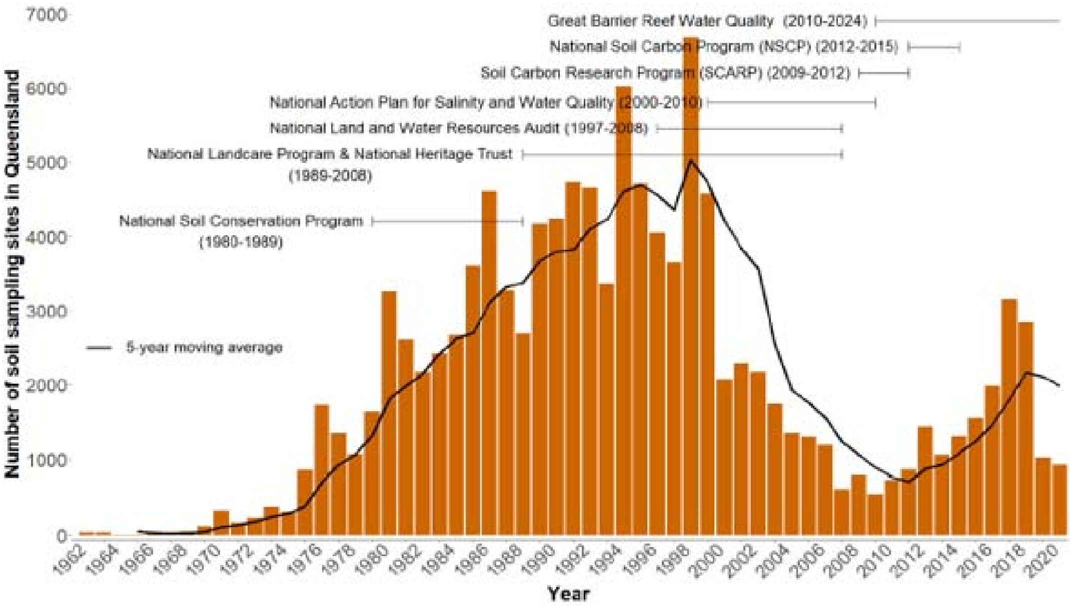


Figure 7. Profile of Australian soil science over the 60-year period from 1962 to 2021 showing the major initiatives in public funding and the focus of scientific outputs, plotted with number of soil data collection sites in Queensland under the funding programmes (Source: de Bruyn et al. 2022).

5. Risks for increasing and maintaining soil carbon

A range of biophysical, socio-economic and policy-related risks have been associated with implementation of management strategies aimed at increasing SOC storage in Australian agricultural lands (Roxburgh et al. 2020, Lee et al. 2021, Harrison et al. 2021). In northern Australian land areas managed primarily for ruminant livestock production, these risks are exacerbated by the more general challenges of managing extensive, low input production systems in remote regions of high natural climate variability and harsh conditions. Biophysical conditions are arguably the most obvious risk for increasing and maintaining SOC stocks. There are additional challenges to participating in C crediting schemes here requirements for eligibility of management actions for SCS and MRV requirements and other standards necessary to ensure the integrity of C offsets, many of which are less practical and more costly to achieve in extensive grazing lands. Other risks for C farming projects risks include unanticipated impacts on production and profitability, loss of the management flexibility needed to respond to events such as climate extremes and wildfires in project areas. The risk of policy changes has also been identified by some C farming stakeholders (Macintosh et al. 2019). The overview of a range of risks relevant to northern producers is given below, focusing on biophysical aspects.

5.1 Biophysical risks

Climate variations, fire, extreme weather events including prolonged dry periods, pest and disease outbreaks are amongst factors that affect the balance between SOM inputs and loss and hence SCS (Richardson et al. 2014, Poulton et al. 2018, Mitchell et al. 2021). There is considerable uncertainty but growing evidence that climate change could intensify negative impacts of these factors on SCS and increase the risks for grazing land managers interested in engaging in soil C projects. The increasing severity of climate events driven by anthropogenic climate change is exacerbating many risk factors for C sequestration projects (IPCC 2022). The vulnerability of stored SOC to loss and the likelihood that climate change will exacerbate the difficulty for permanent storage have also been highlighted in several recent global studies (Chenu et al. 2019, Lal 2020, Lee et al. 2021, Wang et al. 2022).

As part of their scheduled 2020 review of the ERF, the Climate Change Authority (CCA 2020) identified the need to examine the climate risk to abatement credited under the Australia's C farming legislation and commissioned a review by the CSIRO of the physical risks to carbon sequestration under ERF land sector methods (Roxburgh et al. 2020). Of all land sector methods, including vegetation methods (forest protection and regeneration) and 'blue carbon' (i.e., mangrove and seagrass communities) methods, soil C was rated by the review authors as being at greatest risk from climate change impacts. The dominant threats identified were associated with decreased rates of organic matter input to soil, and increased rates of loss through changes to soil respiration and the microbial biota at higher temperatures. The vulnerability of SCS to climate change was also shown in a modelling study in New South Wales (Wang et al. 2022). Applying a range of future climate change scenarios showed a significant effect on the capacity of soils to maintain levels of stored organic C, with the extent of change in SOC stocks under climate change varying spatially across the state, ranging from 7.6 to 12.9% decrease. These impacts would negatively impact the capacity for projects to meet the 'permanency' requirements and the number of credits able to be earned per hectare of project land. The sensitivity of SOC in the simulations of Wang et al. is consistent with measured findings of climate impacts in Australian field studies (e.g. Allen et al. 2013, Rabbi et al. 2015, Robertson et al. 2016).

