Final report

Time-controlled grazing for soil C sequestration and improved ecosystem services

Project code: P.PSH.2104

Prepared by: David Rowlings, Elaine Mitchell, Liam Grace, David Tucker, Carol Richards and Rudi Messner
Queensland University of Technology

Date published: 4 December 2024

PUBLISHED BY
Meat & Livestock Australia Limited
PO Box 1961
NORTH SYDNEY NSW 2059

This is an MLA Donor Company funded project.

Meat & Livestock Australia acknowledges the matching funds provided by the Australian Government to support the research and development detailed in this publication.

Table of contents

1. Abstract

Time-Controlled Grazing (TCG) has been promoted for its potential to improve soil health, pasture productivity, and livestock performance. However, its adoption in Australia has been limited due to conflicting scientific evidence. This study provides a farm-scale assessment of TCG's impact, focusing on soil organic carbon (SOC) sequestration and biodiversity. Ideally, long-term trials (15+ years) with established baseline conditions would be conducted to evaluate these effects. In the absence of such trials, a paired-site approach was used, comparing TCG-managed farms with conventionally managed farms matched for land use history, soil type, and vegetation.

While this paired-site method offers valuable insights, it has limitations. Even if pairs have been matched closely for land use history, soil type etc. the approach can only show the difference between TCG and conventional sites after a set period, without capturing the dynamics of SOC accumulation over time. To strengthen the paired site analysis, eddy covariance flux towers were employed for high-resolution carbon flux measurements, complemented by long-term remote sensing data (1990–2023) for monitoring vegetation. Additionally, the study included a broader analysis of social and environmental outcomes beyond carbon, providing a broader view of TCG's potential benefits.

Results indicate that SOC stocks were significantly higher in 4 out of 5 TCG sites, with a difference of 17.7 t C/ha. TCG systems also demonstrated a greater amount of stable carbon (MAOM-C) and nitrogen stocks, particularly in the topsoil (0-30 cm), along with greater microbial biomass.

These long-term differences, observed after an average of 22 years of TCG implementation, were not reflected in the short-term flux tower data. Over two to three years, no significant differences in carbon drawdown were observed between TCG and conventional systems, likely due to the overriding influence of rainfall variability. This demonstrates that it is necessary to measure SOC changes over a long (15+ years) duration. In the case of carbon credit schemes, it also suggests that crediting soil carbon projects on management changes over periods of less than three years presents risks of non-additionality i.e. crediting for SOC changes that would have occurred in the absence of the project.

Long-term remote sensing (1990-2023) indicated that TCG sites maintained better ground cover, particularly during dry periods. Biodiversity monitoring, using low-cost sensors, revealed higher levels of audible insect activity in TCG systems, although bird species richness and composition were more influenced by proximity to woody vegetation than by grazing management.

The study also found that TCG farmers rely more on data-driven management, which supports adaptive decision-making and positions them more favourably to benefit from emerging carbon and nature markets. While environmental and social benefits were observed in TCG systems, production and profitability outcomes were not assessed.

This research underscores the value of high-resolution tools like flux towers and ecoacoustics for assessing carbon dynamics and ecosystem health. Future research should aim to integrate these technologies into a national framework for sustainable grazing management to better track the long-term impacts of TCG and other grazing systems.

2. Executive summary

Background

Scientific and anecdotal evidence on the merits of Time-Controlled Grazing (TCG) presents a conflicting picture, with limited data from Australia contributing to more confusion about TCG's effectiveness. The lack of consensus on the definition and merits of TCG stalls the adoption of a potentially useful management option.

Advocates for TCG, within a holistic grazing management system, argue that it enhances soil health, improves pasture composition and growth, and boosts cattle growth and profitability (McCosker, 1994, 2000). While some international scientific studies highlight TCG's benefits (Mosier, 2021; Rowntree et al., 2020) Australian research on the subject is sparse, and those studies that do exist report inconsistent results regarding soil carbon storage (see McDonald et al., 2023).

This study aimed to break through this impasse by conducting a holistic examination of the effects of TCG at the farm scale, incorporating human dimensions such as producer decision-making and ecosystem services such as biodiversity and carbon storage. We hypothesised that TCG grazing, characterised by the combination of high daily animal stock densities, fast rotations, long pasture rest, iterative monitoring, and adaptive management of stocking rate, would have greater SOC sequestration by maintaining ground cover and increasing biomass inputs.

Objectives

- To quantify differences in soil organic carbon (total carbon stocks, stable and labile SOC fractions) between conventional grazing and TCG in subtropical systems in the Brigalow Belt Bioregion.
- To quantify biodiversity generated with different grazing management.
- To qualitatively assess differences in producer wellbeing.

Methodology

We used a paired site approach to compare TCG farms with a variety of other farms employing different management practices, ranging from set-stocking to rotational systems – defined in this report as ‘conventionally’ grazed systems. This method enabled a broad comparison across common industry practices.

We examined five pairs of sites, focusing on key variables such as soil carbon, soil nitrogen, plant biomass, net carbon drawdown, evapotranspiration, and biodiversity. Ideally, studying these differences over a longer period (15+ years) would be necessary to ensure that any observed differences between sites were due to management changes. However, to provide more timely insights, we adopted a paired site approach where TCG had been in place for an average of 22 years.

The paired farms were matched as closely as possible in terms of land use history, soil type, mineralogy, vegetation, topography, and climate[1]. To ensure the robustness of our conclusions, we

[1] In 2021-2022, SOC was measured on five TCG properties and five conventionally grazed properties. Since it was not possible to measure baseline SOC stocks at the time of TCG implementation, a paired site approach was employed. To minimise the potential confounding effects of differing land use and management histories on current SOC stocks, sites were matched as closely as possible in terms of these factors, with particular attention to (a) time since tree clearing and (b) cropping history. We assumed the impact of forest clearance on SOC to be minimal, as research indicates that after an initial rapid loss of SOC following forest clearance (~3 t C/ha), a new steady state is typically reached within five years (Dalal et al., 2021). In contrast, the legacy effect of cropping on SOC is likely more significant, requiring a

employed complementary research methods beyond the paired site analysis. For instance, we used eddy covariance flux towers to capture high-resolution, real-time data on carbon drawdown (net ecosystem carbon exchange) under different management regimes, we analysed long-term remote sensing data (1990 to 2023) to assess changes in ground cover before and after the implementation of TCG, and we examined broader social and environmental outcomes from TCG.

While this paired-site method offers valuable insights, it has limitations. Even if pairs have been matched closely for land use history, soil type, climate etc. the approach can only show the difference between TCG and conventional sites after a set period, without capturing the dynamics of SOC accumulation over time. For instance, the difference observed could either be due to a decline in SOC under conventional management relative to TCG, or SOC levels in conventional grazing might have remained stable while TCG led to an increase (see Appendix 12.1 for visualisation of these scenarios). Having said this, the most likely scenario for SOC under conventional grazing is stable over time as indicated in the Brigalow Catchment Study (Dalal *et al.,* 2021) (Appendix 12.1).

Results/key findings

- SOC stocks were significantly greater in TCG in comparison to conventionally grazed systems in 4 out of 5 pairs across vertosol soils in the Brigalow Belt Bioregion. Across all 5 pairs, there was significantly greater SOC in TCG systems (~17.7 t C/ha greater).
- Mineral associated organic matter (MAOM-C) (stable carbon) was significantly greater in TCG systems (30% greater in TCG systems).
- The greatest differences in SOC between TCG and conventional systems were observed in the top 55 cm, while there was no significant difference >55 cm.
- N stocks were significantly greater in TCG systems (27% greater in TCG systems).
- There was significantly greater soil microbial biomass in TCG systems (45% greater in TCG systems).
- Ground cover retention during dry periods was greater in TCG systems.
- In contrast to the significant difference in soil organic carbon (SOC) stocks observed between paired sites (with an average of 22 years of TCG implementation), no detectable difference in carbon drawdown was found over the short term (2 to 3 years) between TCG and conventional farms, as measured by flux towers using net ecosystem exchange.
- We suggest that a lack of difference in carbon drawdown between TCG and conventional in the short-term was likely due to the dominant influence of rainfall on SOC gain during the measurement period, which was characterised by favourable La Niña conditions.
- Audible insect activity, as indicated by the high frequency cover (HFC) acoustic index, was higher in TCG compared to conventional grazing pastures. This increase was attributed to greater ground cover and pasture height in TCG farms. Bird species richness and composition was not influenced by grazing management and was instead significantly influenced by the proximity to woody vegetation.
- The qualitative approach provided a nuanced understanding of graziers' experiences during favourable climate and market conditions, where optimism and satisfaction were high across all management types (TCG and conventional). A key difference noted between TCG and conventional farms was the reliance on data-driven decision making, which likely reduced

longer period to achieve a new steady state under pasture management. Only one pair of farms had different cropping histories (pair 1). In this pair, the TCG site was cropped from 1976 to 1990 (14 years), while the conventional site was cropped from 1960 to 1992 (32 years).

stress, improved management, and enhanced mental wellbeing. TCG farms demonstrated a greater use of digital technology and structured planning, compared to non-TCG farms, which often relied on intuition and unwritten plans. Data-based management practices not only supported business success but also positioned these farms to benefit from emerging opportunities in carbon and nature markets. Broader adoption of improved data management practices, with support from industry bodies, could foster wellbeing across all grazing systems while advancing sustainability outcomes.

Benefits to industry

The research demonstrated that SOC was significantly greater (~17.7 t C/ha) on TCG farms in the Brigalow Belt bioregion (measured after 20+ years of TCG implementation) than on conventional grazing systems, possibly indicating a long-term potential for SOC accumulation through the implementation of combined management practices such as those used in TCG systems (cell based grazing, adaptive grazing methods based on pasture production, shorter grazing/longer resting periods).

Future research and recommendations

We have demonstrated the proof-of-concept for generating high resolution data on soil carbon storage (flux towers) and ecosystem outcomes (ecoacoustics) at the property scale. The recommended next step is to incorporate these state-of-the-art observation tools into a nationally consistent framework for sustainable grazing management that can rapidly assess innovation and drive on-the-ground change. This will allow producers to access independent data on the impacts of management change and the potential for soil carbon sequestration in their region. Long-term monitoring networks will also be crucial for measuring, reporting and verification of emerging natural capital markets.

3. Background

3.1 Introduction

Emissions from livestock account for 10-15% of Australia's greenhouse gas emissions. In response, the Australian red meat industry has set an aspirational target of net-zero emissions by 2030. The target, known as CN30, necessitates various actions, including the identification and adoption of grazing management approaches that reduce emissions and/or sequester carbon in both soil and vegetation. Additionally, these strategies should demonstrate environmental co-benefits, be economically viable, and uphold the industry's social license to operate (Harrison et al., 2021).

3.2 What is soil organic carbon and how is it formed?

Soil organic matter (SOM), the largest terrestrial carbon (C) pool, is fundamental to soil and ecosystem functions across a wide range of scales, from site-specific soil fertility and water holding capacity to global biogeochemical processes that influence carbon-climate feedbacks (Paustian et al., 2016). Human appropriation of land for agriculture has decreased soil organic carbon (SOC) by ~25% to 75% depending on climate, soil type and the management of soil, resulting in the emission of at least 150 Petagrams (one billion metric tonnes) of carbon dioxide to the atmosphere. Recapturing even a small fraction of these legacy emissions through improved land management would represent significant GHG mitigation, whilst restoring soil health (Sanderman et al., 2017).

In agroecosystems, SOC content is determined by the balance between inputs of C through plant residue and the return of C to the atmosphere through the decomposition of organic matter i.e. heterotrophic soil respiration. Therefore, any practice that increases carbon input (e.g. residue retention, fertilisation, frequency of fallow, crop type and pasture management), or reduces decomposition rates (e.g. reduce soil disturbance through no-tillage) typically increases SOC stocks. Improved soil management also provides multiple co-benefits, such as enhanced nutrient cycling, boosting plant productivity, and increasing farm profitability.

Soils accumulate organic matter primarily from plants through the continued release of exudates from plant roots, root tissue turnover and deposition of aboveground plant residues. These inputs are defined as soil organic matter (SOM) from the moment they are found in soil and less than 2 mm in size. Within the soil, SOM (approximately 60% of which is SOC) undergoes various chemical and physical transformations. Throughout these processes, a large portion of the SOC is converted to CO_2 through microbial respiration. The efficiency of SOC formation is defined by the ratio of SOC gained to carbon lost during decomposition, typically ranging from 3% to 33% (e.g. Mitchell et al., 2021; Parton et al., 2007).

The majority of plant C inputs are mineralised by soil microorganisms and respired to the atmosphere over short time scales. However, a proportion cycles through the soil slowly, persisting for centuries to millennia as it is 'protected' from microbial degradation (Lützow et al., 2006). Plant carbon inputs can be protected (or stabilised) within the mineral soil through strong physicochemical sorption to mineral surfaces (e.g. ligand exchange) and/or spatial separation from soil microorganisms (e.g. via occlusion within microaggregates).

3.3 What factors drive changes in SOC stocks over time in grazing landscapes?

The main factors that influence SOC stock changes over time in grazing systems are the impacts of climatic changes and management practices, through their effects on the inputs of C from plant litter and roots (Stockmann et al., 2013).

Grazing management influences various factors such as ground cover, plant productivity, C input allocation (root versus shoot allocation), input quality (C:N ratio) and plant diversity. Alterations in these ecosystem components due to grazing subsequently impact soil biogeochemistry, shaping pathways of SOC formation.

Rainfall is the primary driver of variability in Australia's carbon cycle, with seasonal, annual and decadal variability interacting to mediate plant composition, productivity, carbon inputs, and carbon losses from microbial activity (Gray et al., 2015; Hobley et al., 2015; Parton et al., 2012; Parton et al., 2015; Rabbi et al., 2015). Generally, increased rainfall enhances primary productivity and the delivery of carbon inputs to the soil organic matter pool through litterfall, root growth, sloughing and exudation (Wiesmeier et al., 2019). The most apparent trend in plant growth is intra-annual variation, causing a seasonal saw-tooth pattern (Del Grosso et al., 2008; Del Grosso et al., 2018). Australia also has high year-to-year and decade-to-decade variability in rainfall and pasture growth driven, in part, by the El Niño Southern Oscillation (Mckeon et al., 1990; Nicholls, 1991) and Inter-decadal Pacific Oscillation (Power et al., 1999), although the latter may simply reflect clustering of El Niño and La Niña years (Power et al., 2006). Depending on the location, other persistent climate drivers such as the Southern Annular Mode (Meneghini et al., 2007) and Indian Ocean Dipole (Meyers et al., 2007; Risbey et al., 2009) also contribute to year-to-year variability in rainfall, which is around 23% more variable than any other country (Love, 2005).

While climatic changes and management practices influence C inputs from plant litter and roots, soil type is the primary determinant of the ability of soil to retain SOC over time. The capacity of soil to retain additional C inputs will largely depend on the ability of the soil to 'protect' added organic material (Bai & Cotrufo, 2022; Lehmann & Kleber, 2015), which in turn depends on clay content and mineralogy, soil structure (micro and macro aggregation), location within the soil profile, chemical nature and composition of organic matter inputs, and the occupancy of mineral surfaces by pre-existing carbon compounds, i.e. the degree of SOC saturation (Stewart et al., 2007).

3.4 Types of grazing systems

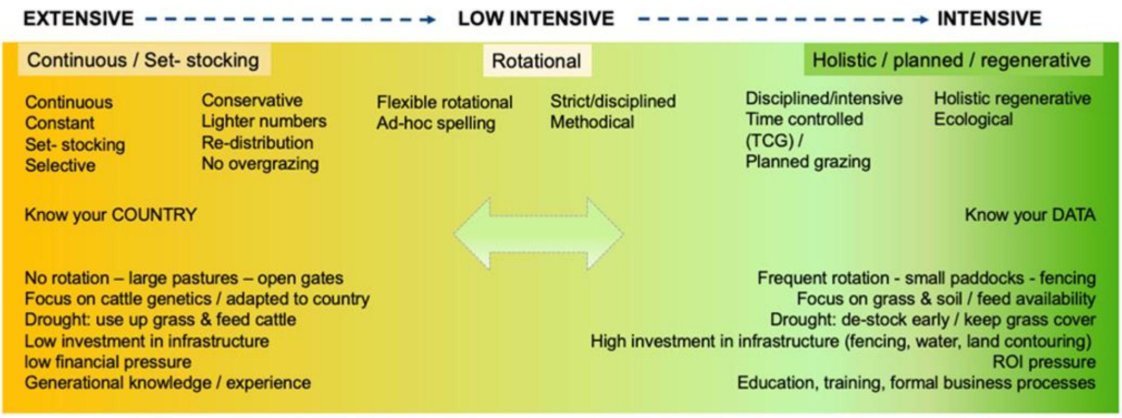
In the Australian beef industry, it is common to refer to three broad categories of grazing systems. These are continuous (or ‘set stocking’), rotational, and time-controlled grazing (‘TCG’ or ‘cell grazing’) (Bartley et al., 2023; Hall et al., 2014) However, the distinctions between different grazing systems reflect more of a continuum of practices rather than clear and separate typologies. We have articulated the continuum of grazing in Fig. 1. (as part of social science outputs),

Continuous grazing systems, also known as set stocking, are often considered a conventional or traditional approach to livestock management (Hall et al., 2014). According to Hall et al. (2014), continuous grazing involves livestock being left in one paddock for extended periods with little or no adjustment in numbers in response to changes in forage supply or body condition. Allen et al. (2011) describes this practice as characterized by unrestricted and uninterrupted access to pastures. Well-managed continuous grazing can be simple to implement, requires minimal labour, and can yield good outcomes in certain circumstances (MLA, 2024). However, the disadvantages include the risk of pasture under- or over-utilization and the potential for overgrazing or the depletion of preferred forage species (Hall et al., 2014).

Rotational grazing addresses some of the concerns around grazing systems based on set stocking by introducing objectives of ground cover, rotation and resting of pasture and conditional stocking rates. It is organised around plant growth cycles and moving cattle through various paddocks to optimise pasture utilisation and allow pastures to recover (Hall et al., 2014).

Time-Controlled Grazing (TCG), commonly referred to by producers as cell grazing, is a relatively recent addition to Australia's grazing systems. While similar to rotational grazing, TCG is more intensive, involving a greater number of paddocks or 'cells'. Unlike fixed rotational systems, TCG adjusts the duration of grazing and rest periods based on specific criteria such as plant regrowth, soil health, and animal nutrition. The primary advantage of TCG lies in its focus on grazing plants during their vegetative growth phase (commonly referred to as phase 2 growth – see appendix for explanation) for shorter durations. This approach aims to reduce the overgrazing of preferred species, a common issue in continuous grazing. After grazing, pastures are rested, allowing perennial plants to replenish root reserves, improving both soil structure and overall land condition (MLA, 2024). However, TCG requires additional infrastructure and labour, making it less practical in certain conditions, such as during periods of poor plant growth or during lambing and calving. It is also difficult to implement on broad scale, low productivity rangelands where the increased capital cost of creating smaller paddocks can be difficult to justify. Additionally, the reduced opportunity for selective grazing in TCG systems may lead to a decrease in per-head animal production, as livestock are often required to graze less nutritious plant species (MLA, 2024).

Figure 1: Grazing practices along a continuum with an indication of where each paired farm in the study are situated along the continuum. This conceptual diagram was generated as an output from the social science component of the project.



3.5 Towards a consensus on the impact of grazing on SOC and ecosystem outcomes

A recent meta-analysis of Australian studies (n=31) found no significant effect of stocking intensity (high *versus* low) or method (continuous *versus* rotational) on SOC (McDonald et al., 2023). Of the studies that reported a difference in SOC with stocking method (continuous versus rotational) results were extremely varied. The variability in measured SOC responses to grazing management have led to confusion rather than consensus on the impact of TCG. To advance a consensus on the effects of TCG on SOC this study was structured to address the shortcomings noted in prior research (Table 1).

Table 1: Addressing the shortcomings noted in prior research on grazing impact on SOC

Shortcomings of prior research	Addressing the shortcomings in this research
Common agronomic methods used in grazing research typically involve basic grazing treatments on small (circa 25 m x 25 m), closely monitored, and replicated plots to establish cause and effect. However, increasing evidence suggests that results from these small-scale experiments often differ from those conducted at the farm scale. This discrepancy arises because accurately simulating and replicating adaptive TCG in experimental designs is challenging. Researchers do not engage in the same decision-making processes as producers, as noted by Teague (2013).	We conduct a comprehensive analysis of the impact of various grazing management approaches at the farm scale. Our study incorporates multiple aspects of the ecosystem, such as plants, soil, water, and GHG emissions to ensure a thorough system-wide evaluation. This approach contrasts with the more limited scope of reductive plot-scale experiments focused solely on cause and effect.
Detecting a significant change in SOC using soil coring can be challenging because changes relative to existing carbon stocks are minor in magnitude and vary spatially across different scales. As such, a comprehensive and sophisticated sampling plan is required to detect smaller changes in SOC soil that are attributed to grazing management (Stanley et al., 2023)**.**	When conducting soil core sampling, we ensured 'a comprehensive and sophisticated sampling plan' – see section 4.3 for details. We also employed analytically sensitive measurement approaches to detecting SOC change over time. This involved the use of (a) flux tower technology to measure frequent and highly accurate measurements of CO_2 exchange between the atmosphere and the land surface, and (b) measurements of 'stable' soil C rather than changes in total organic C content, as total organic C content can fluctuate greatly over time due to seasonal variations.
Prior studies only measured the top 10 to 30 cm of soil, whereas SOC accumulation may occur in the sub-soil.	We measured to 1 m depth.
Some studies measured differences in C concentration over time (% C) and did not account for variations in bulk density.	We converted %C to SOC stocks at multiple depth layers to account for differences in bulk density.
Some studies used sites where management had not been implemented for a sufficient period of time (e.g. <5 years). Numerous studies indicate that a minimum of seven to 10 years is required to detect soil organic C (SOC) change from management.	Our study sites had implemented TCG for at least 10 years.

Sustainable grazing outcomes should not be reduced solely to biophysical and environmental variables but should also be related to social benefits such as increased social capital and community.	This study explored grazing system holistically by including a social science module on management variables such as dimensions of wellbeing, including achievement, community, health and empowerment, decision making and socio-economic outcomes.
Prior studies on TCG were affected by confounding factors e.g. (Allen et al., 2013) **whereby TCG and conventional farms were compared across different climates and soil types.**	This study used paired sites that were co-located in the same climate, soil type, land use history (see methods).

4. Objectives

In response to the issues described above, the overall aim of this project was to determine if TCG can increase soil C stocks and improve the delivery of ecosystem services. The specific project objectives and progress against them are listed in the table below.

1.	To deliver a scientific assessment and review of the current research on the effect of TCG on soil C stocks within an Australian context and identify critical knowledge gaps and potential.	Achieved
2.	To quantify soil C differences between TCG and non-TCG systems in subtropical grazing systems.	Achieved
3.	To determine if flux tower measurements (combined with pasture production and remote sensing) can detect and quantify smaller annual soil C changes associated with TCG at the landscape level.	Achieved
4.	To quantify ecosystem services generated with different grazing management.	Achieved
5.	To disseminate the key findings of our study on TCG to a wide range of stakeholders. This will include a framework for evidence-informed decision-making on TCG uptake.	Achieved
6.	To develop a sustainable grazing framework that incorporates economic, social and environmental aspects of management that regenerates soil in the subtropics.	Achieved
7.	To develop a draft Carbon EDGE module for TCG that can be incorporated into the Carbon EDGE package designed in CSP module 1.	Submitted and awaiting feedback

5. Methodology

5.1 Paired site approach

TCG farms were paired with a control farm that was managed 'conventionally' (CONV). See Fig. 2 for the location of farm pairs, which were largely located in central Queensland, with one additional pair in southern Queensland. The paired site approach is commonly used in scientific studies to compare treatments to each other in the absence of the pretreatment baseline for SOC stocks (e.g. Chan et al., 2010; Murphy et al., 2003).

The paired site method assumes that two sites with similar initial conditions - but under different management regimes - can serve as proxies for a temporal sequence. For instance, if one site has undergone a specific management change for 20 years, researchers might conclude that a comparable site, if subjected to the same management change, would likely exhibit similar outcomes after a similar duration. This approach allows for the assessment of long-term management impacts without waiting for real-time changes to unfold over decades. The paired site approach is especially valuable in agricultural systems, where understanding management impacts quickly is crucial for guiding practices and policies, rather than waiting decades to see the effects of a management change.

However, the paired site approach comes with limitations, including the assumption that the paired sites are similar in all significant aspects other than management practices. In reality, differences in soil type, prior management, vegetation (including pasture species), microclimate, historical land use, and other environmental factors could influence outcomes, thereby complicating the attribution of observed differences to management alone. The non-linear and complex ecological responses to management practices such as grazing further complicates the extrapolation of results.

To mitigate the limitations of the paired site approach, the paired farms were matched as closely as possible in terms of land use history, soil type, mineralogy, dominant pasture species, topography, and climate. Details on the paired sites are provided in Tables 2 and 3. We also employed complimentary research methods to ensure that our conclusions were not solely based on the outcome of paired site analysis. For example, we used the eddy covariance flux towers to determine real-time carbon drawdown (as measured by net ecosystem exchange, NEE) under the different management regimes and long-term remote sensing of vegetation (2000 to present) to examine long-term trends in ground cover with TCG implementation.

A potential confounding factor in the establishment of paired sites was that for four of the five pairs, tree clearing occurred approximately 15 years later in the TCG site compared to the non-TCG site. However, the legacy effect of differing tree clearance timelines on SOC was assumed to be negligible, as research from the Brigalow Belt indicates that following forest clearance and establishment of a pasture phase, there is an initial rapid loss of SOC (~5 t C/ha). However, a new steady state at lower SOC levels is typically reached within five years in the pasture phase (Dalal et al., 2021) (see Appendix for data on the conversion of forest to pasture in the Brigalow Belt).

In contrast, the legacy effect of cropping to pasture on SOC stocks is likely more significant, requiring a longer period to adjust to a new steady state under pasture management (Jones et al., 2016). We encountered challenges in determining the legacy impact of cropping in pair 1. In pair 1, the TCG site was cropped from 1976 to 1990 (14 years), while the CONV site had been cropped from 1960 to 1992 (32 years). The longer cropping history at the CONV site had the potential to cause greater SOC depletion in comparison to the TCG site. However, the CONV site in pair 1 had greater SOC in 2022 compared to the TCG site. Thus, the differing cropping histories at pair 1 did not affect the overall study outcome, which found that TCG sites generally had greater SOC stocks.

5.2 Paired site selection

TCG farms were selected on the basis of the following criteria:

- TCG had been implemented for at least 10 years.
- Grazing rotation decisions are made adaptively rather than according to a set regime.
- Farms were subdivided into multiple small paddocks where livestock rotation was based on adaptive decision-making according to forage availability and recovery.
- Grazing periods were short (1-7 days per paddock), allowing for extended rest periods.
- Grazing management plans or apps (e.g., Maia Grazing) were used to guide decisions on livestock rotations.
- Paddock monitoring included, at a minimum, tracking forage availability through in-field visual monitoring and/or remote sensing tools (e.g., Cibo Labs) to guide livestock rotations and targeted rest periods.
- Animal stocking densities were higher than average (typically > 5-10 head/ha).

Paddocks of similar soil type, slope and vegetation between sampling pairs were identified using a combination of remote sensing, available soil maps, producer interviews and preliminary soil sampling (including X-ray diffraction (XRD) for mineralogy).

The study included five pairs of TCG (Time-Controlled Grazing) versus CONV farms. Four of these pairs were located within 200 km of Rockhampton in Central Queensland, while the fifth pair was situated approximately 25 km northeast of Goondiwindi in southern Queensland (Fig. 2). Paired paddocks in central Queensland were no greater than 5 km apart. In southern Queensland, the paired paddocks were 25 km apart. TCG practices had been implemented on the TCG properties for 14 to 26 years (with a mean of 22 years) prior to soil sampling in 2022. Sampling of paired sites occurred concurrently (i.e., within days of each other).

Control farms, managed conventionally, represented a range of management intensities from frequent rotational grazing to continuous set-stocking. It was essential to select control farms that did not exhibit poor management practices, such as obvious overgrazing, to avoid biased results that might inherently favour any grazing system when compared to poorly managed farms. To ensure this, paddocks in condition C or D (as determined by the Land Condition Assessment Tool, Queensland Government) were excluded. The goal was to provide a rigorous comparison between TCG farms, which adhered to specific, predefined criteria, and CONV farms that did not follow these strict TCG guidelines.

Table 2: Paired farms (1 to 5) and associated attributes that were matched as closely as possible.

Pai r	Grazing management	Landform	Vegetation	Soil type	Dominant pasture species	Bioregion	Tree clearing	Cropping history	TCG established
1	Time-controlled grazing	Cainozoic clay plains	Open pasture of natives and exotics	Vertoso l	Dichanthium sericeum	Brigalow Belt	1972	1976-1990 (15 years)	2009
1	Conventional	Cainozoic clay plains	Open pasture of natives and exotics	Vertoso l	Dichanthium sericeum	Brigalow Belt	1960	1960-1992 (33 years)	
2	Time-controlled grazing	Cainozoic clay plains	Open pasture dominated by exotic C4 grasses	Vertoso l	Cenchrus ciliaris	Brigalow Belt	1988	None	1998
2	Conventional	Cainozoic clay plains	Open pasture dominated by exotic C4 grasses	Vertoso l	Cenchrus ciliaris	Brigalow Belt	1977	None	
3	Time-controlled grazing	Alluvial clay plains	Open pasture dominated by exotic C4 grasses	Vertoso l	Cenchrus ciliaris	Brigalow Belt	1960	None	2000
3	Conventional	Alluvial clay plains	Open pasture dominated by exotic C4 grasses	Vertoso l	Cenchrus ciliaris	Brigalow Belt	1950-1960	None	
4	Time-controlled grazing	Mesozoic igneous rocks	Open pasture dominated by native grasses	Vertoso l	Bothriochloa ewartiana	Brigalow Belt	Not available	None	1996
4	Conventional	Mesozoic igneous rocks	Open pasture dominated by native grasses	Vertoso l	Bothriochloa ewartiana	Brigalow Belt	Not available	None	
5	Time-controlled grazing	Cainozoic clay plains	Open pasture of natives and exotics	Vertoso l	Cenchrus ciliaris	Brigalow Belt	1960	None	1996
5	Conventional	Cainozoic clay plains	Open pasture of natives and exotics	Vertoso l	Cenchrus ciliaris	Brigalow Belt	1950	None	

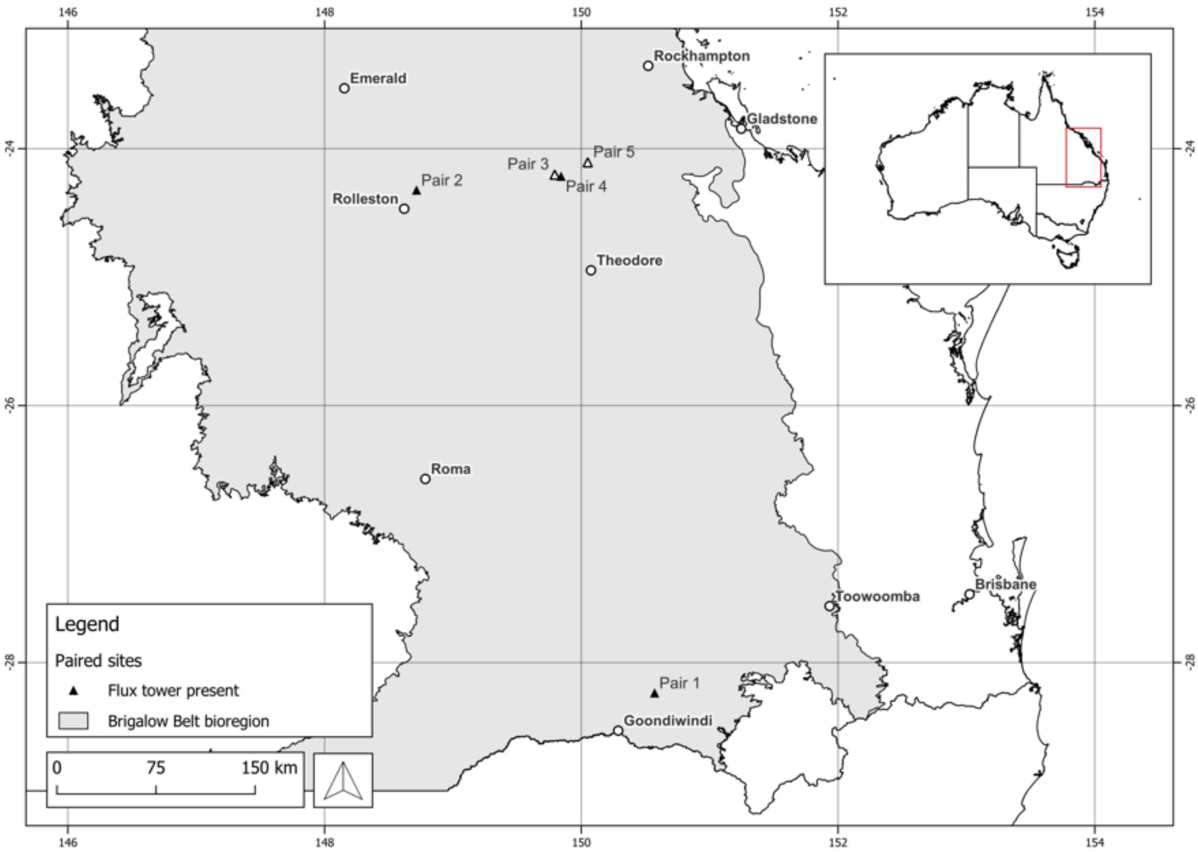
Table 3a: Matching of farm pairs according to soil physical and chemical properties (0-30 cm)

Pair	Grazing management	Sand (%)	Silt (%)	Clay (%)	CEC (cmol/kg)	EC (µS)	pH
1	Time-controlled grazing	38.0	14.7	47.3	29.4	179.2	8.4
1	Conventional	28.3	14.4	51.1	33.9	260.4	7.7
2	Time-controlled grazing	50.6	9.6	39.8	32.1	226.0	7.5
2	Conventional	48.6	7.8	36.5	34.6	191.4	8.3
3	Time-controlled grazing	29.9	16.4	53.8	31.9	259.1	8.1
3	Conventional	67.5	17.3	50.3	31.2	270.2	7.9
4	Time-controlled grazing	39.9	16.2	43.9	19.1	63.0	7.1
4	Conventional	44.0	13.7	42.4	14.7	36.6	6.8
5	Time-controlled grazing	47.7	16.4	35.9	32.9	173.6	7.9
5	Conventional	44.4	14.6	41.0	29.2	213.2	8.3

Table 3b: Matching of farm pairs according to soil physical and chemical properties (30-100 cm)

Pair	Grazing management	Sand (%)	Silt (%)	Clay (%)	CEC (cmol/kg)	EC (µS)	pH
1	Time-controlled grazing	41.1	12.3	46.6	33.5	570.7	8.7
1	Conventional	26.8	15.4	48.0	35.2	723.0	7.2
2	Time-controlled grazing	46.8	8.2	45.0	44.0	720.4	8.7
2	Conventional	41.5	9.9	43.2	37.6	485.7	8.7
3	Time-controlled grazing	26.4	15.5	58.1	35.1	1223.7	7.4
3	Conventional	32.7	10.6	56.6	32.1	1069.1	6.4
4	Time-controlled grazing	44.3	12.7	43.0	22.8	82.5	7.9
4	Conventional	55.2	12.7	37.5	14.4	41.7	7.6
5	Time-controlled grazing	49.9	10.2	39.9	49.0	949.8	9.0
5	Conventional	43.0	12.4	44.6	43.3	985.8	8.9

Figure 2: Approximate locations of paired sites within the study. Closed triangles represent the co-location of eddy covariance flux towers.



5.3 Soil sampling for C and N and soil properties

Soil samples were taken along 100 m transects within the same paddock. Transects were identified according to the factor likely causing the greatest variation in the SOC within the paddock e.g. slope, distance to watering point. A total of four transects, with 6 samples along each transect were taken (n=24 soil cores per farm).

Soil coring was completed to a fixed target depth of 100 cm or maximum achievable depth. Soil cores were extracted using a hydraulic sampler fitted with PVC-lined push-probe with a typical cutting diameter of 42mm (range 40.8 to 44mm). All soil analysis was conducted according to SCARP protocol (Sanderman et al., 2011) and the Clean Energy Regulator, (2023) for carbon projects registered under the Carbon Credits (Carbon Farming Initiative – Estimation of Soil Organic Carbon Sequestration using Measurement and Models Methodology Determination 2021.

Intact cores were returned to the laboratory and cut to fixed depth intervals (0-10, 10-30, 30-50, 50-70, 70-100cm) for analysis.

Whole soil within each depth layer was oven-dried at 40°C and weighed. Soil moisture was determined from a subsample of ~50 g, dried at 105°C (oven dry weight). The remaining whole soil was sieved to <2mm to remove gravel and coarse organic material (roots and litter). After sieving, the air-dried weights of the <2mm (air-dried fine fraction) and >2 mm (gravel) portions were recorded. The bulk density was calculated by dividing the oven-dried weight of the sample by the volume of the sample (as determined by the dimensions of the coring device).

Bulk density (g/cm^3) = whole dry soil mass/core volume

Samples were analysed for Total C and N using Dumas high temperature oxidative combustion (LECO Corporation). The presence of inorganic C was tested by treating a 1-2 g subsample with 5% v/v of Hydrochloric acid and observing any effervescence. If any inorganic carbon was present, samples were pre-treated using 5-6% sulphurous acid and heated on a hot plate. The process was repeated until the effervescence ceased prior to oxidative combustion.

5.4 Calculating carbon and nitrogen stocks

Soil carbon stocks are commonly quantified at fixed depths as the product of soil bulk density, depth and organic carbon concentration (Sanderman et al., 2011).