Lee et al. (2021) used publicly available Australian datasets and an optimised version of RothC soil C process model to compare SOC (0 – 30 cm) response over 100 years under constant climate or future climate change scenarios for four land use classifications (ALUM 2016). In the baseline scenario, modelling showed that SCS differed between land uses with an assumed annual increase in C inputs of 1 t C ha^{-1}, with a potential SOC increase (interquartile range) of 13.58 (12.19–15.80), 14.21 (12.38–16.03), 15.57 (12.07–17.82), and 3.52 (3.15–4.09), t C ha^{-1} under cropping, modified grazing, native grazing, and natural environments, respectively. Soils under native grazing were found to be the most potentially vulnerable to C mineralisation loss, while soils under natural environments were the least vulnerable. While there was some variation with interacting climate and land characteristics in the response to global warming scenarios (1.5, 2 and 5.0^{o}C rise over 100 years), simulations generally showed that soils would have a net loss in soil carbon of up to > 30%. Of most relevance to northern Australia, the modelling showed that soils under native pastures grazed by livestock lost from 1.67% to 3.12% of SOC as a result of climate change. These results are indicative of future risk but have a high degree of uncertainty, with other studies emphasising the limited capacity of models such as RothC to simulate SOC dynamics (Badgery et al. 2020).

Of importance for land managers is the growing number of studies showing that management strategies adopted to increase SCS can help to mitigate the risk of loss of SOC due to weather extremes and climate change while also providing net benefits for resilience to climate impacts

(Powlson et al. 2014) and reduce exposure to fluctuations in income and economic returns from farming (Chabbi et al. 2017, Rumpel et al. 2020). However, the weight of evidence currently indicates that climate change represents an increasing risk for maintaining as well as increasing SOC levels.

5.2 Socio-economic risks

The socio-economic risks associated with increasing SOC stocks in northern grazing lands vary enormously depending on production systems, individual situation and producer values, which affect the motivation for implementing a management change to increase SCS. Objectives such as increased productivity, improved resilience, environmental goals (e.g., reduced erosion risk, enhanced biodiversity and water use efficiency), or other sustainability values as well as climate change mitigation and income may all benefit to some extent from increasing the SOM content of soils. The amount of rapidly cycling SOC in the form of labile POC generally increases in surface soil in favourable seasons or following management to increase SOM inputs, with benefits for soil health, soil function and productivity. Both gains and losses in labile SOC can occur relatively rapidly so the risks also tend to be mor short-term. However, increasing the stored stable SOC (MAOC) fraction as needed for SCS is a longer-term, more complex process and business and income risks, particularly those associated with participation in C farming schemes can also be more enduring. Implementing an eligible management activity and registering a project in the ERF is a long-term commitment (at least 25 years), and producers need to be informed of costs and obligations as well as the opportunities and level of confidence for success in earning SCS ACCUs. They may need to initially invest in expert advice to understand financial and non-financial risks due to the complexity and also the inconsistency in information on SOC processes and SCS projects. White (2022) provides an outline of the economic risks for ERF soil C project, including those associated with a contract to sell C credits and uncertain future delivery of SCS.

Farm financial risks: It is likely that no income from soil C credits would be received within at least five years of registration of a project, i.e., the project could represent a net financial loss for several years due to initial transaction and implementation costs and baseline measurement. Examples of transaction costs are the preparation of a land management strategy, development of a soil sampling strategy and auditing, while implementation involves the time and costs of baseline soil sampling and any new infrastructure such as fencing or planting. Badgery et al. (2020) note that the uncertainty in long-term SCS may mean that income from C credits may never be enough to cover costs such as baseline measurement. Contracts for a registered ERF project can also have associated agreements with third party service providers with fee payments. These vary but may be in the form of a proportion of the ACCUs earned for SOC sequestered. An ERF sequestration project, which has a 25-year or 100-year permanency period, is tied to the registered project area and approval must be sought from all holders of interest in that land, which may include banks and family members. There may be implications for succession planning or property sale over within the project period.

The biophysical risks arising from increasing frequency of drought-induced limitations on NPP (Love 2005) and global warming induced accelerated decomposition that can limit SCS and negatively impact a producer's ability to deliver contracted abatement under the ERF. In addition, climate change and market forces can negatively affect the producer's capacity to maintain an eligible management activity which risks requirements for a registered project, such as permanence period obligations. Financial, market or personal circumstances may also be a risk to ERF projects through change in producer priorities. These risks apply not only to selling ACCUs in C markets but increasingly to the use of SOC credits in accounting for C neutral or low C production claims (https://www.climateactive.org.au/be-climate-active/certification). This may, in future, translate to an extended risk to access to some international markets or opportunities for price premiums for livestock products. Up to the end of 2023, the European Union *Carbon Border Adjustment Mechanism* which acts as a 'tariff' on imports has had a minimal or no impact on agricultural products (https://www.austrade.gov.au/news/insights/the-limited-impact-of-the-european-union-s-carbon-border-adjustment-mechanism-on-australian-agriculture) but the future is less certain. Future increase in consumer or country focus on climate change mitigation may also result in increasing scrutiny and auditing of the integrity of offsets with associated increase on costs for auditing and verification (Smith et al. 2020).

5.3 Policy settings and risks

The major policy in the Australian government's climate change response is the *Carbon Credits (Carbon Farming Initiative) Act 2011* which was legislated to support reductions in GHG emissions by crediting and purchasing ACCUs issued through the ERF, and continues to be funded to help meet Australia's emissions reductions targets under the Paris Agreement (www.minister.industry.gov.au/ministers/bowen/media-releases, 1 July 2022). Changes in politics There is ongoing strong support for SCS opportunities to create offsets, including in eligible grazing land projects as discussed in the Introduction to this report and illustrated in Figure 8).