The stock of soil organic carbon in all sub-layers collected and analysed was calculated according to:

SOC t C/ha = OC x BD x d x (1-g)

where:

SOC is the soil organic carbon stock within an individual soil sub-layer (tonnes of soil carbon/ha)

OC is the gravimetric concentration of organic carbon determined for the sub-layer (g organic carbon/100 g oven dry whole soil)

BD is the bulk density of the sub-layer (g oven dry whole soil/cm3 whole soil)

d is the depth of the sub-layer samples (cm)

g is gravel proportion (g gravel/100 g over dry whole soil)

Depth-based splining

Soils cores could not always be taken to a uniform depth due to the presence of obstacles (e.g. roots, bedrock, highly compacted soil). In order to correct for this, we used depth-based splining to standardise the depth of each core to 1 m. For example, you can use the spline function to estimate the SOC values for missing depths (e.g. if core only extended to 80 cm) based on the trends of the SOC data in the measured depths. The spline function also smooths transitions between measured segments of the soil profile (0-10, 10-30, 30-50, 50-70, 70-100 cm). A Gaussian Process Regression approach was employed to spline the data. This is a non-parametric machine learning method that does not assume the data follows a particular distribution. A total SOC was then calculated for each core to 100 cm.

Statistical analyses

All statistical analyses and graphing were performed using R, version 4.2.3 (www.r-project.org), with the package 'gamlss' (Rigby & Stasinopoulos, 2005).

To determine if there were statistically significant differences between CONV grazing and TCG for total carbon (C), nitrogen (N), and their specific fractions (Mineral-associated organic matter, MAOM, and particulate organic matter, POM), we used a statistical model, Box-Cox t-distributed generalised linear mixed-effects model, and applied it to the aggregated data of total SOC per core across all pairs (with post-hoc pairwise comparisons after fitting the model to assess the treatment effect by pair). Data were fitted to a Box-Cox t-distributed generalised linear mixed-effects model with experimental pair and geographical location as random intercepts, and treatment (CONV versus

TCG) as fixed predictor. Box-Cox t-distributions allowed all responses of interest to be modelled with normally distributed residuals, addressing non-normality constraints in some of the data.

5.5 Soil microbial populations

At each paired site, a 200 m transect was identified according to the factor likely to maximise variation across the paddock. These were established according to three criteria: 1) soil type does not change throughout the transect, 2) sampling is performed away from watering points, cattle tracks and any other areas in which animals congregate, 3) if gilgai are present in the landscape, sampling is to consistently take place on the upside of the land depression. A 25 m^2 quadrat was placed every 100 m, with the latitude and longitude of each quadrat recorded in decimal degrees. Within each quadrat, four soil samples to 10 cm depth were collected and bulked. Sampling equipment was cleaned with ethanol between each sample. All soil samples were placed on ice, transported to the Queensland University of Technology (QUT) and stored at -20°C until analysed.

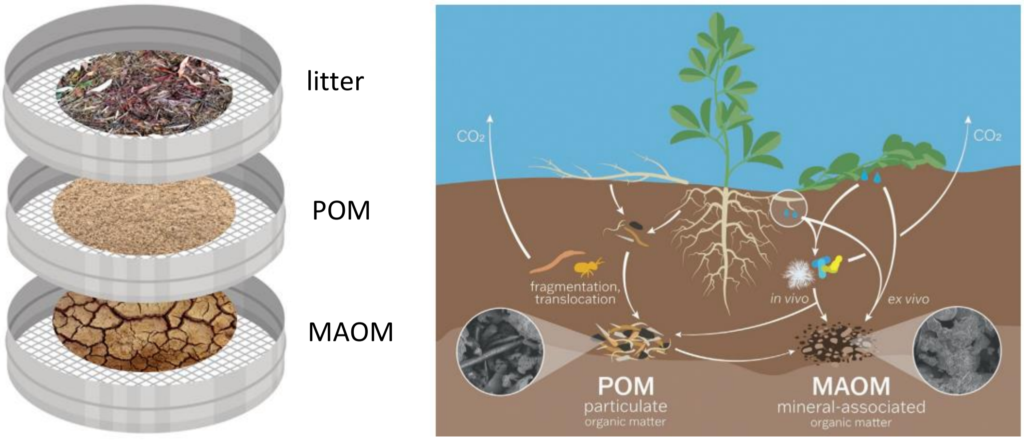
Phospholipid fatty acid (PLFA) analysis was used to quantify the relative biomass of microbial groups in soil samples. The sum of fatty acid biomarkers identified by Frostegard & Baath (1996) was used to estimate the biomass of specific microbial groups. Bacterial biomass was calculated as the sum of fatty acids i15:0, a15:0, 15:0, i16:0, 16:1ω7, i17:0, a17:0, cy17:0, 17:0, 18:1ω7, and cy19:0. Bacterial biomass was further partitioned into two subgroups: gram-positive bacteria, quantified by the sum of i15:0, a15:0, i16:0, i17:0, and a17:0; and gram-negative bacteria, represented by 16:1ω7, 18:1ω7, cy17:0, and cy19:0. Fungal biomass was represented by 18:2ω6,9, while actinomycete biomass was identified by 10me18:0. Total microbial biomass was estimated by summing the biomass of all groups. The fungal-to-bacterial biomass ratio and the gram-positive-to-gram-negative bacterial ratio were calculated by dividing the respective group biomasses.

5.6 Soil carbon fractionation

Fractionation was conducted to isolate two types of carbon in the soil with different residence times. Mineral-associated organic matter (MAOM) is protected through mineral associations and can persist in the soil for centuries or longer unless disturbed (e.g. by tillage or ploughing). This carbon is considered stable (stable C). In contrast, particulate organic matter (POM) is not associated with minerals and is more transient. It is rapidly replenished but also quickly utilised by microbes and released back into the atmosphere as CO_2, making it labile carbon (labile C) (Lavallee et al., 2020).

To determine if the ratio of stable to labile carbon differed across different grazing management practices, we fractionated the soil by size separation into two fractions according to Lavallee et al. (2020): (1) mineral-associated organic matter (MAOM) and (2) particulate organic matter (POM) (Fig. 3).

Figure 3: The fractionation approach isolating litter (>2mm), POM (>53 µm) and MAOM (<53µm). Adapted from (Lavallee et al., 2020)**.**



Soils were sieved to 2mm, and a 5g oven dried soil was shaken in dilute (0.5%) sodium hexametaphosphate and beads for 18h to completely disperse the soil. The dispersed soil was then rinsed onto a 53µm sieve and the fraction passing through (<53 µm) was collected as MAOM; the fraction remaining on the sieve was collected as POM. This fractionation approach was chosen as the most appropriate to separate SOM into two meaningful fractions (POM versus MAOM) with different characteristics and dynamics while being a convenient approach for high throughput. Since the approach defines POM by size (>53µm), very small amounts of very fine POM are recovered in the MAOM fraction, but this does not lead to different interpretations or conclusions regarding the overall functioning of the MAOM versus POM fraction. After drying to constant weight in a 60°C oven, each fraction was analysed for C and N concentration in an elemental analyser (LECO).

5.7 Carbon and water balance using Eddy Covariance flux towers

Eddy Covariance flux towers are one of the most widely used research tools for monitoring ecosystem fluxes (changes) of carbon, water and energy globally (Fig. 4). These towers use eddy covariance methods to monitor the fluxes of carbon dioxide (CO_2), water vapor, and energy between the ecosystem and the atmosphere. Flux towers can collect high-resolution data relatively inexpensively over extensive areas (approximately 10-50 hectares). This capability is particularly valuable for capturing variability at the paddock scale, encompassing the effects of animal movement, plant species diversity and distribution, and the microrelief impacts on hydrology.

Despite their advantages, converting the substantial amount of data from flux towers into practical metrics for monitoring agricultural sustainability presents challenges. One significant issue is the confounding effects that arise when environmental variables, such as soil and rainfall, are not uniform across paired sites, complicating short-term trend assessment at the paddock scale.

In this study, two flux tower pairs were established: one in Central Queensland, where TCG had been implemented for approximately 5 years, and another in Southern Queensland, where TCG had been implemented for around 14 years. The study, conducted between 2021 and 2024, served as a pilot to assess how flux towers could be used to evaluate the impact of management changes on soil organic carbon (SOC) dynamics over time. The difference in TCG establishment time between the two sites provided valuable insight into SOC dynamics at different stages of land management, with the Central Queensland site reflecting earlier stages of TCG implementation and the Southern

Queensland site representing a more mature phase of TCG. This contrast allowed for a more nuanced understanding of how SOC responds to long-term versus short-term management changes across different environmental conditions.

Data from the flux towers was automatically transferred through the TERN analysis pipeline into a centralised database. This process has the advantage of generating real-time (daily) fully processed data through TERN's six quality control levels. It also ensures that the outputs conform to national and international best practices, linking to both the national OzFlux and international FluxNet networks with standardized sensor configurations and analysis methods (Appendix).

For this research, the main tower outputs used were:

- Net Ecosystem Exchange (NEE) – the net balance of CO_2 between an ecosystem and the atmosphere. It represents the difference between the CO_2 taken up by the ecosystem through photosynthesis and the CO_2 released back into the atmosphere through ecosystem respiration, which includes both plant and soil microbial respiration.
- Net Ecosystem Production (NEP) – the net amount of carbon that remains in an ecosystem. NEP is often considered the inverse of NEE, where a positive NEP indicates net carbon uptake (carbon sequestration) and a negative NEP indicates net carbon loss.
- Evapotranspiration (ET) – represents that total amount of water vapour released to the atmosphere from both land surfaces and vegetation.
- Water-Use Efficiency (WUE) – calculated as the NEE divided by ET.

Figure 4: (a) The flux tower set up in field and (b) an aerial image of a flux tower located within a paddock. Note in (b) the heterogeneity of the paddock and how it would be difficult to capture this variability using soil sampling.

5.8 Biomass sampling for pasture growth and animal utilisation

This protocol closely follows the SWIFTSYND method to provide the minimum data set required for calibrating pasture and soil parameters in the GRASP pasture growth model (Day et al., 1997). Pasture samples were collected from within fenced exclusion cages situated within the footprint of flux towers, allowing the measurement of pasture growth over the year. The difference between pasture growth inside and outside the exclusion cages is used to estimate the amount of pasture removed through grazing.

Pasture growth is defined as the increase in pasture dry matter over a set time period, with a baseline reset at 5 cm. This baseline was established in August by mowing the vegetation inside the exclusion cages to approximately 5 cm, removing most of the standing biomass while preserving the crowns. Biomass samples were taken within the flux tower footprint (~10 hectares), with four towers (n=4) used in the study.

Four harvests (H1-H4) were conducted during the growing season:

- H1: Pre-green date (Sept/Oct)
- H2: End of summer growing season (Jan)
- H3: Peak yield (March/April)
- H4: Senesced winter feed (July-August)

To measure pasture growth, electric exclusion cages were placed in paddocks stratified by biomass variation identified through remote sensing indices, such as Normalised Difference Vegetation Index (NDVI). On average, three strata were identified per paddock. GPS points were randomly generated within each stratum to position the exclusion cages. Each cage, measuring 10 m x 10 m, was set up at least 30 m from trees, 20 m from roads, and away from waterways.

Inside each exclusion cage, nine 2 m x 2 m cells were marked out, with a 1 m buffer from the perimeter and 1 m spacing between cells. During each harvest (H1-H4), pasture samples were taken in each cell using a 0.5 m x 0.5 m quadrat, with the biomass cut to a height of 5 cm and the fresh weight recorded.

The same procedure was repeated for four quadrats placed randomly outside the exclusion cage. The difference in biomass between the inside and outside of the cage provided an estimate of the amount of pasture removed by grazing. After the final harvest (H4), the exclusion cage was relocated to a new randomly generated GPS point.

Laboratory procedure for all biomass samples

Samples were taken back to the laboratory and dried at 60°C for a minimum of 48 hours (additional drying may be needed if sample has a high-water content) to determine dry matter (DM) weight. Samples within each exclusion cage were bulked for C and N analysis. Bulked samples were then fine ground and submitted for total C and N analysis through the LECO (Dry combustion).

Plant species composition

Information on plant species composition was collected using a quadrat method. During soil sampling or plant biomass collection event, a quadrat measuring 0.5m x 0.5m (0.25m^2) is placed over the sample area. Plant species present within the quadrat are then recorded, including percent composition (which species are dominant). Once data is digitised, plant species data is then further tabulated to study total diversity, prevalence of native/exotic species, and 3P status (productive, perennial, palatable) of plant species identified.

Remote sensing of vegetative indices

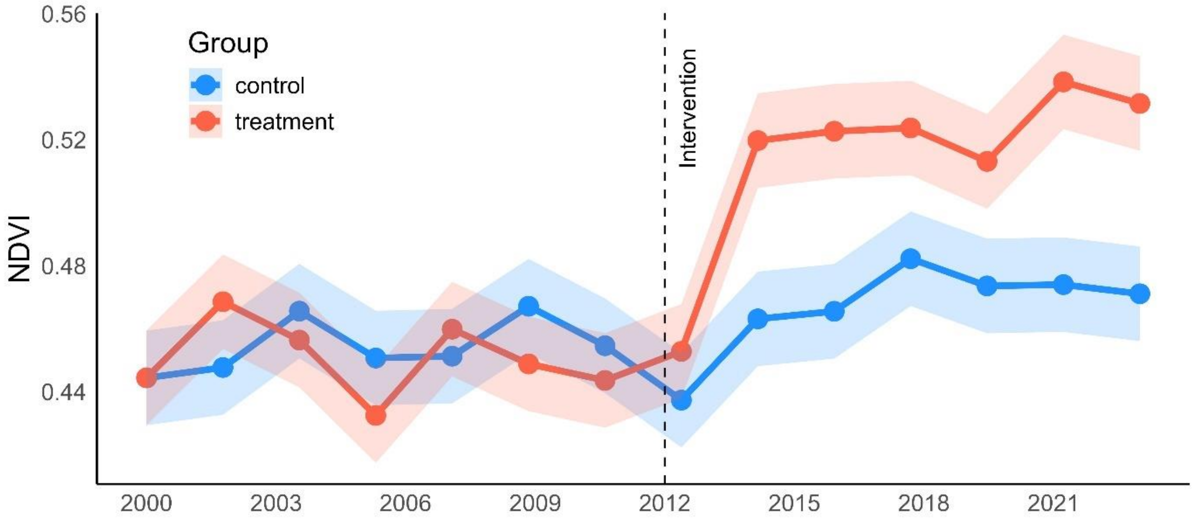
Remote sensing of vegetation indices was accessed to compliment the on- ground vegetation sampling and to understand if remote sensing could detect the impact of management change (Fig. 5). Remote sensing of ground cover using Landsat-8, 30 m resolution was accessed for data from 1990 to 2023.

To estimate the effect of the management intervention (i.e. implementation of TCG grazing) on ground cover, we employed the Difference-in-Differences (DiD) approach using the R package 'DiD'. We compared the difference in ground cover from polygons on TCG farms to polygons from CONV farms. Each polygon was around 20 ha in size. The time series was constructed for the period from 2001 to 2023. The 20 ha polygons were selected to represent the area where soil sampling was conducted.

A 12-month moving average filter (left lagging, including data from the past 12 months) was applied to the ground cover dataset to smooth the data and facilitate trend identification (Li, 2021). Additionally, we applied the same 12-month moving average filter to the rainfall data to reduce noise from intra-seasonal and local-scale variability. Rainfall data were sourced from the SILO Climate Database (SILO, 2021). To further aid in identifying trends, a non-parametric smoothed lined was applied to the ground cover dataset using the LOESS method (Locally Estimated Scatterplot Smoothing), with a span that responded to 50% of the nearest data points.

The DiD method is useful in studies where random assignment to treatment and control groups is not feasible. A key assumption underlying the DiD approach is the parallel trends assumption, which posits that, in the absence of the intervention, the difference between the treatment and control groups would have remained constant over time. By comparing the changes before and after the intervention, DiD isolates the effect of the intervention from other confounding factors, such as climate that might influence the outcome (Fig. 5).

Figure 5: Conceptual representation of Difference-in-Difference analysis on ground cover time-series for treatment (soil carbon project) and control (outside of carbon project). Project intervention represented by dotted black line. Difference in Differences before and after intervention.



5.9 Biodiversity: acoustic monitoring

Measuring biodiversity at scale can be challenging, costly and time-intensive. However, recent advancements in automated, compact, and affordable monitoring equipment, along with powerful analytical tools, offer new opportunities to overcome these challenges. One effective approach for assessing fauna, biodiversity, or ecological health more broadly is passive acoustic monitoring. This method involves deploying acoustic recorders that capture sounds produced by audible organisms such as birds, insects, amphibians and mammals. The collected acoustic data can be analysed to quantify the level of biological activity in the landscape using acoustic indices, identify animals at the species level, and potentially link these findings to biodiversity metrics.

Acoustic recorders were deployed across farm pairs 1, 2, 4 and 5 within the Brigalow Belt bioregion of Queensland (Fig. 2 and Fig. 6). Each pair had two recorder points[2] established in TCG, two in conventionally grazed pasture, and one in a remnant woodland/open forest site of the same pre-clearing vegetation type as the pasture locations (reference site). Recorder point locations were selected to be at least 100 m from surrounding woody vegetation and within paddocks that were considered representative of broader pasture vegetation based on a preliminary walkthrough of each property. Small, battery powered AudioMoth recorders (Pair 1), and larger solar powered Solar BAR units (all other sites) were deployed for selected time periods between November 2022 and November 2023[3].

Figure 6: AudioMoth (left) and Solar BAR (right) acoustic recorders.

---

[2] Random sampling across large properties can be challenging, so long-duration continuous recordings at two points within each treatment (TCG versus conventional) were chosen as a compromise to mitigate the issue of limited spatial coverage. However, it is acknowledged that this approach does not fully eliminate the potential for selection bias in site placement.

[3] The Solar BARs were deployed for an extended period because of their ability to continuously record with minimal maintenance. Recordings from these devices were subsampled for one month during the spring-summer period. On the other hand, AudioMoths were specifically deployed at Pair 1 during the spring-summer for a one-month duration due to their limited battery life and storage capacity. The decision to use AudioMoths at Pair 1 was made because the Solar BARs were allocated to other sites, and Pair 1 was more accessible and regularly monitored.

Pasture surveys measuring vegetation attributes and grazing pressure were conducted within four 1m x 1m quadrats at cardinal points (north, south, east, west) around each recorder point. Quadrat measurements were averaged over the four quadrats. Satellite-derived data (Normalised Difference Vegetation Index, Fractional Vegetation Cover, percent woody vegetation cover within 100m and 500m radius) were calculated for each recorder point. A summary of quadrat vegetation and satellite-derived data can be seen in Table 4.

Table 4: Quadrat and satellite measurements for paired recorder points.

Attribute measurement type	Attribute name
Quadrat	Native grass cover
Quadrat	Exotic grass cover
Quadrat	Total grass cover
Quadrat	Native sedge cover
Quadrat	Native forb cover
Quadrat	Exotic forb cover
Quadrat	Total forb cover
Quadrat	Total ground vegetation cover
Quadrat	Litter cover
Quadrat	Bare ground cover
Quadrat	Native grass species richness
Quadrat	Exotic grass species richness
Quadrat	Total grass species richness
Quadrat	Native sedge species richness
Quadrat	Native forb species richness
Quadrat	Exotic forb species richness
Quadrat	Total forb species richness
Quadrat	Total ground vegetation species richness
Quadrat	Average ground vegetation height
Quadrat	Average grazing pressure
Satellite	Woody vegetation cover with 100m of recorder point
Satellite	Woody vegetation cover with 500m of recorder point
Satellite	NDVI
Satellite	FVC bare
Satellite	FVC green
Satellite	FVC non-green

Acoustic data were collected after 12 months of continuous recording by the Solar BARs, which are capable of storing a full year of data without requiring human intervention. From these recordings, data were subsampled for a one-month period during late spring and early summer of 2022, aligning with peak biological activity. Acoustic data from AudioMoths were collected in late spring and early summer of 2023 to match the Solar BARs subsampled recording period from the previous year. The analyses focused on recordings taken between 04:00 and 06:00 during the day and between 18:00 and 20:00 at night. A summary of the acoustic data collection is presented in Table 5.

Table 5: Survey sites, recorder types and sample dates for paired acoustic recorders.

Site	Recorder type	Recording start	Recording finish
Pair 1	AudioMoth	16/11/2023	21/12/2023
Pair 2	Solar BAR	1/12/2022	31/12/2022
Pair 5	Solar BAR	1/12/2022	31/12/2022
Pair 4	Solar BAR	20/10/2022	24/11/2022

Day recordings were analyzed using BirdNET software, developed by Cornell University (Kahl et al., 2021), along with acoustic indices generated by Analysis Programs (Towsey et al., 2018) and R statistical software. Night recordings were analysed using Analysis Programs and R.

BirdNET is a deep artificial neural network capable of identifying multiple bird species from acoustic data, providing a confidence level for each predicted identification. For these analyses, a confidence level of 80% was set as the threshold for positive bird identification. BirdNET has recently been adapted for use in the Australian context (approximately two years as of 2024) and is well developed for identifying Australian birds, particularly in grazing systems. Preliminary work, which compared BirdNET detections with expert identifications, found a high degree of accuracy (unpublished data).

Remnant woodland and open forest recorder locations were excluded from the night analyses for generating acoustic indices due to the high variability in the size, configuration, composition and structure of patches across the study area. The orthopteran analysis was restricted to pasture areas only, allowing the model to focus on a specific vegetation type heavily influenced by grazing management.

However, remnant wood reference sites were retained for bird species analysis using BirdNET. Despite the variability in patches, BirdNET provides species-level data, which is more specific than the acoustic indices used to measure nocturnal orthopteran activity. Additionally, bird assemblages have been shown to be influenced by the proximity to woody vegetation in the landscape, making it important to include these sites in the analysis.

Bird species richness, represented by both BirdNET and acoustic analysis, was examined across different sites. A two-way table and dendrograms were created for all sites to illustrate the association between recorder points based on bird species presence or absence (using BirdNET data). Night-time acoustic index values were generated for selected sites, with a particular focus on high-frequency cover (HFC). HFC is an acoustic index targeting high-frequency bands from 8 to 11 kHz, which has been linked to audible nocturnal insect activity, predominantly Orthoptera (including crickets and katydids). These insects are valuable indicator species for broader biodiversity and ecological health and are sensitive to fine-scale changes in vegetation (Andersen et al., 2001; Anso et al., 2021; Müller et al., 2022a; Müller et al., 2022b). A statistical model was developed in R to identify significant environmental attributes that drive variability in HFC across different grazing management and vegetation types.

Developing a property scale biodiversity assessment tool using remote technologies

Bird species assemblages derived from audio recordings collected at Pair 1 in southern Queensland were used to build a model predicting BioCondition scores for pasture (pre-clearing brigalow), regrowth brigalow and remnant brigalow, as defined by regional ecosystem (RE) 11.4.3[4].

Pair 1 was the only site used in the modelling because of the high sampling intensity required for this component of the study and the accessibility of these properties for frequent on-site surveys. Pair 1 locations were considered adequate to provide proof of concept for the model development, which will now be expanded to other locations to test whether the approach is generalisable.

This preliminary model aims to make it easier and more cost-effective for producers to assess ecological condition at a property scale using acoustic recorders as a replacement for and/or to augment on-ground surveys. The concept is to send equipment to producers following a pre-survey desktop spatial analysis. Producers would be directed to deploy acoustic recorders in specific locations, potentially combined with minimal vegetation assessments, and to return data and hardware following a pre-defined period. Recordings would be analysed in the laboratory and ecological condition metrics generated.

Across Pair 1, four study locations were surveyed to collect data for the model. Two locations were under TCG (two distinct properties under one grazier practicing TCG), one location CONV grazing, and one was remnant vegetation under management of a local authority preserving a significant area of brigalow open forest and Poplar Box woodland. Survey points were identified for each study location at least 25 metres from the edge of a vegetation unit, generating a total of 18 survey points.

5.10 Modelling and upscaling to landscape

Process-based biogeochemical models are powerful tools for investigating the efficacy of farming practices and monitoring changes in soil organic carbon (SOC) stocks. These models require integration with high-quality field measurements, primarily based on long-term SOC datasets. However, the availability of long-term SOC data is often limited, especially for new management practices.

Flux towers offer opportunities to calibrate and validate models of C cycling with their continuous C flux measurements. Combining process-based biogeochemical models with eddy covariance (EC) flux tower data is a promising approach for robust simulation of soil C sequestration. However, this approach has not been widely tested in agricultural systems in Australia until recently.

In this study, the DayCent-CABBI model was calibrated and validated for pasture systems in the Brigalow Belt bioregion using plant biomass, SOC fractions and EC flux tower data. DayCent is a biogeochemical process model that simulates C and N cycling at the soil–plant–atmosphere interface (Parton, 1993). We used a new version of DayCent developed by the Centre for Advanced Bioenergy and Bioproducts Innovation (DayCent-CABBI) (Berardi et al., 2024).

DayCent-CABBI was calibrated for the Brigalow Belt bioregion using (1) long-term datasets on aboveground biomass, SOC, and SOC fractions from the Brigalow Catchment Study (Dalal et al., 2021), and (2) flux tower data (net ecosystem exchange [NEE] and evapotranspiration [ET]) from the

[4] Regional Ecosystems in Queensland are assigned based on three key factors: (1) Bioregion (Brigalow Belt), (2) Land zone of underlying geology and landform (clay plains), and (3) Dominant vegetation structure and species (Acacia). The Queensland Government, through the Queensland Herbarium, oversees the classification.

current study (2021-2022). The model was then validated against the second half of the time sequence from the current study (2022-2023) for NEE, ET and observed SOC stock data.

5.11 Social science: relationship between grazing practices and producer wellbeing

The social science research used a qualitative research approach to assess economic, social and environmental aspects of grazing management approaches that are implemented to improve soil health in the subtropics. While the social science research utilised the five paired sites used in the wider study, it was necessary to expand interviews to a broader sample to capture diverse perspectives. Researchers conducted qualitative interviews with 31 producers on 19 properties, primarily in Central Queensland, with some in Southern Queensland. These interviews explored management history, styles, decision-making, wellbeing and other management philosophies (Table 6).

This expanded approach enhanced research robustness and allowed for anonymised results, adhering to ethical guidelines set by the National Health and Medical Research Council (NHMRC). This is crucial due to the sensitive nature of social science research, especially when addressing producers' physical and mental wellbeing.

Although this approach doesn't permit a clear causal attribution of grazing methods to specific outcomes on paired sites, it still offers valuable insights into sustainable grazing:

1. It captures the views of producers on various aspects of management, helping us define different management practices based on the producers' perceptions.
2. It places grazing management styles on a spectrum (Fig. 1), showing different levels of intensity in managing the land and the selective adoption of specific grazing practices rather than prescriptive "styles".
3. It creates a detailed framework for understanding how producers make decisions and how these decisions relate to their wellbeing, including aspects like achievement, community, health, empowerment and socio-economic results.

By integrating social science, this research opens up a new field of research that allows for a more comprehensive and nuanced comparison of grazing methods and their sustainability, using an interdisciplinary approach.

The research design was informed by a social constructivist epistemology – that is, it does not seek to find a singular, objective 'truth' or social 'reality' but accommodates the subjectivities of different social groups accounting for their world view, life experiences and perceptions.

The starting position for sampling and data collection was to record producer experiences of their everyday realities managing land, cattle and business. Researchers adopted a purposive approach of selecting research participants based on their ability to contribute to explaining and understanding social research problems, which has been termed 'problem sampling'. In this project, the sample included "paired site producers" for soil carbon and ecosystem services study, and additional producers across a spectrum of grazing systems from intensive (TCG grazing) to extensive (continuous grazing) types of management.

Face to face, semi-structured interviews within the familiar environment of the grazing property were determined as the most appropriate method of data collection. In total, researchers interviewed 31 people across 19 properties during 2022-2023. Many of the properties were represented by a producer couple with some joined by adult offspring. Three of the 19 properties represented also engaged in cropping alongside beef production, and for two of those three properties, beef production was the dominant business.

Table 6: Number of interviews held with Producers by grazing system and gender.

	TOTAL	TCG and Regenerative	Rotational and advanced transitioning (Non TCG/rot)	Set-stocking and early transitioning (Non TCG/set)
F	11	4	5	2
M	20	7	9	4

The formal interview phase lasted around one hour, with open ended questions addressing the background of the property, change over time, management and decision-making practices, wellbeing, environment/natural assets and perceived business success/viability. All interviews were digitally recorded and transcribed. Data was analysed by two researchers using NVIVO14 software and a thematic coding, re-coding, inter-coder reliability regime (O'Connor & Joffe, 2020). To capture the 'voice' of producers, the authors use direct, de-identified quotes in this report (grazing enterprises are represented by a number).

Limitations of the social science research

There are sampling limitations of this approach, relating to the self-selection of participants. That is, those producers who feel positive about their management practices would be more likely to agree to an interview. There were a disproportionate number of producers in this study that would consider themselves TCG producers, or regenerative producers, or at least 'scientific' and strategic in their management practices. The sampling covers the geographic regions chosen for the soil carbon study. The practices and specific outcomes of grazing styles therefore should be interpreted in relation to the specific geographic and environmental conditions of the semi-arid areas of Central and Southern Queensland.

6. Results and discussion

6.1 Soil organic carbon stocks

Total SOC stocks were significantly greater in TCG farms in comparison to CONV grazing farms. On average, across all pairs, SOC stocks were 17.7 t C/ha greater in TCG systems than in CONV systems ($p<0.01$) (Fig. 7). The largest difference between TCG and CONV systems occurred in pair 4, where SOC stocks in the TCG system were 31.9 t C/ha higher than in the CONV grazed paired site (Fig. 7).

The most significant differences in total SOC stocks were observed in the topsoil (0-55 cm), while no notable differences were found in the subsoil (55-100 cm). This is demonstrated visually in Fig 9. with overlapping error bars at depth greater than 55 cm indicating a non-significant difference between TCG and CONV.

Total N stocks were also greater in TCG than CONV ($p<0.01$) (Fig. 8). The only exception to this was pair 1, where the TON stocks were significantly lower in TCG than in CONV. Overall, total N stocks were 27% greater average across all pairs in TCG versus CONV (Fig. 8). Greater N stocks in TCG may have resulted from the more even distribution of N in TCG systems, where N-rich inputs (dung and urine) are more evenly dispersed across the pasture compared to CONV sites, which are more likely to receive more patchy and selective grazing. Greater N stocks may also have resulted from a higher legume content at some TCG sites (see Table 7).

TOC was also separated into fraction POM and MAOM for analysis. Here we found that there were significantly higher ($p<0.001$) MAOM-C and MAOM-N in TCG systems in comparison to CONV systems. MAOM-C was 30% greater in TCG than CONV and MAOM-N was 24% greater. In contrast, there was no significant difference in POM-C or POM-N across TCG versus CONV (Fig. 10).

Our findings indicate that TCG systems not only store more SOC, but this carbon is also stored in a more stable form, increasing its likelihood of persisting over long time periods.

Table 7: Data on pasture species composition in TCG versus CONV sites. Data not available for pasture composition for pair 4.

	TCG	**CONV**	**TCG**	**CONV**	**TCG**	**CONV**	**TCG**	**CONV**
	Pair 1		**Pair 2**		**Pair 3**		**Pair 5**	
Richness	35	24	3	10	29	26	11	5
No. native	17	13	1	4	12	12	5	3
No. exotic	15	10	2	6	14	10	6	2
Graminoids	16	10	1	4	8	7	6	1
Legumes	5	2	0	0	3	1	1	0
Shrubs	2	1	0	1	2	3	1	1
Forbs	12	11	2	5	16	15	3	3
3P count	18	9	1	3	8	8	6	2
3P:Richness	51%	38%	33%	30%	28%	31%	55%	40%

Figure 7: SOC stocks in conventional (green) and TCG (yellow) grazing systems for individual pairs 1 – 5 and a summary plot for all sites combined. Box plots display the median and the interquartile range (the middle 50% of the data). Significance between the pairs is shown on the plot. *: p < 0.05, **: p<0.01. *** p<0.001.

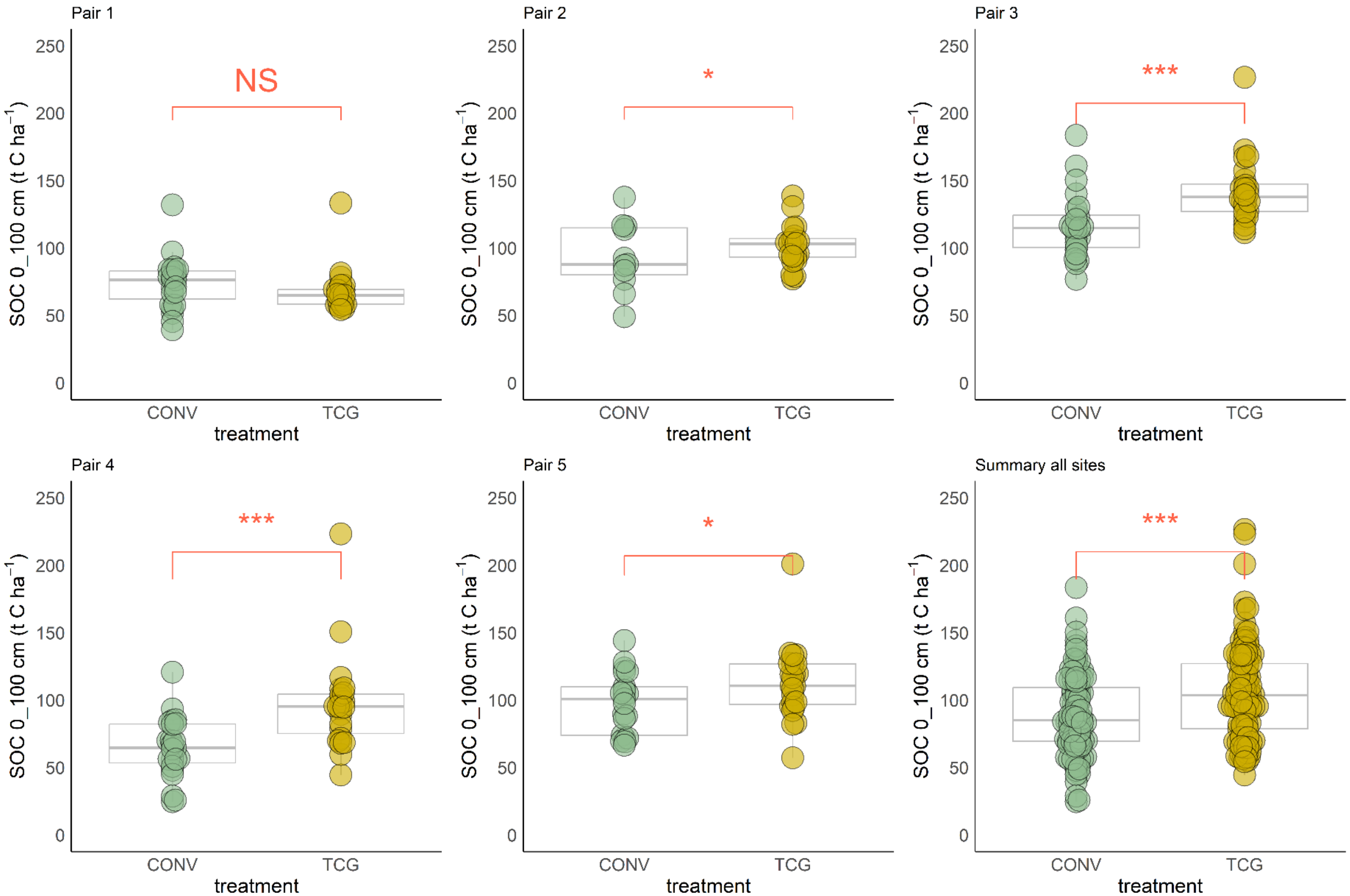


Figure 8: Total soil Nitrogen in conventional (green) and TCG (yellow) grazing systems for individual pairs 1 – 5 and a summary plot for all sites combined. Box plots display the median and the interquartile range (the middle 50% of the data). Significance between pairs is indicated on the plot. *: p < 0.05, **: p<0.01. ***p<0.001.

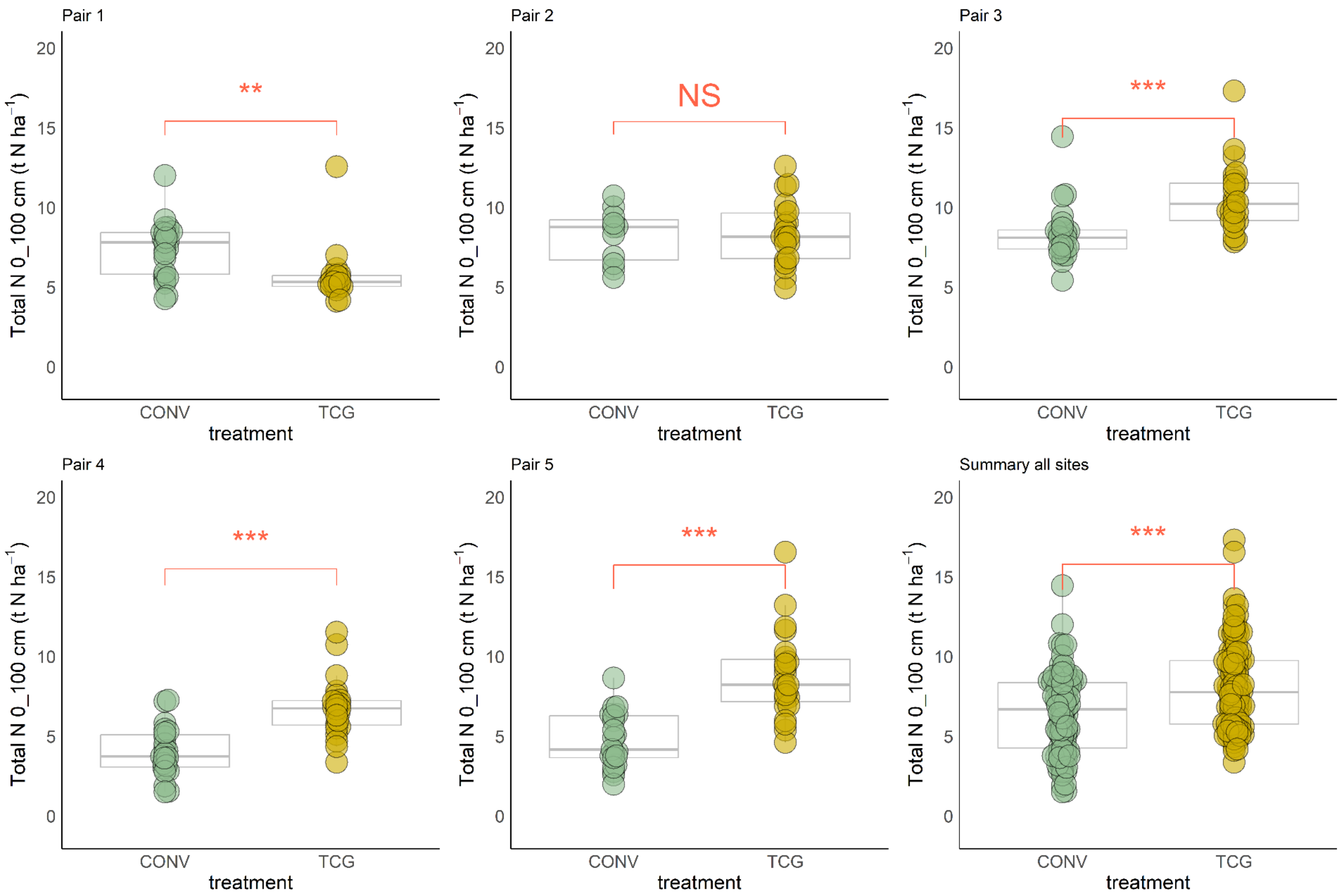


Figure 9: Soil organic carbon (left) to a depth of 1 meter with 95% confidence intervals (grey shaded). The shaded area indicates the range within which the true values are expected to fall with a 95% level of confidence. Overlapping confidence intervals at >55 cm (in the case of SOC) means that there isn't a significant difference in SOC stocks at depths >55 cm. Total nitrogen to a depth of 1 meter with confidence intervals shown on the right. In the case of N, there was no significant difference between TCG and CONV beyond 60 cm in depth.