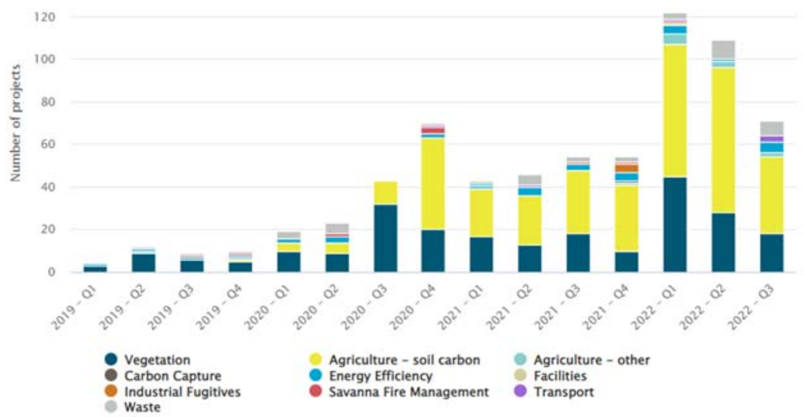


Figure 8. New registered projects per quarter from 2019 to September 2022 showing the dominant growth in soil C projects. (Source: www.cleanenergyregulator.gov.au/Infohub/Markets/Pages/qcmr/september-quarter-2022/Australian-carbon-credit-units-(ACCUs).aspx)

There are many domestic and international policy settings that now and, in the future, influence the price of C credits under the government purchasing scheme and secondary market (commercial contract arrangements) frameworks but the demand for high quality offsets is continuing to grow. Of importance are maintaining confidence in the integrity of ERF crediting (and specifically soil C credits) and growth in demand. Industries with obligations under the Safeguard Mechanism policy and those making commitments to 'net zero emissions' or 'C neutrality' will continue to need to purchase C offsets. Of note is the Australian red meat industry target to be C neutral by 2030 (www.mla.com.au/research-and-development/Environment-sustainability/carbon-neutral-2030-rd/delivering-cn30/).

Requirements legislated in ERF methods aim to manage the risks to government and to participants for the biophysical and financial uncertainty associated with sequestration projects, including permanence period obligations of projects, with an option of 25- or 100-years during which carbon stored by the project must be maintained. Projects electing a 25-year permanence period receive a 20% reduction in the number of carbon credits issued. This is on top of the 5% 'risk of reversal' buffer applied to all projects to manage government exposure to unintentional and unavoidable losses including losses due to extreme weather events (CER undated). Land managers carry the risk of reduced business and management flexibility associated with the 'carbon maintenance obligation' to continue a practice or activity for SCS throughout the permanence period.

6. Gaps and research needs

Review of the evidence for the potential for SCS in Australian agricultural land, and specifically in the extensive northern grazing lands, has identified several knowledge and capability gaps that constrain support for policy development, decisions by land managers across large areas of land, and potentially opportunities for producers to diversify income through participation in C offset markets. Incomplete understanding and shortcomings in data are not surprising since C accounting and C crediting are a relatively new and very complex area of science, despite being able to draw on and re-purpose R&D from agronomy. The inconsistencies in estimates of potential SCS rates and related outcomes reported from field trials and modelling experiments for management strategies are, in part, a reflection of interpretation and definitional issues and in part technical issues of science and procedure. There has been limited research and properly conducted measurements that have been conducted in northern Australia, and few opportunities for communication and training to educate new entrants into the C farming discipline, to share information and to learn from land managers' experience. The complexity of SOC and C dynamics in soils and ecosystems and evolving impacts of climate change and climate change policy. An outcome of these knowledge and data gaps and limitations in understanding is a degree of confusion and rejection by some key stakeholders.

Early investment in trials and experiments globally and in Australia was designed to answer agronomic questions relating to the role of soil in improving plant growth for increasing agricultural yields. While valuable, this research focused more on the rapid turnover fraction of SOM and less on understanding long-term storage of SOC in stable forms as needed for climate change response. Measurement requirements for sequestration, a mass accumulation, differ from the more straightforward measurement of % C in soil traditionally used to inform agronomic decisions. In addition to significant gaps in understanding the impacts on SCS of management strategies the building capacity for practical, accurate cost-effective monitoring of SOC stock change is an important technology gap.

Data and knowledge gaps and research needs to improve the evidence base for policy and producers are discussed in this section under three broad areas: (1) Understanding soil C dynamics and links with livestock production practices and SCS; (2) Overcoming challenges for improved capacity to monitor SCS; and (3) Identifying and removing impediments and risks to optimise opportunities for SCS in extensive grazing lands.

Understanding soil carbon status and dynamics in northern grazing lands

- *Baseline SOC data:* Collection of baseline SOC data using consistent measurement protocols consistent with ERF reporting requirements that are representative of the range of land types and major grazing systems in northern Australia would assist in understanding the potential to increase sequestration by informing how SOC varies with climate, soil properties and management history. Identifying soils depleted of C relative to typical steady state levels can provide information on opportunities to restore SOC and improve soil condition and productivity. Monitoring baseline SOC stocks and change would also help to identify management strategies that maintain or increase stored C. Measurement protocols should be consistent with requirements for determining SCS under the ERF.

- *Long-term trials for well-defined management strategies:* Assessment of the opportunities for land managers to increase SCS in northern Australia is hampered by inconsistent data on practical management strategies for grazing and pasture improvement and land conversion that have been linked in publications to increases in SOM or SOC. Changes in SOC stocks are typically small and variable in magnitude and direction and poorly described management in some published field trial results contributes to lack of clarity in potential SCS through implementation of various strategies.

- *SOC forms and dynamics:* To date there have been few studies measuring SOC in tropical/sub-tropical rangelands and grazed savanna regions. Better understanding of factors affecting SOM transformation processes, SOC dynamics, and stabilisation processes would assist in understanding of strategies that increase the persistence of SOC in tropical/semi-tropical savannas and woodlands and semi-arid grazing lands and the risks to permanence of sequestered SOC due to climate variability, global warming, and factors such as fire.