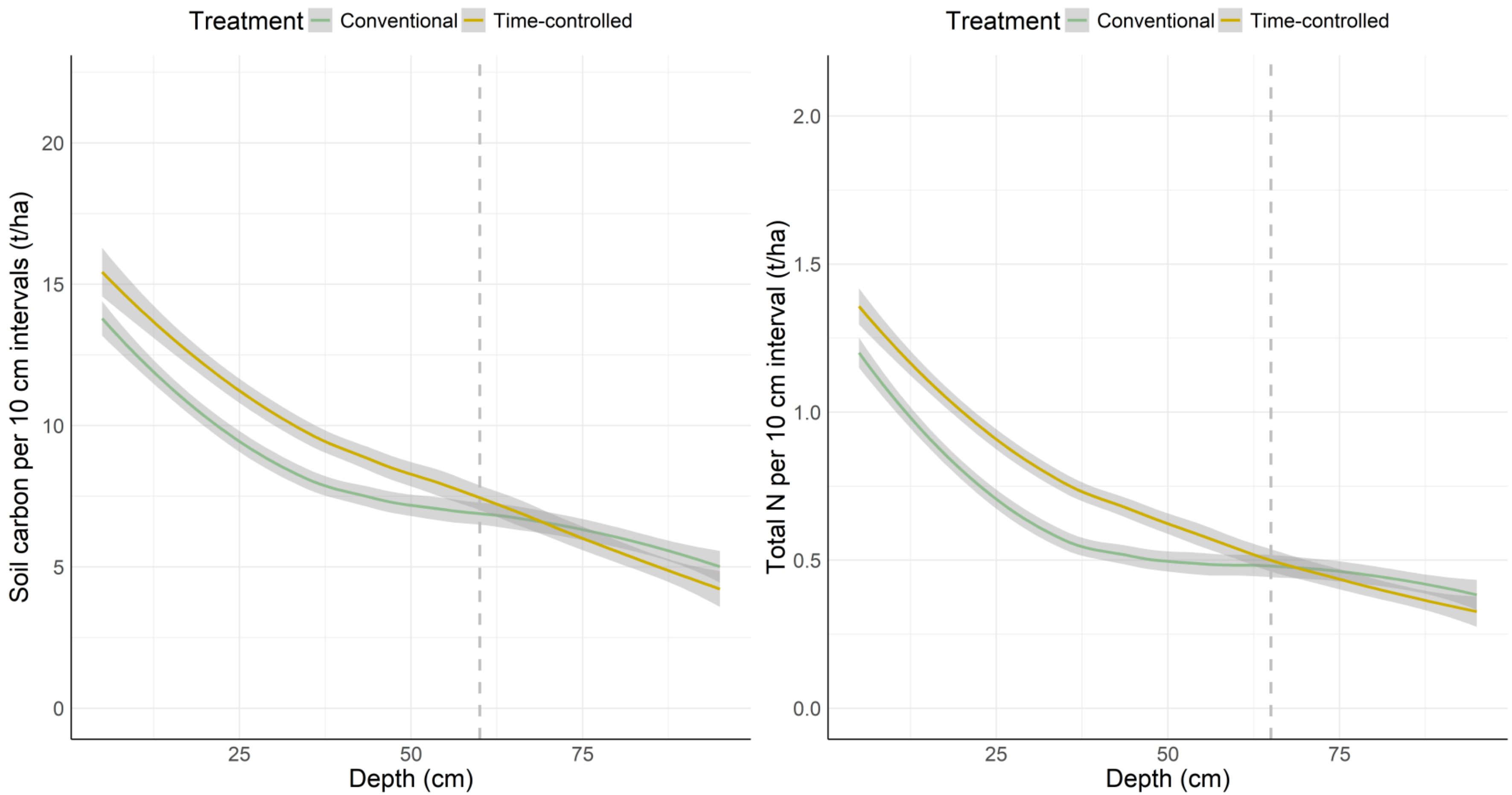


Figure 10: A summary of differences in mineral-associated organic carbon (MAOM-C) and particulate organic carbon (POM-C) between TCG and CONV on average across the five paired sites. Significance between pairs is indicated on the plot.*: p < 0.05, **: p<0.01. *** p<0.001.

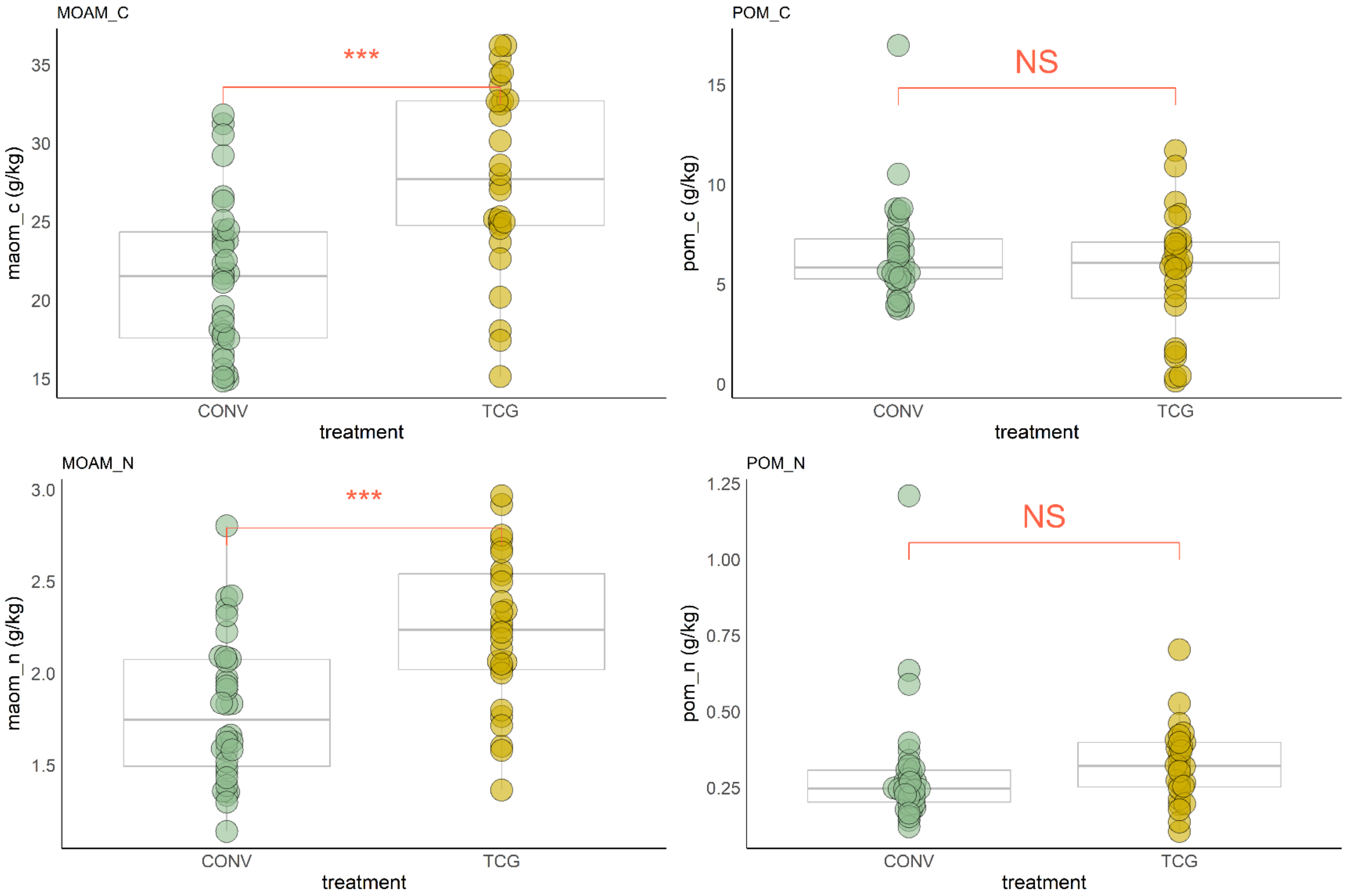
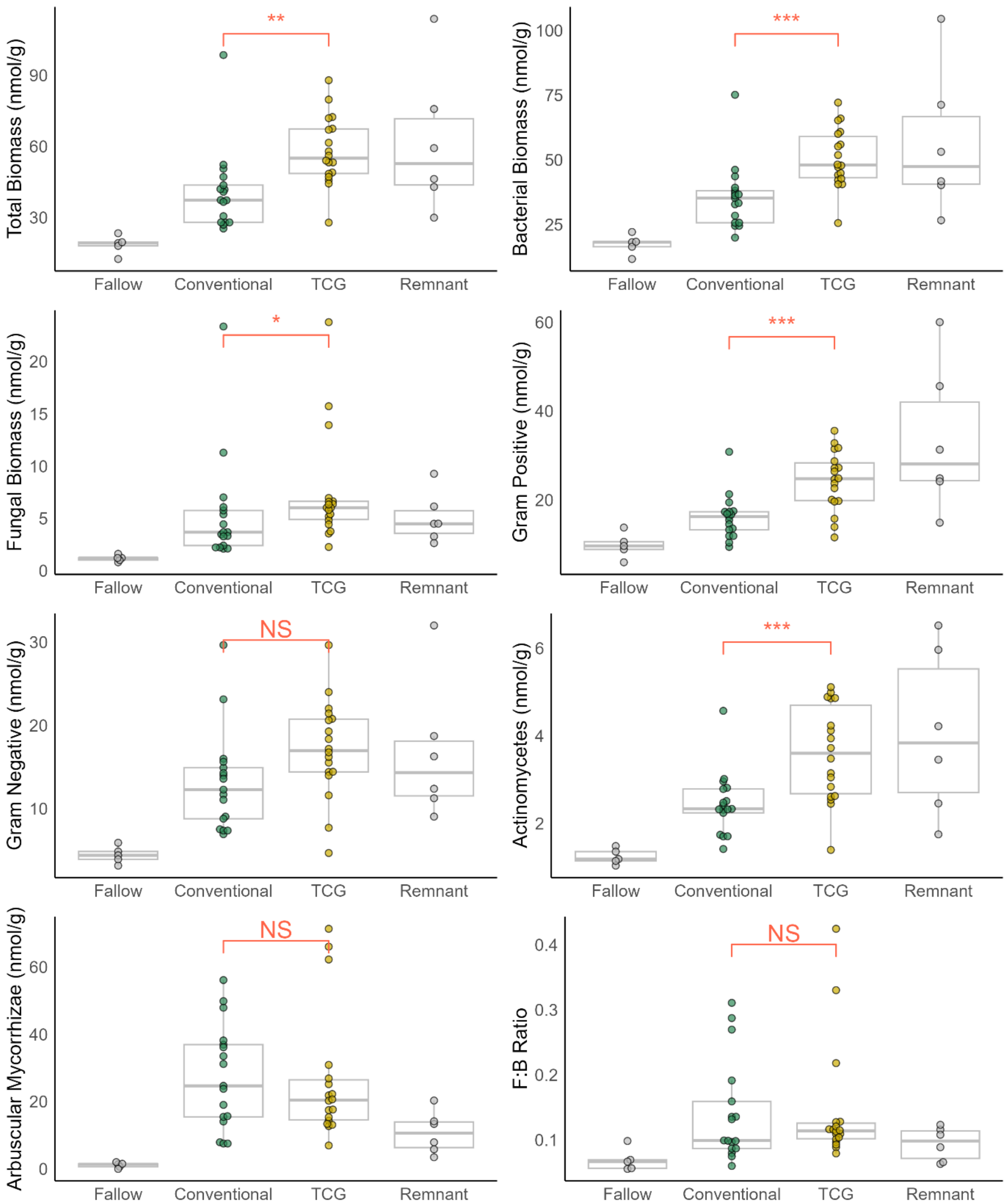


Figure 11: A summary of microbial biomass indicators aggregated across all paired sites. Fallow and remnant sites included for reference (grey). Conventional and TCG compared for significance between treatments (denoted by *: p < 0.05, **: p<0.01. *** p<0.001).



6.2 Microbial biomass

Greater amounts of saprotrophic microbial biomass (fungi, bacteria and actinomycetes) were observed under TCG (Fig.11). Saprotrophic microbial biomass refers to the collective mass of microorganisms that decompose dead or decaying organic matter. These saprotrophic microbes obtain their energy and nutrients by breaking down complex organic materials such as dead plants, animals and other organic residues. In the process, they play a crucial role in nutrient cycling, returning essential elements like carbon, nitrogen and phosphorous back to the soil.

The observation of higher saprotrophic microbial biomass in TCG sites aligns with the presence of higher organic carbon, as microbial biomass tends to increase with organic carbon levels (Fierer et al., 2009), and organic carbon is significantly derived from microbial residues (Kallenbach et al., 2016). However, the unchanged AMF biomass and fungal-to-bacterial (F/B) ratio, despite increased soil organic carbon (SOC), challenge some hypothesised mechanisms of organic carbon sequestration commonly cited in the literature (e.g. Khangura et al., 2023) and in online sources and the grey literature (e.g. Ingham, 2022).

Specifically, increases in AMF biomass and the F/B ratio have been proposed to enhance SOC by improving soil aggregation, substrate use efficiency, and promoting the synthesis of stable organic compounds, such as glomalin or hydrophobins (Bonner et al., 2018; Rillig et al., 2007). Cropping soils often experience conditions that disproportionately reduce fungal populations, such as tillage, fumigation, and limited organic residue inputs. In such soils, management interventions that restore a functional fungal component can re-establish degraded biochemical processes, including those related to SOC sequestration. Many empirical studies reporting positive correlations between F/B ratio, AMF biomass and SOC have occurred in these degraded soil contexts.

In contrast, grassland and forest soils generally host a sufficiently large and active fungal community to support key biochemical processes, regardless of site-to-site variation in microbial ratios. Consequently, there is likely little scope or need to "restore" fungal populations in grazed grasslands through management practices, as these ecosystems already maintain functional fungal communities that support SOC dynamics.

6.3 Soil carbon sequestration as measured by flux towers

The flux tower set up allowed short-term (2-3 years) insights into carbon drawdown into soils and pasture under the different management systems.

Flux towers are increasingly being promoted for carbon and natural capital accounting due to their capacity to obtain high-resolution and spatially integrated data on carbon drawdown, water-use and productivity (Novick et al., 2022). In this study, the flux towers were used to determine the effects of management decisions on these parameters.

We set up a total of four flux towers, with one pair located in Central QLD near Baralaba and the other in Southern QLD near Goondiwindi (pair 1 sites). In Central QLD, one tower was placed in paddock with TCG (TCG site which had only been implemented for 5 years and was therefore not part of paired site comparison and CONV from pair 2)[5]. In contrast, the Southern QLD pair of towers

[5] Due to delays in obtaining permissions for the CONV site in Pair 3, we had to use data from the CONV site in Pair 2 instead. We recognize the geographical separation of the flux towers in Central Queensland and the limitations this introduces to interpreting the results from this pair. Additionally, we chose not to present

was situated on a farm where TCG had been established for over ten years (Fig. 2). These instruments allowed us to gain insights into how the impact of management practices on SOC changes over time, comparing the effects of newly implemented versus more established TCG practices.

Grazing intensity

In Central Queensland, the TCG paddock had an average grazing intensity of 13.5 AE per hectare, with an average of 8 grazing days per year (Table 7). The average number of days between grazing events was 39 days, with the longest rest period applied being 113 days. Grazing removed 1,732 kg DM ha^{-1} on an annual basis. In the CONV control site, the paddock was grazed for an average of 241 days per year at an average of 0.7 AE per hectare, removing 1,628 kg DM/yr (Fig. 13).

In Southern Queensland, the TCG paddock was grazed on average 4 days per year with an average intensity of 16 animal equivalents (AE) per hectare, removing 1,135 kg of DM per hectare annually. The average and maximum paddock rest time was 69 and 137 days, respectively. In contrast, the CONV grazed control paddock was grazed for an average of 120 days per year at an average rate of 1.62 AE per hectare, removing 1705 kg DM ha^{-1} (Fig. 12).

Table 7: A summary of grazing days and stocking density in animal equivalents (AE) per hectare.

Metric	Central QLD TCG	Central QLD CONV	Southern QLD TCG	Southern QLD, CONV
Number of days per year paddock grazed	8	241	4	120
Animal equivalent/ha	13.5	0.7	16	1.62

Carbon balance (as measured by Net Ecosystem Productivity, NEP)

In Southern QLD, the impact of high rainfall seasons of 2021-2022 was evident, with consistently good conditions resulting in high net ecosystem productivity (NEP = soil C + pasture C), particularly in the TCG grazing system. However, by 2022, both the TCG and CONV systems experienced a sharp decline in NEP, with a more pronounced decrease in TCG. This decline also caused a corresponding reduction in water use efficiency (WUE), which was again more substantial in the TCG system.

During this period, the TCG system experienced extended rest intervals between grazing (e.g., 137 days between February and June 2022) and lower animal density (~5 AE ha^{-1}), resulting in limited biomass removal (~400 kg DM ha^{-1}). The reduced stocking rate coincided with record-high cattle prices, which likely restricted the ability to increase herd size. Consequently, the pasture at the TCG site likely remained in stage 3 growth (the mature phase where plants cease active growth) for an extended time (see appendix for growth stage details). This prolonged phase limited further carbon input while soil carbon losses continued through microbial respiration.

results from the paired flux tower sites in Pair 2 due to the complex net ecosystem exchange (NEE) signal caused by the presence of numerous trees at the TCG site. A longer sampling period is needed to better understand the differences in carbon sequestration at the Pair 2 flux tower sites.

Although TCG had sequestered more carbon than CONV in 2020-2022, the advantage was balanced out by 2023-2024. By the end of the 3-year measurement period, there was no significant difference in carbon drawdown between the TCG and CONV sites in Southern QLD.

The lack of a significant difference in carbon drawdown between TCG and CONV over the short-term (~3 years) in Southern Queensland was likely due to the overriding influence of rainfall on SOC dynamics. This finding underscores the risks associated with issuing soil carbon credits in projects based on short measurement periods, some as brief as one year after management implementation (see Appendix for Clean Energy Regulator credit issuances). Soil carbon projects have been credited for gains of up to ~6 t C ha^{-1} yr^{-1}, which seems excessive and may lead to over-crediting in the short term, potentially requiring farmers to relinquish credits over the long term (25-year project crediting period)

The lack of difference in carbon drawdown between TCG and CONV could also be due to the TCG site in Southern Queensland (implemented for over 15 years) reaching a new steady state at higher carbon input levels. However, this is unlikely to explain the results in Central Queensland, where TCG has been implemented for only ~5 years.

Figure 12: Flux tower and grazing data from the Southern QLD pair of flux towers.

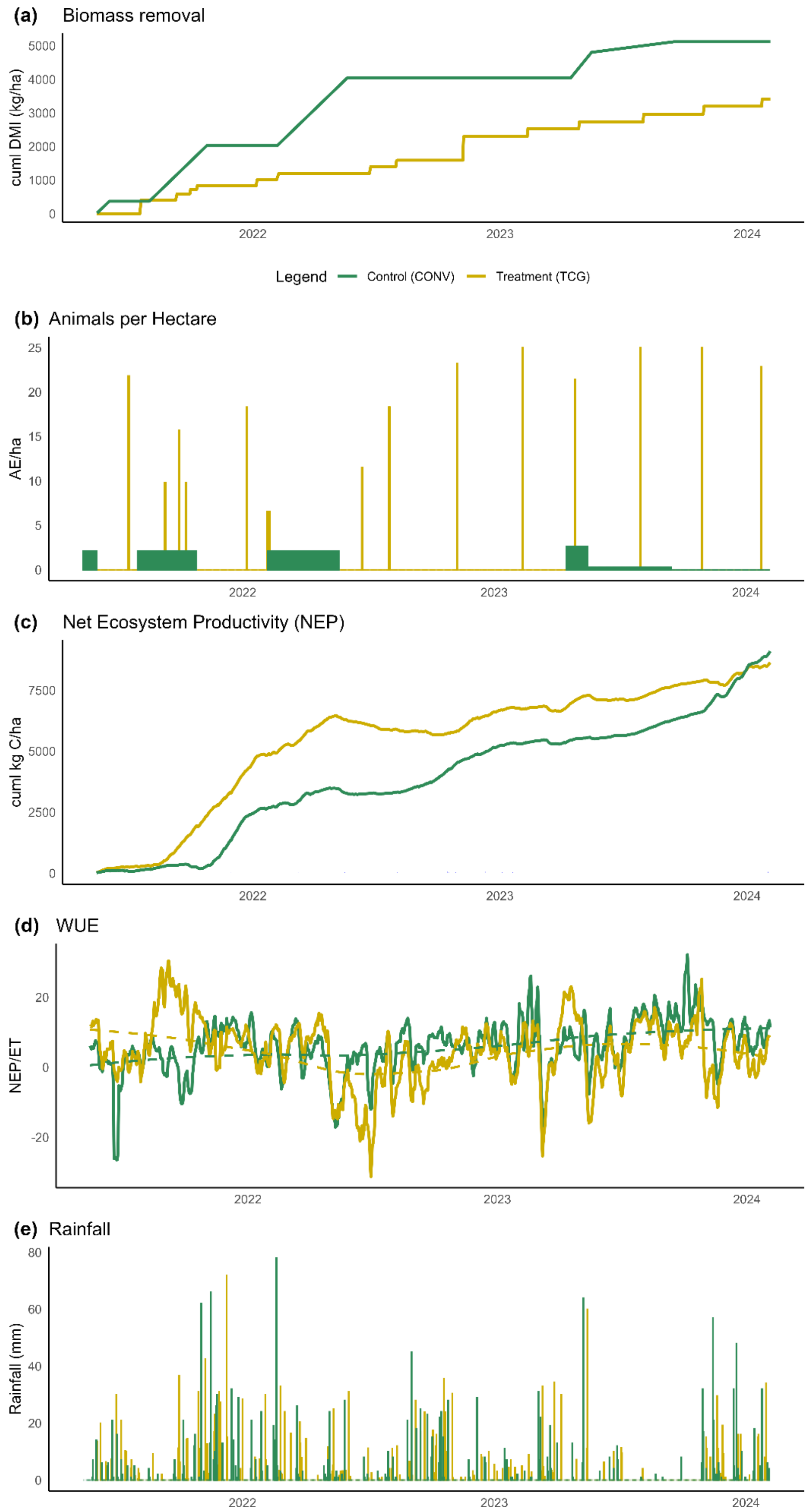


Figure 13: Flux tower and grazing data from the Central QLD pair of flux towers.

6.4 Ground cover analysis

The Difference-in-Differences (DiD) analysis before and after the implementation of TCG yielded mixed results. Overall, the impact of TCG implementation on ground cover was generally non-significant using the DiD approach (Fig. 14). However, some variations were observed across different pairs:

- Pair 1: Post-TCG implementation, the impact was near-significant with a p-value of 0.0732.
- Pair 2: There was a significant divergence between TCG and CONV (p<0.05), but the ground cover in CONV increased relative to TCG.
- Pair 3: A significant increase in ground cover was observed in TCG relative to CONV after TCG implementation.
- Pair 4: No significant impact of TCG implementation was found.
- Pair 5: No significant impact of TCG implementation was found.

In contrast, when analysing the impact of dry periods (defined as 8 consecutive months where rainfall was below the long-term average monthly rainfall), the results indicate that TCG sites generally responded more favourably during these dry periods, exhibiting less ground cover loss compared to CONV sites. The exception was Pair 1, where there was no discernible difference in ground cover loss post-dry period. For the remaining pairs, cumulative ground cover loss was considerably higher in CONV sites, with the differential response being most notable in pair 5 (Table 8).

For example, during the 2019 drought, TCG sites experienced an average ground cover loss of -4.9%, while CONV sites lost an average of 10.1% (over an 8 month period). This suggests that TCG management may provide some resilience against ground cover loss during extended dry periods. This result is consistent with reports of TCG farmers being more likely to de-stock during dry periods, but we do not have enough data to draw conclusions about the relationship between the maintenance of ground cover during dry periods and de-stocking during dry periods.

Furthermore, a notable difference was observed between TCG and CONV in the number of months when ground cover fell below 80% (Table 9). In general, TCG systems maintained ground cover above 80% for more months compared to CONV systems. However, pair 1 was an exception to this trend, being the only pair where TCG had more months with ground cover below 80% than CONV. This is consistent with the SOC data from this site where SOC stocks in TCG were lower than in CONV.

Table 8: Ground cover loss over 6 months during prolonged dry periods since TCG implementation (where rainfall is less than long-term monthly average for 9 consecutive months)

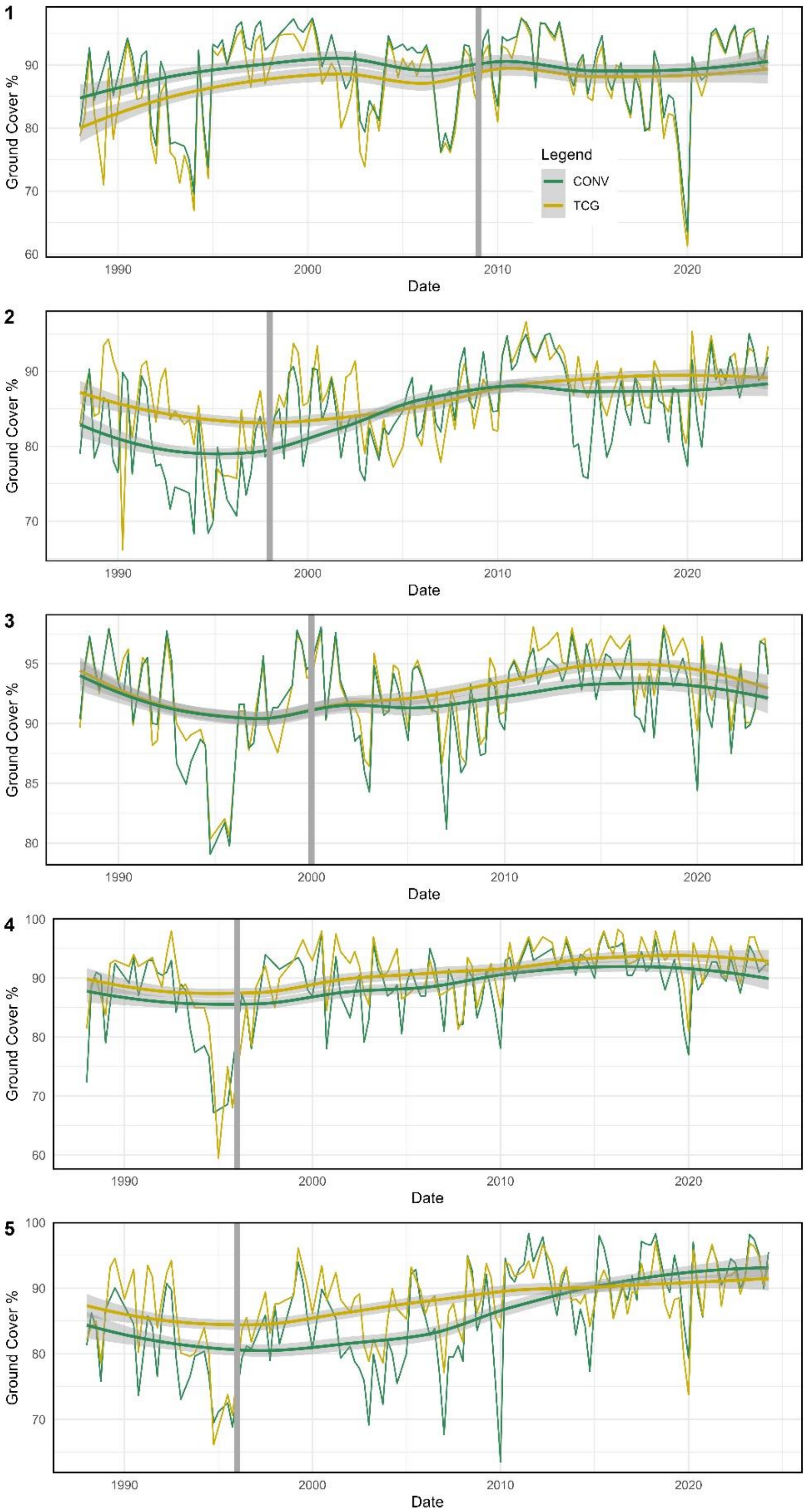
Pair	**Average ground cover loss (%)**		**Loss during 2019 drought (%)**	
	TCG	CONV	TCG	CONV
Pair 1	-12.6	-12.4	-12.6	-12.4
Pair 2	-1.65	-5.2	2.2	-7.1
Pair 3	-2.3	-4.2	-6.5	-9.2
Pair 4	-3.9	-6.7	-9.1	-11.7
Pair 5	-2.3	-6.6	-6.3	-12.1
Average	**-2.5**	**-5.7**	**-4.9**	**-10.1**

Table 9: Ground cover thresholds: number of months when ground cover fell below the 80% threshold.

	Months where ground cover <80% (post TCG intervention)	
Pair	**TCG**	**CONV**
1	14	11
2	18	32
3*	26	56
4	18	45
5	11	67

**Threshold increased to 90% due to no months where ground cover fell below 80%.*

Figure 14: Ground cover (%) at TCG and CONV pairs from 1990 to 2023 taken from VegMachine (Beutel et al., 2019). The grey line indicates the implementation of TCG. A smoothed LOESS function has been applied to highlight trends over time. Red dashed lines represent dry periods where rainfall was below the long-term average for 9 consecutive months. Note that only dry periods post-TCG implementation were analysed to assess differences in response between TCG and CONV sites.



6.5 Biodiversity

This project explored the effectiveness of acoustic monitoring in detecting changes in biodiversity resulting from variations in management practices, vegetation structure and composition, landscape heterogeneity, and ecological conditions. Additionally, it examined the practical applications of using acoustic methods to measure and monitor on-farm biodiversity over time.

Research question 1: Can acoustic monitors be used to measure pasture biodiversity and discriminate between paired sites of time-controlled and conventional grazing?

High frequency cover (HFC) acoustic index

High frequency cover (HFC) was shown to be significantly higher in TCG pastures when compared to CONV grazed pastures across paired sites (Fig. 15). A statistical model indicated that increased HFC values were driven by higher ground cover and pasture height in TCG systems, as well as latitudinal effects on a landscape scale.

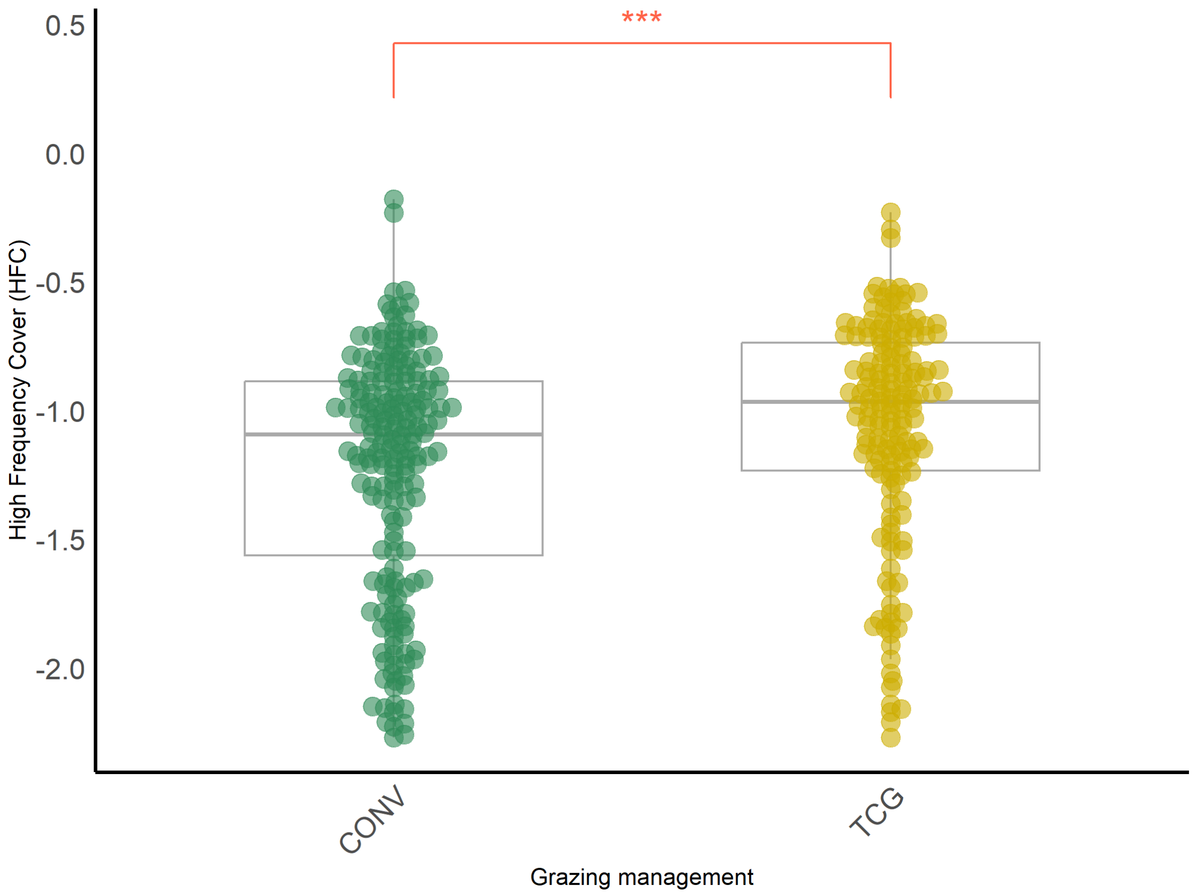
High HFC in TCG pastures may indicate increased insect activity in these systems, and potentially, improved biodiversity outcomes. These conclusions assume that Orthopteran species are representative of broader biodiversity and ecological health due to their important roles in pasture food webs as herbivores and prey for other animals. Orthopterans may also require vegetation complexity in grasslands, with cover and height providing resources which allow them to persist in the landscape. The broader effect of latitude may be related to higher temperatures for northern sites, driving increased biological activity in these pastures.

Bird species richness and composition (using BirdNET)

There has been a long history of using suites of indicator species to measure different ecological states. Birds have often been used as they are highly visible, respond to environmental change, fill a wide range of ecological niches, and have been shown to represent broader biodiversity and ecological condition or health. For automated detection using audio recorders, birds are an ideal target group for broader biodiversity assessment as many birds produce distinctive calls.

BirdNET results for day recordings (04:00 – 06:00) across the four paired sites indicated that bird species richness and composition did not have a significant relationship with grazing management. Instead, bird species richness and composition were significantly related to the amount of woody vegetation cover (area covered). There was a 500 m radius buffer of no woody vegetation around the recorder.

Figure 15: High frequency cover (HFC) and grazing management (TCG vs conventional grazing) for three paired sites in the Brigalow Belt bioregion, Queensland.



Research question 2: Can acoustic monitors be used to measure biodiversity at a farm-scale?

Bird species assemblages derived from audio recordings collected at Pair 1 in southern Queensland were used to develop a model for predicting BioCondition scores across different vegetation types: pasture (pre-clearing brigalow), regrowth brigalow and remnant brigalow. The aim of this preliminary model is to provide a more accessible and cost-effective method for producers to assess ecological conditions at a property scale by utilising acoustic recorders, either as an alternative to or in conjunction with traditional on-ground surveys.

The proposed approach involves sending acoustic recording equipment to producers after a pre-survey desktop spatial analysis. Producers would then deploy the acoustic recorders at specific locations, potentially with minimal vegetation assessments, and return the data and hardware after a designated period. The recordings would be analysed in a laboratory, generating ecological condition metrics.

At Pair 1, AudioMoth acoustic recorders were deployed for approximately one month across four sites (TCG, CONV grazed, and remnant vegetation = training data), with an additional TCG grazing site serving as a validation site. BioCondition surveys, which provide biodiversity value scores based on site and landscape-level vegetation attributes, were conducted at each location.

The AudioMoth data were analysed using BirdNET with an 80% confidence level for bird species identification. A clustering technique was then employed to identify indicator bird species associated with different Biocondition levels[6] (high/remnant, moderate/regrowth, low/pasture) in brigalow forests across two cattle properties and a conservation reserve. An ornithologist reviewed the same recordings to validate the bird species identified by BirdNET. Where BirdNET's identification could not be fully validated, the ornithologist either confirmed or denied the presence of the indicator species.

A multivariate model was developed using partial least squares regression to assess whether the presence or absence of bird species, as detected by the audio recorders and identified with BirdNET, could predict BioCondition scores in brigalow forests of varying condition states. This model was then validated against a new dataset of bird recordings and BioCondition scores.