- *Linking management to SCS outcomes:* Attribution of SCS to management and non-management factors is difficult due to interacting influences on SOC and, in some cases, poor quality SOC stock change data, leading to gaps in understanding of which are the best-bet strategies for SCS and which strategies are unlikely to successfully increase SOC stocks permanently. Targeted research and measurements needed to identify possible opportunities for livestock producers to participate in C crediting schemes and offset markets include:
  - Identification of SOC response to incorporating different forage legumes in pastures, including time to reach a new equilibrium and variability in response to climate patterns. Clarifying how additionality and newness requirements in the ERF methods apply to well-established practices when taken to new locations or new species/varieties is important for understanding the eligibility and opportunities for legume-grass pastures under the ERF soil carbon methods.
  - Conducting well-designed measurements at the Kidman Springs Fire Study site or other locations with control sites using new and archived samples is needed to improve understanding of the response of SCS to fire regimes in grazed savannas across variable seasonal conditions.
  - Despite substantial past investment in grazing management R&D, more high-quality SOC stock change data are needed under well-defined strategies, including forms of rotational grazing. Wambiana grazing trial and other trials with established treatments provide the best opportunity to strengthen understanding under well-controlled grazing regimes of the impacts of grazing intensity on SCS. Existing and new survey data, when detrended for climate and soil type influences provide additional information across grazing systems.

Measurement and modelling technologies

- *Guidelines for consistent measurement data:* Consistent measurements of SOC stock change across trials and sites using protocols applicable in northern grazing systems and soil types would help to fill gaps in data and understanding. There is a need for guidelines and training to assist technicians and C service providers to better apply the protocols set out in the ERF soil C methods and to assist other stakeholders understand procedures and identify possible problems early in trials. This would help to minimise inconsistencies due to application and maximise the value of future data on SCS response to management.

- *Enabling access to data for analysis and model calibration:* There is an ongoing need for qualityassured baseline soil data consistent with SCS measurement protocols for research and to improve the accuracy of models, including the capacity to represent SOC dynamics. Providing access to data for northern Australian grazing lands for analysis, to calibrate new technologies (e.g., remote or proximal sensors), and for model calibration and validation would accelerate development of cost-effective, accurate alternatives to field sampling.

- *Improvements in dynamic baseline monitoring:* Development of the capacity to measure SOC stock changes under different management strategies against dynamic baselines is needed to isolate natural variations in SOC due to climate variability and longer-term climate trends from SOC response to management change, especially in regions of high variability.

Impediments, risks, and opportunities

- *Improved understanding of SCS opportunities:* Livestock producers interested in participating in C farming need reliable, unbiased information on the opportunities, requirements, costs (financial and time), and risks. There is a need to regularly update information on specific management strategies and emerging measurement technologies applicable in northern grazing lands to inform stakeholders.
- *Understanding non-carbon benefits of SOM* This review [and others] has indicated that current evidence indicates limited economically viable opportunities in northern Australian rangelands for substantially increasing SCS in extensive grazing lands. While delivering a permanent increase in SCS for genuine, additional and measurable C credits is difficult, there is more confidence in opportunities to use management strategies to improve the SOC status for soil health and productivity. SOC increase in the labile fractions may be lost readily in poor seasons and droughts, but soil condition is expected to be improved on average over extended periods. Enhancing understanding of these benefits has social, economic and environmental value at a producer, industry and state level.
- *Uncertainty and risks:* Uncertainty regarding costs, requirements and realistic prospects for benefits is an impediment to the uptake of SOC enhancing practices by livestock producers. Building a capacity for economic analyses and modelling scenarios would inform decisions by producers and their advisers.

7. Conclusions and recommendations

Interest in 'soil carbon sequestration' (SCS) has been accelerating, especially over the last 10 to 20 years. SCS, the process in which CO_2 is removed from the atmosphere and stored in the soil in stable forms 'permanently', meaning it remains part of the soil C pool for a nominal period of 100 years. Stakeholders across policy, agricultural industries, climate change, environmental science and research are seeking to better understand the potential for increasing SCS by implementing new land management activities that result in a net increase in SOC, and the benefits or trade-offs of this increase for food security, ecosystem services, and mitigating global warming. However, soil organic carbon (SOC) and its dynamics are complex and many interacting factors affect their response to how it responds when management changes. Uncertainty in the effectiveness of various management strategies to increase SCS is limited in many regions, especially those areas like the large savanna and grassland areas of northern Australian where extensive grazing ruminant livestock is the primary land use which have had relatively low investment in SOC measurement and research.

A comprehensive review of published papers and reports found that currently there is little consistent and reliable information on the potential for SCS in northern Australian grazing lands. This review was expanded to include relevant evidence from national and global research on practical management strategies with practical application to tropical/sub-tropical grazed grasslands and woodlands, but total data was still insufficient to provide confident estimates of SCS potential under key management strategies. The data from studies with credible methods and measurement protocols (to enable calculation of mass accumulation to a depth of at least 30 cm over a multi-decadal period) were used to estimate a simple average of SCS for key grazing and pasture management strategies. The findings must be considered preliminary only and have high uncertainty due to the small number of reliable trials and measurements. The review led to the identification of key knowledge gaps and research needs which are presented along with recommendations to improve the capacity to estimate the potential for SCS in northern Australia, grazing lands and to support policy development and decisions by land managers and other stakeholders interested in the potential contribution of SCS to soil health for productivity and ecosystem service and/or for participating in Australia's ERF scheme to earn [soil] C credits and contribute to climate change mitigation.