BirdNET, in conjunction with an ornithologist, identified 27 bird species as indicators of various condition states within brigalow forests. Of these, 12 species were associated with high condition brigalow, 7 species were associated with moderate-high/low condition brigalow, and 8 species were linked to low condition brigalow (Table 10).

The multivariate model showed significant accuracy, with indicator bird species presence or absence strongly predicting BioCondition scores based on the training data. However, when applied to new data, the model's predictive performance was reduced due to inherent variability. This limitation could potentially be mitigated by incorporating additional environmental factors, such as woody vegetation cover, and standardising the timing of targeted sampling.

Table 10: Bird indicator species for high (H), moderate (M), and low (L) condition brigalow forest.

Species	Condition	Ornithologist detected
Eastern Yellow Robin	H	Y
Friarbird sp.	H	Y
Grey Shrike-thrush	H	Y
Mistletoebird	H	Y
Pied Currawong	H	Y
Shining Bronze-Cuckoo	H	Y
Spotted Pardalote	H	Y
Striated Pardalote	H	Y
Weebill	H	N (confirmed to be in area)
Whistler sp.	H	Y
White-throated Treecreeper	H	Y
Yellow-faced Honeyeater	H	Y
Fairywren sp.	M/H	Y
Grey Fantail	M/H	Y
Silvereye	M/H	Y
Singing Honeyeater	M/H	Y
Yellow-rumped Thornbill	M/H	Y
Pied Butcherbird	M/L	Y
Willie Wagtail	M/L	Y
Brown Quail	L	Y
Common Myna	L	Y
Golden-headed Cisticola	L	Y
Little Corella	L	Y
Masked Lapwing	L	Y
Magpie-lark	L	Y
Miner sp.	L	Y

[6] Biocondition framework was used to assess ecological condition. This includes stand age, diversity and structure as well as ground cover etc. https://www.qld.gov.au/environment/plants-animals/biodiversity/biocondition

Tawny Grassbird	L	Y

6.6 Modelling of TCG using DayCENT

Well-designed direct measurement over time remains the most reliable method of change quantification for agricultural soil GHG fluxes and SOC stocks, but it has several drawbacks (Lavallee et al., 2024).

Direct soil coring measurements are costly, time-intensive and lack predictive capabilities. Due to SOC's slow rate of change and high spatial variability, detecting SOC change through direct measurements within 5-10 years is typically infeasible due to high sampling effort required (e.g. Bradford et al., 2023). Moreover, establishing a counterfactual baseline – what would have occurred in the absence of management changes – which is essential for understanding project impacts, cannot be directly measured. Despite these challenges, well-designed direct sampling remains an important part of MRV systems. But these limitations highlight the necessary for alternative methodologies to aid in optimising sampling, project planning, and quantifying management (as opposed to climatic) impacts (Lavallee et al., 2024).

SOC process-based models can help fill this gap:

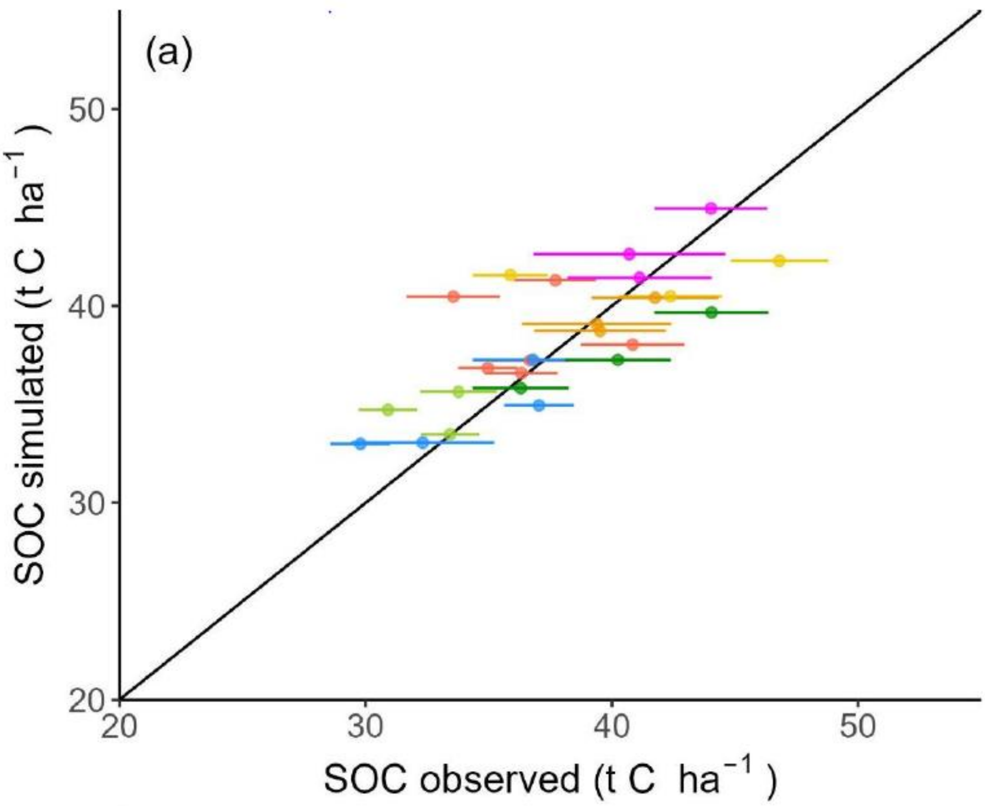
- SOC models can be applied at a relatively low cost.
- SOC models provide forward-looking predictions tailored to specific contexts, accounting for anticipated conditions on the ground including weather and management. These predictions are useful for decision making e.g. producers choosing whether to participate in carbon farming.
- SOC models can be used to make short-term predictions over timescales where direct sampling would not detect change, thereby supporting crediting on an annual basis.
- SOC models can simulate what would happen without specific management interventions, while keeping all other conditions equal to those in the project simulation.
- SOC models can be used in strategic decision-making (e.g. informing on ideal project locations and scales) and are viewed as a cost-effective means to lessen or optimise soil sampling for direct field validation.

In our research, we were able to calibrate and validate the DayCent model for subtropical grazing systems in Australia. The model fit (between SOC observed and modelled data) is shown in Fig 16.

Figure 16: **Observed and simulated soil organic carbon stock in the 0-0.3 m soil depth (t C ha-1) across the flux tower trials in northeast Australia, shown against the 1:1 line[7]. RMSE = 2.81 t C ha-1[8].**

[7] A 1:1 line is a reference line that represents perfect agreement between the observed values and the simulated (or predicted values). This line helps to visually assess how well the model predictions match the actual observations. If the model predictions perfectly match the observations, all points will lie exactly on the 1:1 line. Points above the 1:1 line indicate that the model is overestimating the observed values. Points below the 1:1 line indicate that the model is underestimating the observed values. Therefore the 1:1 line is a key tool in model evaluation.

[8] If the points on the observed versus simulated plot are close to the 1:1 line, the root mean square error (RMSE) is likely to be low. The RMSE is a single numerical value that quantifies the overall differences between observed and simulated values. It measures the standard deviation of the residuals (prediction errors).



6.7 Relationship between grazing practices and producer wellbeing

Although producer wellbeing remains an under-studied field, a limited number of studies suggest a positive association between regenerative grazing practices and a sense of wellbeing. Similarly, in the current study, we observed an 'association' between wellbeing and Time-Controlled Grazing (TCG). However, due to the small sample size, we refrain from asserting causality at this stage.

The mental health and overall wellbeing of Australian producers has been explored through the Regional Wellbeing Survey Australia (RWS) (Peel et al., 2016) and the Australian Rural Mental Health Study (Brew et al., 2016). An RWS survey targeting producers in the grassy woodlands bioregion of New South Wales found regenerative producers reported higher profitability and greater wellbeing compared to other NSW producers, even during periods of drought (Ogilvy et al., 2019). Regenerative practices have been linked to eudaimonic wellbeing (a sense of worthwhileness based on meaning and self-realisation) (Brown et al., 2021) and self-efficacy (self-belief in the capacity to successfully execute tasks) (Ogilvy et al., 2019).

Canadian and US studies have delivered similar findings. Sherren et al. (2022) surveyed TCG producers in Canada, finding they were more likely to think in terms of ‘systems’ and had a higher capacity to adapt to changing conditions, such as drought, when compared with non-TCG producers. Other characteristics associated with a positive sense of wellbeing included a break with traditional values and practices and a priority of enjoying life. In the US, Spratt et al. (2021) report that TCG has positive benefits for financial wellbeing as it offers pathways to profitable farm businesses and greater resilience to financial shocks. In this study, we asked broad, open-ended wellbeing questions about:

1. [Standard of Living] How do you describe your standard of living? (Table 11)
2. [Achieving in Life] How do you describe what you are achieving in life? (Table 12)

3. [Community-Connectedness] Can you describe your community and in what ways you are a part of it? (Table 13)
4. [Future Security/Empowerment] How would you describe your sense of future security? How would you describe your ability/empowerment to take action to improve your wellbeing? (Table 14)
5. [Personal Health] How do you describe your overall health and wellbeing? How does this relate to your occupation? (Table 15)

Questions relating to these concepts were posed to each producer, with key findings summarised below. Quotes are used as exemplars, capturing producer sentiment. The numbers following quotes signify the property number allocated by researchers to maintain confidentiality. The sample size and qualitative methodology offer in-depth insights into matters of wellbeing, and factors that support wellbeing (rather than measures). Research was conducted during a period of high rainfall and good cattle practices, and positive sentiment in the industry.

1. <u>Standard of Living</u>

The timing of the interviews coincided with significant rainfall events, rising land prices and good cattle prices and responses about the standard of living were mostly, but not exclusively positive.

Table 11: Wellbeing insights re Standard of Living

Concept	Example quotes
Income	Like we're not flush with cash, but we are not, you know, wanting for anything. Kids, get to, 'I want to go on a footy trip' or whatever, we have the money that we can go and do that. I wouldn't say we live a lavish lifestyle but we certainly do not want for anything (TCG #04)
Off-farm work	[Off-farm income] helped us tremendously, it helped us tremendously with boarding school fees and through the drought, you know, because as well, it enabled us not to put the pressure back on the business. Yeah, we got through it. We still got in front [TCG #02].
Vulnerability of the family /business enterprise	I had to sell my herd, which I'm still grieving over, but the fact is, I had to sell them because of family matters. So we've been mainly agisting since (TCG #01)

Good seasons were seen as an opportunity to put income aside with options such as superannuation [#01], farm management deposits [#03] or off-farm diversified investments to "not have all eggs in one basket" [#09].

Overall, most producers, across TCG and non-TCG groups spoke positively of their standard of living and lifestyle. Where this was not the case, it was life circumstances, rather than being involved in the beef industry that disrupted a sense of satisfaction with the standard of living.

2. <u>Achieving in life</u>

Beyond purely financial success, other areas of achievement included overcoming past crises, success in managing land, well raised children, and managing a healthy business that proactively moves forward with technology.

Table 12: Wellbeing insights re Achieving in Life

Concept	Example quotes
Self-efficacy to improve to the land and business	I think painting the picture back then, it was a quite a sad place. It lacked energy. There wasn't a lot of grass, just a lot of woody weeds and tried doing things like spraying paddocks. And we were feeding [TCG #13]. I do love cattle, but I primarily love the place and the land. So just to see it in the condition it's in and I believe it's improving" [TCG #05]
Raising a family	The biggest achievement in our life is [x number of] level-headed kids. They are healthy, open minded, yeah, resilient, you know [TCG #13]. So because of our focus and vision is for sustainability because, I've brought [x number] of kids in the world. I don't want to give them a chemical, industrial wasteland to say, well, I had a great time. I was here. Here's a mess [Non-TCG #10].
Professionalism	We've moved with technology. Yeah. And to keep up to date with all the latest and grazing in meat qualities and standards and to meet specifications and breeding of cattle, different breeds of cattle that now there's premiums for. I like to think we're ahead of the game [Non TCG (advanced transitioning) #11].
Professional pride	I am also pretty proud of our staff, and how they're going their wellbeing, and their satisfaction I think is pretty high and that makes us really happy. They're young people and we're giving them a good go and they relishing that. So it's a win win [non-TCG #08].

TCG as a sub-group articulated a strong sense of self-efficacy, purposefulness and strategic approach the work, business and life. These attributes were also detected in non-TCG groups, especially those adopting purposeful rotational, or regenerative practices. Whilst TCG producers were more likely to exhibit these traits, it was not exclusive to that group. As noted above, the context of the 'good seasons' during the data collection phase meant that most producers were optimistic about their property, lifestyle and the industry more broadly.

3. Community-Connectedness

For families working side by side on properties in remote regions connection to community plays a critical role. Many of the respondents indicated they are well connected and integrated into local communities.

Table 13: Wellbeing insights re Community-Connectedness

Concept	Example quotes
Local community	In a small community there's just you, you have to make things happen! And the more effort goes in, the better the community is" [TCG #03].
Community of Practice	It's very important, especially for people like us, who you know there's no one really else. There's other people who look over the fence locally, but very important to have that ability to go out and talk to like-minded people and realise, hey, we're not the only one in the world [TCG #02].
Reliance on community	We had a massive fire here … and there were neighbours here like within an hour sort of thing in the middle of the night. So there's a pretty awesome bunch of people really when, when the chips are down [non-TCG #08]

Shared effort and connection leads to mutual trust and reliance on the community to step up when help is needed, which results in greater resilience to adversity. Digital technology also emerged as a positive development enabling rural producers to expand beyond their geographical communities to broader virtual communities of what several respondents called “like-minded people”. Communities of practice, such as the ‘cell grazing community’ are making an important contribution to developing the confidence needed to make big decisions in property management. TCG practitioners were notably more proactive in sharing learnings with a broader community, helping a younger generation to apply TCG practices with greater confidence and success, building more cohesion into the TCG community and gaining wider acceptance for rotational and management intensive practices. Whilst non-TCG practitioners also noted the value of community connectedness, they were not as pro-active in promoting or engaging with others regarding their own method of grazing management. A key tenet of time-controlled grazing is proactive engagement with others via a ‘community of practice’, often through formal associations via intermediaries that promote variations of time controlled grazing / cell grazing. This is significant as community connectedness is a well-known mediator/predictor of mental wellbeing (for example see Ding et al., 2015).

4. Future Security and Empowerment

Future security is a key concern amongst beef producers. Those that have professionalised their practice through the purposeful adoption of TCG or regenerative practices appeared better empowered to handle external pressures; by reframing them as opportunities or acknowledging pressures but setting them aside. This aspect of producer wellbeing could offer a key intervention point for support from producer-focussed organisations.

Table 14: Wellbeing insights re Future Security and Empowerment

Concept	Example quotes
Concerns for the future	So I feel less secure than I ever have [researcher: why is that] Oh, it's because of how the view of the livestock with the methane gases how the controlling, or the regulation of that… I’m wondering where this is going [non TCG #12]
External forces	The big the biggest threat is ignorance out there in the public and the livestock industry being a really soft target, because we're such a diverse bunch. Put a hundred livestock producers in a room, you get a hundred different opinions [non TCG #08] I'd like to have a maximum amount of control over how I manage my life in that I don't want to be tied. I want to be tied to as least number of external influences as possible [Non-TCG #10]
Controlling what can be controlled	All we can do is try and be on top of what we're doing and do as much as we can at that point in time. [TCG #05]

On balance, TCG producers expressed a strong sense of control over future directions, which they attributed to their structured data-driven business planning and management process. Across the sample of both groups, very similar future concerns were expressed, including the political impact of “greenies”, biosecurity, lab grown ‘meat’, plant-based diets and climate change. TCG producers were more likely to downplay external impacts, and attitudes favoured only worrying about the things you can control. Some TCG producers saw climate change mitigation as an opportunity rather than a threat and were advanced in their own research on engaging with carbon markets.

5. Personal Health

In general, producers reported good physical health but also noted the inconvenience of needing to travel to cities or regional centres for health interventions, such as surgery. Inevitably this left a management gap at the property that needed to be addressed.

Table15: Wellbeing insights re Personal health

Concept	Example quotes
Mental strain	When it is a tough time or there is the shocks, mentally this can be challenging. Because you've got to rise above the mental strain [non-TCG #12].
Decision support tools can help mental wellbeing	Producers need to feel a sense they are controlling, there needs to be systems that support the sense of control, it's better for [producers] and their land and economics [non-TCG #14].
Data and decision making	You are never really totally separating emotions from the business, but trying to set up a system takes a lot of that out of it for you [TCG #13] [our work relies upon] measurements and data rather than experience and tradition [non TCG (transitioning) #11]. I think we're pretty good at using the data to make those decisions. Really. Be it environmental or financial, I think we're, we're pretty good at that. That's why we collect all the data and we use it [TCG #04].

Making a living off the land requires independence and self-reliance, as producers face major decisions over capital, livestock and people while potentially feeling "isolated" and "insulated".

In Australia, producers have been recognised as an occupational group that are of higher risk of suicide despite mental ill-health across rural and urban areas being comparable (Perceval et al., 2018). Higher levels of risk in rural areas may include factors such as socio-economic decline and barriers to service utilisation. Unfortunately, this has not been resolved for rural producers with poor access to mental health services flagged several times in the study, both within the TCG and non-TCG groupings.

The prevention and management of stresses is an important factor in mental wellbeing. Data from the study reveals ways in which digital technologies and the data they produce are harnessed to manage the complexities of production. Those adopting these practices framed their digital management practices distinctively in terms of supporting 'mindspace' and mental wellbeing. This research indicated TCGs' practices are setting new norms through reliance on data (pasture, weight gain, time of cattle rotations, market prices) and digital decision support systems. For TCGs, 'knowledge is power'. However, it is not necessarily the practice of TCG that may/may not support personal health and mental wellbeing, but rather the self-efficacy derived from close management, and hence control, of grazing systems. For TCGs in the study, this close monitoring control was directly related to sustainability, nature capital, animal welfare, enhanced income, and wellbeing. These factors were observed as serving as a source of pride for producers and indicators of being a 'good farmer'.

Conclusion

This study provides a snapshot on grazing management and producer wellbeing across a spectrum of management styles. The qualitative research methodology that fits the small sample size allows a deep and nuanced understanding of the grazier's experiences and perceptions. This research took place under generally positive climate and market conditions (MLA, 2022), which meant graziers across all practice typologies were reporting high levels of optimism, satisfaction and wellbeing.

Self-efficacy and eudemonic wellbeing - The findings from this study align with prior studies that report a) self-efficacy is high among regenerative, holistic and TCGs and that b) self-efficacy is an important attribute of wellbeing. Without overstating its importance, a key difference from the comparison of practice between TCG and non-TCG farms is the shift toward data informed decision making. It is apparent that a shift to TCG (or similar) requires high levels of professionalisation across all aspects of the enterprise, including pasture management (monitoring and budgeting), cattle management, markets and trading. Implications for future research may be that comparisons do not only need to address TCG versus Non-TCG, but structured data-based management versus unstructured management styles.

Purposeful management styles - As noted in Fig 1. the comparison between TCG and non-TCG is not ‘black and white’ due to selective adoption of practices across a spectrum. Nevertheless, this research has confirmed that TCG farms have a much stronger focus than non-TCG farms on the adoption of digital technology for monitoring, efficiency improvement, and decision making. Moreover, TCG respondents were invariably able and prepared to share management data records with the researchers while several non-TCG respondents reported low or no levels of data records. This difference also extends to budgeting and planning, where TCG producers generally claimed to have an updated written grazing plan, while non TCG producers cited reliance on experience, intuition and ‘unwritten plans’ to support decisions.