7.1 Key findings

General findings on the potential SCS in northern grazing lands

An overarching conclusion from research and field studies globally and in Australia is that SOC levels are determined primarily by climate variables, notably rainfall and temperature which are measures of aridity and drivers of soil moisture availability for plant growth, and secondly by soil properties, particularly those such as clay content that influence mineralisation (the process in which organic C is returned to the atmosphere as CO_2). Within the constraints due to climate and soil factors, management of land can influence how much organic carbon is stored. The influence, which has been shown in Australian studies to account for 10% or less of the difference in SOC stocks between sites, occurs through management modification of the balance between inputs of organic matter to soil, and loss as CO_2 to the atmosphere.

Outcomes sought by livestock producers implementing new management strategies with a view to increasing SOC are productivity and profitability benefits, opportunity to earn offsets and possibly participate in C markets, or a combination of productivity and climate change mitigation benefits. Greater productivity is largely linked to improvements in soil health and function mediated by increases in rapidly cycling of labile forms of SOC, and the second is linked to enhanced storage of SOC in stable forms down the soil profile (i.e., SCS).

Many management strategies identified in this review as having potential for SCS, such as incorporating forage legumes in grass pastures, are also associated with positive outcomes for productivity. However, livestock producers interested in undertaking SCS activities need to should seek accurate, unbiased information on the impacts of new management, any financial and resource costs, possible benefits, co-benefits, risks and trade-offs for their farm business before implementing a management change and before entering in a contractual arrangement associated with C farming. Requirements and eligibility rules in the ERF 2021 soil C method are complex and most producers have found a need to engage specialist technical skills before participating. To date no SOC projects in northern grazing lands have received ERF C credits (ACCUs).

Findings on the SCS potential with adoption of specific management strategies

- *Livestock management* studies generally show that, relative to moderate grazing, high grazing pressure in rangeland production systems results in soils having lower SOC content. High stocking rates decrease the plant residue organic matter entering the soil and increase the exposure of soil surface accelerating SOM decomposition and loss as CO_2. Results in northern Australia are consistent with global stocking rate trials, but the long-term

Wambiana grazing trial is a key resource for understanding grazing impacts in a variable climate and for understanding differences in SOC response across land types typical of northern Australia. Apart from the negative effect on SCS of high grazing pressure, no significant impacts on SOC were found for livestock grazing strategies and there was no evidence that SCS differed with animal type other than as a result of total grazing pressure. No significant difference in SOC stocks were reported from several studies comparing rotational grazing with traditional/ continuous stocking strategies.

- *Destocking and exclosure* experiments indicated a small increase in SCS, averaging in the order of 0.04 t C ha^{-1} yr^{-1}. This strategy is unlikely to be adopted as a strategy to increase SOC content except in limited non-productive parts of grazing properties. Under the 2021 ERF soil C method (Australian Government 2021, refer to Clauses 10(3) and 11(2)), destocking is not an eligible activity on production pasture land so is not a strategy that not earn ACCUs[7].

- *Pasture improvement* activities include sowing more productive grasses or incorporating nitrogen-fixing legume forages. These strategies for producing higher biomass pastures as forage have potential to result in higher SOM inputs. Estimated as a simple average, the rate of SCS for pasture improvement was 0.3 t C ha^{-1} yr^{-1}. Where baseline plant growth is constrained by N availability, N-fixation in legume-grass pastures may also increase feed quality and digestibility adding to the benefits for animal growth rates. Research on the agronomic and forage quality benefits of legumes and more recently on enteric CH_4 reductions using *Leucaena* and *Desmanthus spp.* is also continuing to provide more consistent evidence for significant SCS potential. For legume species such as *Stylosanthes spp.* that have been widely planted over many years for pasture improvement, the 'additionality' standard under the ERF requiring an eligible activity to be 'new or materially different' activity will need to be tested with the CER for project registration. However, modelling studies have indicated that productivity gains from pasture improvement strategies that increase SOC content would be very likely to provide greater income benefits for producers than participation in C markets unless offset prices become much higher than the 2022 level of around AUD30.

- *Fire management* studies indicated that small gains in SOC levels may be possible with reduced frequency and intensity of burning, but C sequestration in soil would be modest relative to that in woody biomass. It is likely a change in fire regime to increase sequestration in landscapes would lead to decreased pasture growth as tree cover increased and the production trade-off would be expected to limit the adoption of this a SCS strategy.

- *Land conversion* strategies most relevant to northern Australia involve changes between tree cover and grasslands. The results reported from land use change studies were strongly dependent on factors such as the time since conversion and baseline condition, notably whether soil was initially degraded and depleted of SOC relative to natural levels, and these factors contributed to some inconsistencies. In summary:

[7] ERF 2021 soil carbon method:

Clause 10(3) If a CEA includes land that is a permanent pasture, or has been used as pasture for a period of at least 2 years, the pasture must be grazed by production livestock at least once every 2 years, unless the land is de-stocked in compliance with subsection 11(2).

Clause 11(2) Land under pasture must not be de-stocked unless:

(a)the land is to be converted to a cropping system; or

(b)the de-stocking period is within the relevant drought period for the land; or

(c)the Regulator agrees in writing that exceptional circumstances exist.

- Conversion from cultivated crop production to perennial grasslands from various regions consistently show an increase in SCS with an average rate of 0.4 t C ha^{-1} yr^{-1}. This is a land use change with limited application in northern Australia.
- Published results for SCS following conversion from forest or woodland cover to perennial grassland ranged from a decrease of 0.62 to an increase of 0.12 t C ha^{-1} yr^{-1}, with the average being a small decrease (-0.19 t C ha^{-1} yr^{-1}). This average has little meaning as the data were confounded by differences in time since conversion, measurement methods and sometimes multiple management impacts after conversion, e.g., difference in fire regimes as well as land cover change. Overall, there is insufficient reliable data to quantify potential SCS for conversion from forest to grassland cover, but the impact appears small and possibly not significant.
- There was little evidence from global or Australian data that conversion of well-managed pasture to forest cover significantly increases SCS. Some studies showed that regeneration of woody cover through retention of regrowth on degraded land may result in increased sequestration in both soil and biomass. However, there are too few reliable data for northern Australia to predict the SCS potential across the range of conversion strategies (afforestation, reforestation, vegetation thickening, regrowth retention). Well-designed studies are needed to quantify the changes in C stocks and productivity and farm business impacts to understand full benefits and trade-offs for producers interested in conversion from grassland to tree cover.

7.2 Recommendations

1. ***Enhance the availability of reliable SOC data for SCS predictions in northern Australia***
   - *Maintain and monitor long-term studies in northern Australia:* Continue collection of high quality soil data in northern Australian studies, giving high priority to Wambiana Grazing Trial, Brigalow Catchment Study, and Kidman Springs Research Station, ensuring that sampling enables calculation of SOC stock change consistent with ERF C credit requirements. The data and time-series observations should be made available for calibration and verification of sensors and soil process models to build capacity for predicting SCS more widely and cost-effectively than currently possible with in field sampling and analysis. This investment would improve confidence in estimates of the potential for SCS under current conditions and future climate scenarios.
   - *Investigate opportunities to re-measure archived soil samples from past field studies:* Re-analysis of SOC stocks in soil samples from past field studies using up-to-date methods consistent with ERF requirements would cost-effectively expand the data available to evaluate effects of past management strategies and provide baseline data for new activities. These data would also contribute to understanding legacy effects of past management on SCS with new changes.
   - *Use survey data to evaluate linkages between SOC and management across northern Australia:* Well-designed surveys of SOC stocks and site characteristics at locations representing major production systems across northern Australian have the potential to generate soil C data able to be detrended for non-management influences and enhance understanding of the potential for SCS with improved grazing and pasture management strategies.
2. ***Improve understanding of the links between SCS, soil health and pasture production***
   - *Investigate causes of variations and inconsistencies in reported SCS potential:* Preliminary analyses as part of this review indicated limited prospects for SCS with most relevant management strategies but were confounded by inconsistent findings. If the reasons for the different

reported results could be clarified by re-examination of methods or supplementary data, e.g., soil type, management, production history, climate, land use/land cover information, prospective management strategies and SCS potential may be elucidated.

- *Investigate possible links between land condition variables and SOC dynamics:* While previous research has shown no clear link between indicators of land condition, such as ground cover, and total SOC stocks, further analyses on the dynamics of SOC and fractions (labile POC, stable MAOC) may establish whether, and on what timeframes, linkage may occur creating opportunities for their use as simple proxies for SCS management decisions.

3. Development of information materials

- *Developing and updating an accessible SOC database:* Collate all available reliable measurement data on SOC stocks and metadata for land types and climate systems across northern grazing lands and records of management strategies. This resource would be of value to a range of stakeholders across research, policy, production and C market industry.
- *Developing explanatory material:* The rapid expansion of SCS-related research and knowledge in areas of science and policy has raised the risk of conflicting and confusing information. Clear reference material on soil C and its role in productive landscapes and climate change mitigation would provide a valuable resource for a range of stakeholders seeking clear, factual material on SOC and opportunities for engaging in SCS activities. A series of online factsheets targeting northern Australia lands on issues such as measurement methods, ERF methods and opportunities, prospective management strategies, co-benefits and trade-offs and risks may help to address this need[8].

8. References

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[8] An example of similar regional information provided as factsheets is given by Western Australia DPIRD: https://www.agric.wa.gov.au/sites/gateway/files/Soil%20Carbon%20Measurement%20and%20Analysis%20Factsheet.pdf

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Appendices

Appendix A: Studies analysed for management strategy impacts on SCS

Table A1. Livestock management strategies: Published studies with quantified SOC stocks data used for analysing the potential for SCS. (NS – Not significant; NR – Not reported). See Section 2.3.1.

Region	Depth observed	Rate of SCS	Average C stock	Period of observation	Study information	Reference
		t C ha⁻¹ yr⁻¹	**t C ha⁻¹**	**Years**		
Grazing Intensity						
N Qld - Wambiana	0-30 cm	-0.087	20.3	12	High vs moderate stocking rate	Bray et al 2014
Qld - Toorak Pasture utilisation rate study	0-50 cm Vertisol	0 (NS)		26	Mitchell/Sheep. TN decreased with high grazing pressure	Pringle et al 2014
NSW New England Tablelands	0-0.3 cm	0 (NS)	103 (High) 102 (Low)			Young et al 2016
Destocking/ Exclosure						
NT - Kidman Springs	0-30 cm	0.08	32.51	57	Century modelling Destocking	Hunt et al. 2014
E Australia mulga lands	0-30 cm	0.05	22	30-40	Exclusion of grazing	Witt et al 2011
N Qld Wambiana	0-30 cm	0 (NS)	16.56 (5.21-33.73)	12	Exclosure vs Continuous (17.86 (4.79–75.49)	Allen et al. 2013
Qld - central, N, NW	0-5 cm				Soil Type	Carter&Fraser 2009*
Wambiana	0-5 cm	-0.02	8.53	7	Brown Duplex	
Galloway (1)	0-5 cm	-0.53	12.80 (66%)	3	Duplex	
Galloway (2)	0-5 cm	-1.53	18.9	3	Alluvial	
Galloway (3)	0-5 cm	-0.25	13.47 (65%)	3	Duplex	
Galloway (4)	0-5 cm	0.67	17.75	3	Alluvial	
Leyshon View	0-5 cm	0.06	3.7	15	Yellow Earth	
Meadowvale	0-5 cm	0.24	7.12	15	Yellow Earth	
Kirk River	0-5 cm	-0.23	9.4	15	Yellow Earth	
Silver Valley	0-5 cm	-0.01	5.27	15	Yellow Earth	
Croxdale (1)	0-5 cm	0.05	8.87	24	Red Earth	
Croxdale (2)	0-5 cm	-0.06	11.93	24	Red Earth	
Toorak	0-5 cm	-0.28	10.49±2.06	16	Vertisol	
Average		–0.47 ± 0.85	10.69 ± 1.32			
Rotational grazing strategies vs continuous grazing						
NSW-Brewarina; Cobar	0-30 cm	0		>8	Brewarina sites	Orgill et al 2017b
NSW -ridge sites	0-30 cm	~ 0.8	13.3	>8	Increase to 21.6 (site-specific; did not apply more generally)	Orgill et al 2017b*
NSW rangelands (Vertisols)	0-30 cm	0 (NS)		>8	Av % C change - Rotational	Waters et al 2016

					grazing+exclosure	
NSW rangelands (Lixisols)	0-30 cm	0.23 - 0.3%		>8	% SOC only. Rotational grazing**+exclosure**	Waters et al 2016*
NT - Douglas Daly Research Farm	0-30 cm	0(NS)	16.81—17.35	5	IRG (Cell grazing) vs Set stocking rate	Schatz et al. 2020
SA (rainfall gradient)	0-30 cm	0 (NS)	48.3 (20—80)	5—15	12 paired sites (rotational vs continuous)	Sanderman et al. 2015
N Qld Wambiana	0-30 cm	0 (NS)	29.04 (9.07—54.09)	12	Rotational vs Continuous Detrended for climate	Allen et al. 2013
N Qld Wambiana	0-30 cm	-0.01	34.72 (13.6—83.71)	12	Cell vs Contin grazing. Change detrended for climate (estimated)	Allen et al. 2013

* Results (shaded grey) included in this table to illustrate diversity across sites but not included in assessment of indicative SCS values due to lacking adequate measurement quality of SOC stock change and/or localised site characteristics and insufficient data on representativeness.

Table A2. Pasture management strategies: Published studies with quantified SOC stocks data used for analysing the potential for SCS. (NS – Not significant; NR – Not reported). See Section 2.3.2.

Region	Depth observed	Rate of SCS t C ha^{-1} yr^{-1}	Average C stock t C ha^{-1}	Period of observation Years	Study information	Reference
Pasture improvement						
Southern NSW (Review)	0-30 cm	0.5	NR	Various		Conyers et al. 2015
NSW Wagga Wagga	0-30 cm	0.5-0.7		Predicted long term	Nutrient additions + pasture management	Chan et al. 2011
NSW New England Tablelands	0-30 cm	0 (NS)	43.76 ± 2.07	> 7	P added every 2-3 yr; Baseline 43.04 ± 1.70 (Native pasture)	Wilson & Lonergan 2013
NSW New England Tablelands	0-30 cm	0 (NS)	36.11 ± 2.83	> 10	Lightly wooded; Baseline 43.04 ± 1.70	Wilson & Lonergan 2013
Qld Condamine	0-40 cm	0.46		0-10	Sown pastures GRASP simulations	Clewett 2015*
		0.01		10 - 20		
		0.015		20 - 30		
		-0.036		30 - 40		
Incorporating legumes in pastures						
Qld - Condamine Sown legume pastures	0-40 cm	0.6		0-10	GRASP simulations	Clewett 2015*
		0.113		10 - 20		
		0.032		20 - 50		
Qld – Leucaena grass pasture	0-30 cm	0.27 ± 0.12	NR	Various	average of other studies	Harrison et al. 2015, 2020
Qld – Leucaena grass pasture	0-30 cm	0.267		20	N gain 0.017 t N ha^{-1} yr^{-1}	Radrizzani et al. 2011
	0-30 cm	0.14		31	0.011 t N ha^{-1} yr^{-1}	
	0-30 cm	0.079		38	0.014 t N ha^{-1} yr^{-1}	
	0-30 cm	0.762		14	0.062 t N ha^{-1} yr^{-1}	
Qld - Brian Pastures Leucaena	0-30 cm	0.28		40	0.036 t N ha^{-1} yr^{-1}	Conrad et al. 2017
WA SW Tagasaste	0-200 cm	0.9	30.4	22	Tagasaste at 15% landscape	Wocheslander et al. 2016

* Data summed to give the value for 0-30cm

Table A3. Fire management strategy: Simulation study of fire management strategy effect on SOC stocks in grazed savanna woodlands and grasslands, NT Kidman Springs trial site (Hunt 2014) See Section 2.3.3.

Region	Depth observed	Rate of SCS t C ha^{-1} yr^{-1}	Average C stock t C ha^{-1}	Period of observation Years	Study information	Reference
NT - Kidman Springs	0-30 cm	0.03	32.51	57	Long term grazing	Hunt 2014
Century modelling		0.08	32.51	57	Destocking	
		-0.08	23.3	57	Fire Early 2-yearly	
		-0.05	25.14	57	Fire Early 4-yearly	
		-0.03	26.42	57	Fire Late 4-yearly	
		0.01	28.1	57	Fire Late 6-yearly	

Table A4. Land conversion strategies: Published studies with quantified SOC stocks data used for analysing the potential for SCS. (NS – Not significant; NR – Not reported). See Section 2.3.5.

Region	Depth observed	Rate of SCS t C ha^{-1} yr^{-1}	Average C stock t C ha^{-1}	Period of observation Years	Study Information	References
Conversion of cropland to grassland						
Australian meta-analysis	0-15 cm	0.30-0.60	27.5	4 – 42	Data from field trials	Sanderman et al 2010
Australian Survey	0-30 cm	0.22-0.76	43	10		Chan et al. 2011
NSW Central west (Cowra Trough)	0-30 cm	0.78	35	5		Badgery et al. 2020a
NSW Central west (Cowra Trough)	0-30 cm	0.74	35	5		Badgery et al. 2014
NSW Wagga Wagga	0-30 cm	0.4	42.6	13	Kandosol soils	Chan et al. 2011
	0-30 cm	0.26	42.6	25	Kandosol soils	Chan et al. 2011
Narayan Research Station, Queensland	0-15 cm	1.25	37.19	12		Skjemstad et al. 1994*
	0-15 cm	0.86	41.91	12		
	0-15 cm	1.28	36.84	12		
National synthesis of meta-analysis	0-30 cm	0.172 (–0.144 –0.453)			3 soil types, woodland sites)	Lam et al. (2013)
NW NSW soil type and LU-intensity gradient	0-30 cm	0.06 – 0.15	46, 102, 121	>15 to >100	3 soil types, woodland sites)	Wilson et al 2011
NSW Liverpool Plains (Vertisol)	0-20 cm	0.17	24-26	7		Young et al 2009
Conversion of forest to grassland						
Qld - Brigalow Catchment Study	0-30 cm	–0.05	54.8 ± 3.9	33	Baseline: 0.177 ± 0.059 (5.85 t C ha−1 increase)	Dalal et al 2021b
NSW - N-W soil type and land use gradient	0-30 cm	-0.86	101.83	20-30	Native woodland to pasture – Av. for pasture type and soil types	Wilson et al 2011*
NT Daly R, Katharine regions	0-30 cm	0.34	15.1	28	NEP = –0.76 t Cha-1 y-1	Livesley et al 2021*
Mulga View, SW Queensland	0-30 cm	0.12	27	20	Mulga cleared to Buffel grass	Dalal et al. 2005
Qld - Brigalow Catchment Study	0-40 cm	0/NS	84	23	Native brigalow to pasture – small negative effect	Dalal et al. 2011
Qld - Brigalow Belt; native brigalow to pasture	0-30 cm	-0.38 (-0.15 – -0.61)	46 (27–116)	18–73	Vertosol (est. median and age range)	Allen et al. 2016
	0-30 cm	-0.62 (-0.38 – -0.87)	49 (31–87)	15–34	Dermosol (est. median and age range)	Allen et al. 2016
NT - Douglas Daly catchment	NR	-1.1	NR	25–30	Estimated – flux measurements	Grover et al. 2012*

NT - Douglas Daly catchment	NR	-0.2	NR	2	Estimated – flux measurements	Bristow et al. 2016*
Conversion grassland to forest						
S & E Australia	0-30 cm	0.57 ± 0.06	46.5 (15.4—160.2)	2 —29	Significant for 52% of sites (cropping+grazing)	England et al 2016*
Australia – forest plantings	0-30 cm	0 /NS	NR	NR	Initial loss (~5 yrs) followed by recovery	Paul et al. 2002
Eucalyptus grandis planted on Qld pastures	0-30 cm	-0.2	NR	40	FullCam model; lacks calibration data for N Australia	Paul et al. 2003*
N NSW, SW WA sheep regions	0-30 cm	0/NS	NR	NR	Review for tree plantings on pasture	Henry et al. 2015
Qld - Brigalow Belt	0-30 cm	0/NS	35 (22–76)	21-45	Brigalow regrowth (Vertosol)	Allen et al. 2016
	0-30 cm	0/NS	36 (16–56)	10–58	Brigalow regrowth (Dermosol)	Allen et al. 2016
Global grassland conversion to forest	Various	NS	NR	NR	Review of 124 global studies	Deng et al. 2016*

* Included for information but not included in averaging due to unsuitable measurement methods: insufficient depth (Skjemstad et al. 1994); location not relevant to N Australia; no clear link between land conversion and SOC due to multiple management changes (Livesley et al. 2021); measurement method not established as reliable for SCS monitoring (Grover et al. 2012)+; period of observation since conversion too short to assess SCS (Bristow et al. 2016); data for SCS following reforestation does not separate initial land use (cropping vs grazing) (England et al. 2016); suitability of model calibration data for N Australian grazing lands unknown (Paul et al. 2003); unclear relevance of global review averages with very few Australian studies (Deng et al. 2016).

Appendix B: Acronyms

ACCU	Australian Carbon Credit Unit
BD	Bulk Density
C	Carbon
CCA	Climate Change Authority
CEA	Carbon Estimation Area
CER	Clean Energy Regulator
CFI	Carbon Farming Initiative
CH_4	Methane
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent [emissions]
COP	Conference of Parties [to the UNFCCC]
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DISER	Department of Industry, Science, Energy and Resources
DPIRD	Department of Primary Industries and Regional Development
ERF	Emissions Reduction Fund
ESM	Equivalent Soil Mass
FAO	Food and Agriculture Organisation of the United Nations
FullCAM	Full Carbon Accounting Model
GHG	Greenhouse gas
GWP	Global Warming Potential
GWP_{100}	Global Warming Potential over a 100 year period
HM	Holistic Management
IPCC	Intergovernmental Panel on Climate Change
IRG	Intensive Rotational Grazing
MAOC	Mineral Associated Organic Carbon
MAP	Mean Annual Precipitation
MDD	Minimum Detectable Difference
MRV	Monitoring, Reporting and Verification
N_2O	Nitrous oxide
NDC	Nationally Determined Contribution
NPP	Net Primary Productivity
POC	Particulate Organic Carbon
POM	Particulate Organic Matter
R&D	Research and Development
RothC	Rothamsted Carbon model
SCS	Soil Carbon Sequestration
SOC	Soil Organic Carbon
SOM	Soil Organic Matter
TC	Time-controlled [grazing strategy]
TERN	Terrestrial Ecosystem Research Network
TGP	Total Grazing Pressure
UNFCCC	United Nations Framework Convention on Climate Change
VPD	Vapour Pressure Deficit