Data-based practice - This has emerged as a central feature of successful business management, but also a decision support mechanism that reduces stress and mental strain. Using data for informed decision making, alongside knowledge sharing among a community of practice and mutual security formed through local communities, emerged as important factors in mental wellbeing. Many of these ‘wellbeing attributes’ can be promoted across all grazing systems with support from producer organisations and peak bodies.

Sustainability - In terms of sustainability outcomes, including soil C sequestration, the structured and data-driven management practices associated with production might provide competitive benefits in future climate markets, including carbon and nature credits, which fundamentally rely on measurement and availability of data. A broader effect would be the potential to diversify income into carbon markets, presenting options for a diversified farm income – which is strongly associated with sustainable livelihoods and general wellbeing.

7. Conclusion

Key findings:

We have presented analysis of the impact of TCG grazing management on SOC stocks in subtropical grazing systems (Vertosols, 500-600 mm rainfall). Our findings are specific to higher rainfall areas on clay soils in central and southern Queensland and may not be directly applicable to other grazing regions. While there are acknowledged limitations associated with the paired site approach, it remains valuable in the absence of long-term trials established from the same baseline.

- Paired site analysis demonstrated that SOC was 17.7 tC/ha greater in TCG systems in comparison to conventionally grazed systems after an average of 22 years of TCG implementation.
- Over the short term (2 to 3 years), no significant difference in carbon drawdown, as measured by net ecosystem exchange (NEE), was observed between TCG and CONV grazing systems. This is likely due to the dominant influence of rainfall variability on SOC stocks, which can overshadow management effects in the short term.
- TCG sites had a greater proportion of SOC stored as 'stable' mineral-associated organic matter, likely due to higher soil nitrogen content, as stable SOC has a low C:N ratio.
- Ground cover analysis revealed that TCG sites experienced less ground cover loss during extended dry periods (defined as 8 consecutive months of below-average rainfall) compared to conventionally grazed sites.
- Audible insect activity, indicated by the high frequency cover (HFC) acoustic index, was higher in TCG systems compared to conventional grazing. This increase in HFC was driven by higher pasture cover and height in TCG systems. TCG management did not significantly affect bird species richness and composition; instead, these factors were more closely related to the proximity and amount of woody vegetation within a 500m radius around the recording site.
- A key difference noted between TCG and conventional farms was the reliance on data-driven decision making, which likely reduced stress, improved management, and enhanced mental wellbeing. TCG farms demonstrated a greater use of digital technology and structured planning, compared to non-TCG farms, which often relied on intuition and unwritten plans. The shift to data-based management practices not only supported business success but also positioned TCG farms to benefit from emerging opportunities in carbon and nature markets. Broader adoption of improved data management practices, with support from industry bodies, could foster wellbeing across all grazing systems while advancing sustainability outcomes.

8. Benefits to industry

Informed decision-making for soil carbon projects: The project provides evidence and establishes a 'reasonable bound' on the magnitude of long-term SOC sequestration rates that farmers can expect in grazing systems. The research showed a difference of 17.7 t C/ha between management systems under 'best-case scenario' conditions in Queensland (i.e., >600 mm rainfall and good clay soils). This demonstrates the potential for soil carbon gains under improved grazing management, contrasting with earlier studies (e.g., Allen et al., 2014) that showed limited potential.

We are concerned about the high SOC sequestration rates being communicated to farmers, especially based on the short-term issuance rates granted by the Clean Energy Regulator (e.g. 6 tC/ha/year – see Appendix). These short-term rates should not be presented as the long-term potential for SOC sequestration. Providing a realistic indication of long-term SOC sequestration potential under favourable conditions will better equip producers to make informed decisions about participating in soil carbon projects.

Impact of seasonal conditions on carbon sequestration: The research revealed that carbon sequestration responded strongly to seasonal conditions over the short term (3 years), even without changes in management practices. No discernible difference in carbon drawdown was observed between TCG and CONV grazing over this period. The study highlights the need for caution when using short-term data (<10 years) to make management decisions.

Guidance for grazing best practices: The project established a protocol and a network of long-term monitoring sites that could help guide best practices in the grazing industry.

Low-cost biodiversity monitoring: We have provided a proof-of-concept study to show that acoustics can be used as a viable, low-cost option for monitoring biodiversity outcomes at the farm scale. Further on-farm testing and commercialisation will be explored in a future project.

9. Future research and recommendations

We have successfully demonstrated the proof-of-concept for generating high-resolution data on soil carbon storage (via flux towers) and ecosystem outcomes (via ecoacoustics) at the property scale. The next step is to integrate these advanced observation tools into a nationally consistent framework for monitoring sustainable grazing management.

A major challenge for Australia's agricultural sector in demonstrating sustainable outcomes is the lack of standardization in monitoring, reporting and verification (MRV) processes. This gap hampers both the research and development of innovative farming practices and the critical extension, adoption and reporting of sustainability outcomes. Currently, data generation is largely industry-led, resulting in (1) a reliance on remote-sensing products that, while cost-effective, lack the resolution to adequately capture sustainability outcomes without proper calibration, and (2) the proliferation of farm-scale measurement approaches and metrics that are not standardized, publicly accessible, or cost-effective, and are difficult to apply consistently across Australia's diverse landscapes.

Fortunately, the capacity and expertise to produce nationally consistent, high-resolution, scalable farm-level data exists within Australia, particularly in organizations like the Terrestrial Ecosystem Research Network (TERN). TERN employs cutting-edge landscape observation tools such as flux towers, ecoacoustics, and camera traps to generate open-access data. However, TERN's current reach is limited to natural ecosystems, and its primary users are the research community and non-profit organizations.

Building on the success of this project, we propose expanding TERN's scope to include managed agricultural systems through a 'hub and satellite' approach. This would enable MRV of on-farm and integrated supply chain sustainability outcomes, providing critical data to 'upstream' users for tracking progress on sustainability targets.

The proposed network would consist of centralized 'hubs' (n=10), each representing fully instrumented farms that capture data on carbon, water use, nitrogen, and biodiversity across relevant agroecological zones. To ensure cost-effectiveness and scalability, 'satellite' sites (initially 5 farms per hub) would utilize low-cost sensors, remote sensing, and modelling (as demonstrated in this project) to extend data collection to the regional scale. This strategy offers a cost-effective pathway to leverage existing infrastructure and networks, enabling the capture, streamlining, and standardisation of a sustainability data pipeline, and allowing Australia to narrate its sustainability achievements in a nationally coherent manner.

10. Recommendations for the industry

Our paired site analysis has provided valuable insights into the potential for SOC sequestration with TCG adoption. However, to fully realise this potential, the industry would greatly benefit from investing in long-term monitoring networks. These networks should implement management practices from the same baseline, helping to avoid some of the limitations and potential confounding factors associated with paired site analysis.

Long-term monitoring networks are essential for the emerging carbon and natural capital markets. Given the extended time frames required to observe the impacts of management changes, it is critical that the industry has access to reliable, independent data and advice. This initiative should be industry-led and financed, with support from government and research organisations such as TERN.

11. References

Allen, D. E., Pringle, M. J., Bray, S., Hall, T. J., O'Reagain, P. O., Phelps, D., Cobon, D. H., Bloesch, P. M., & Dalal, R. C. (2013). What determines soil organic carbon stocks in the grazing lands of north-eastern Australia? *Soil Research*. https://doi.org/10.1071/SR13041

Allen, V. G., Batello, C., Berretta, E. J., Hodgson, J., Kothmann, M., Li, X., McIvor, J., Milne, J., Morris, C., Peeters, A., & Sanderson, M. (2011). An international terminology for grazing lands and grazing animals. In *Grass and Forage Science* (Vol. 66, Issue 1, pp. 2–28). https://doi.org/10.1111/j.1365-2494.2010.00780.x

Bai, Y., & Cotrufo, M. F. (2022). Grassland soil carbon sequestration: Current understanding, challenges, and solutions. *Science*, *377*(6606), 603–608. https://www.science.org

Bartley, R., Abbott, B. N., Ghahramani, A., Ali, A., Kerr, R., Roth, C. H., & Kinsey-Henderson, A. (2023). Do regenerative grazing management practices improve vegetation and soil health in grazed rangelands? Preliminary insights from a space-for-time study in the Great Barrier Reef catchments, Australia. *The Rangeland Journal*, *44*(4), 221–246. https://doi.org/10.1071/rj22047

Bonner, M. T. L., Shoo, L. P., Brackin, R., & Schmidt, S. (2018). Relationship between microbial composition and substrate use efficiency in a tropical soil. *Geoderma*, *315*, 96–103. https://doi.org/10.1016/j.geoderma.2017.11.026

Bradford, M. A., Eash, L., Polussa, A., Jevon, F. V., Kuebbing, S. E., Hammac, W. A., Rosenzweig, S., & Oldfield, E. E. (2023). Testing the feasibility of quantifying change in agricultural soil carbon stocks through empirical sampling. *Geoderma*, *440*. https://doi.org/10.1016/j.geoderma.2023.116719

Brew, B., Inder, K., Allen, J., Thomas, M., & Kelly, B. (2016). The health and wellbeing of Australian farmers: A longitudinal cohort study. *BMC Public Health*, *16*(1). https://doi.org/10.1186/s12889-016-3664-y

Brown, K., Schirmer, J., & Upton, P. (2021). Regenerative farming and human wellbeing: Are subjective wellbeing measures useful indicators for sustainable farming systems? *Environmental and Sustainability Indicators*, *11*. https://doi.org/10.1016/j.indic.2021.100132

Chan, K. Y., Oates, A., Li, G. D., Conyers, M. K., Prangnell, R. J., Poile, G., Liu, D. L., & Barchia, I. M. (2010). Soil carbon stocks under different pastures and pasture management in the higher rainfall areas of south-eastern Australia. *Australian Journal of Soil Research*, *48*(1), 7–15. https://doi.org/10.1071/SR09092

Clean Energy Regulator. (2023). *Understanding your soil carbon project. Emissions Reduction Fund simple method guide for soil carbon projects registered under the Carbon Credits (Carbon Farming Initiative - Estimation of Soil Organic Carbon Sequestration using Measurement and Models) Methodology Determination 2021* . https://www.cleanenergyregulator.gov.au/DocumentAssets/Documents/Understanding%20your%20soil%20carbon%20project%20-%20Simple%20method%20guide.pdf

Dalal, R. C., Thornton, C. M., Allen, D. E., Owens, J. S., & Kopittke, P. M. (2021). Long-term land use change in Australia from native forest decreases all fractions of soil organic carbon, including resistant organic carbon, for cropping but not sown pasture. *Agriculture, Ecosystems and Environment*. https://doi.org/10.1016/j.agee.2021.107326

Del Grosso, S. J., Parton, W. J., Derner, J. D., Chen, M., & Tucker, C. J. (2018). Simple models to predict grassland ecosystem C exchange and actual evapotranspiration using NDVI and environmental variables. *Agricultural and Forest Meteorology*, *249*, 1–10. https://doi.org/10.1016/j.agrformet.2017.11.007

Del Grosso, S., Parton, W., Stohlgren, T., Zheng, D., Bachelet, D., Prince, S., Hibbard, K., & Olson, R. (2008). Global potential net primary production predicted from vegetation class, precipitation, and temperature. *Ecology*, *89*(8), 2117–2126. https://doi.org/10.1890/07-0850.1

Fierer, N., Grandy, A. S., Six, J., & Paul, E. A. (2009). Searching for unifying principles in soil ecology. In *Soil Biology and Biochemistry* (Vol. 41, Issue 11, pp. 2249–2256). https://doi.org/10.1016/j.soilbio.2009.06.009

Frostegard, A., & Baath, E. (1996). The use of phospholipid fatty acid analysis to estimate bacterial and fungal biomass in soil. *Biology and Fertility of Soils*, *22*(1–2), 59–65. https://doi.org/10.1007/bf00384433

Gray, J. M., Bishop, T. F. A., & Wilson, B. R. (2015). Factors Controlling Soil Organic Carbon Stocks with Depth in Eastern Australia. *Soil Science Society of America Journal*, *79*(6), 1741–1751. https://doi.org/10.2136/sssaj2015.06.0224

Hall, T. J., Mcivor, J. G., Reid, D. J., Jones, P., Macleod, N. D., Mcdonald, C. K., & Smith, D. R. (2014). A comparison of stocking methods for beef production in northern Australia: Pasture and soil surface condition responses. *Rangeland Journal*. https://doi.org/10.1071/RJ13075

Harrison, M. T., Cullen, B. R., Mayberry, D. E., Cowie, A. L., Bilotto, F., Badgery, W. B., Liu, K., Davison, T., Christie, K. M., Muleke, A., & Eckard, R. J. (2021). Carbon myopia: The urgent need for integrated social, economic and environmental action in the livestock sector. In *Global Change Biology* (Vol. 27, Issue 22, pp. 5726–5761). John Wiley and Sons Inc. https://doi.org/10.1111/gcb.15816

Hobley, E., Wilson, B., Wilkie, A., Gray, J., & Koen, T. (2015). Drivers of soil organic carbon storage and vertical distribution in Eastern Australia. *Plant and Soil*, *390*(1–2), 111–127. https://doi.org/10.1007/s11104-015-2380-1

Ingham, E. (2022). *Fungi and Bacteria Ratios in Soil* [Broadcast]. YouTube. https://www.youtube.com/watch?v=9nTTnIHg8gs

Jones, A., Orton, T., & Dalal, R. (2016). The legacy of cropping history reduces the recovery of soil carbon and nitrogen after conversion from continuous cropping to permanent pasture. *Agriculture, Ecosystems and Environment*, *216*.

Kallenbach, C. M., Frey, S. D., & Grandy, A. S. (2016). Direct evidence for microbial-derived soil organic matter formation and its ecophysiological controls. *Nature Communications*, *7*. https://doi.org/10.1038/ncomms13630

Khangura, R., Ferris, D., Wagg, C., & Bowyer, J. (2023). Regenerative Agriculture—A Literature Review on the Practices and Mechanisms Used to Improve Soil Health. In *Sustainability (Switzerland)* (Vol. 15, Issue 3). MDPI. https://doi.org/10.3390/su15032338

Lavallee, J. M., Soong, J. L., & Cotrufo, M. F. (2020). Conceptualizing soil organic matter into particulate and mineral-associated forms to address global change in the 21st century. *Global Change Biology*. https://doi.org/10.1111/gcb.14859

Lavallee, J., Mcconkey, B., Kyker-Snowman, E., Dietze, M., Harrison, M., Liu, K., Smith, W., & Grant, B. (2024). *Modeling Soil Carbon and Greenhouse Gas Emissions: Identifying challenges and advancing guidance for using process-based models in soil emission reduction and removal projects*.

Lehmann, J., & Kleber, M. (2015). The contentious nature of soil organic matter. In *Nature*. https://doi.org/10.1038/nature16069

Love, G. (2005). Impacts of climate variability on regional Australia. . *ABARE Outlook Conference Proceedings (National Agricultural and Resources Outlook Conference Proceedings*.

Lützow, M. V, Kögel-Knabner, I., Ekschmitt, K., Matzner, E., Guggenberger, G., Marschner, B., & Flessa, H. (2006). Stabilization of organic matter in temperate soils: Mechanisms and their relevance under different soil conditions - A review. In *European Journal of Soil Science*. https://doi.org/10.1111/j.1365-2389.2006.00809.x

McCosker, T. (1994). The dichotomy between research results and practical experience with time control grazing. *Australian Rural Science Annual*, 26–31.

McCosker, T. (2000). Cell grazing - the first 10 years in Australia. *Tropical Grasslands*, *34*, 207–218.

McDonald, S. E., Badgery, W., Clarendon, S., Orgill, S., Sinclair, K., Meyer, R., Butchart, D. B., Eckard, R., Rowlings, D., Grace, P., Doran-Browne, N., Harden, S., Macdonald, A., Wellington, M., Pachas, A. N. A., Eisner, R., Amidy, M., & Harrison, M. T. (2023). Grazing management for soil carbon in Australia: A review. In *Journal of Environmental Management* (Vol. 347). Academic Press. https://doi.org/10.1016/j.jenvman.2023.119146

Mckeon, G. M., Day, K. A., Howden, S. M., Mott, J. J., Orr, D. M., Scattini, W. J., & Weston, E. J. (1990). Northern Australian Savannas: Management for Pastoral Production. *Savanna Ecology and Management: Australian Perspectives and Intercontinental Comparisons*, *17*(4), 355–372.

Meneghini, B., Simmonds, I., & Smith, I. N. (2007). Association between Australian rainfall and the Southern Annular Mode. *International Journal of Climatology*, *27*(1), 109–121. https://doi.org/10.1002/joc.1370

Meyers, G., McIntosh, P., Pigot, L., & Pook, M. (2007). The years of El Niño, La Niña and interactions with the tropical Indian Ocean. *Journal of Climate*, *20*(13), 2872–2880. https://doi.org/10.1175/JCLI4152.1

Mitchell, E., Scheer, C., Rowlings, D., Cotrufo, F., Conant, R. T., & Grace, P. (2021). Important constraints on soil organic carbon formation efficiency in subtropical and tropical grasslands. *Global Change Biology*, *27*(20), 5383–5391. https://doi.org/10.1111/gcb.15807

MLA. (2022). *Cattle market in 2022: a year in review*. https://www.mla.com.au/news-and-events/industry-news/cattle-market-in-2022-a-year-in-review/

MLA. (2024). *MLA Research and Development: Grazing Strategies*. https://www.mla.com.au/research-and-development/Grazing-pasture-management/native-pasture/grazing-management/grazing-strategies/

Mosier, S. (2021). *Adaptive multi-paddock grazing increases soil carbon and nitrogen stocks and stabilization through mineral association in southeastern U.S. grazing lands*.

Murphy, B., Rawson, A., Ravenscroft, L., Rankin, M., & Millard, R. (2003). *Paired Site Sampling for Soil Carbon Estimation-New South Wales*. http://www.greenhouse.gov.au/ncas

Nicholls, N. (1991). The El Nifio / Southern Oscillation and Australian vegetation. *Vegetation*, *91*, 23–36.

Novick, K., Williams, C., Runkle, B., Anderegg, W. R. L., Hollinger, D., Litvak, M., Normile, C., Shrestha, G., Almaraz, M., Anderson, C., Barnes, M., Baldocchi, M., Colburn, L., Cullenward, D., Evans, M., Guan, K., Keenan, T., Lamb, R., Larson, E., … Woodall, C. (2022). *The science needed for robust, scalable, and credible nature-based climate solutions in the United States*.

O'Connor, C., & Joffe, H. (2020). Intercoder Reliability in Qualitative Research: Debates and Practical Guidelines. *International Journal of Qualitative Methods*, *19*. https://doi.org/10.1177/1609406919899220

Ogilvy, S., Gardner, M., Mallawaarachchi, T., Schirmer, J., Brown, K., & Heagney, E. (2019). *GRAZIERS WITH BETTER PROFITABILITY, BIODIVERSITY AND WELLBEING Exploring the potential for improving environmental, social and economic outcomes in agriculture*. www.vbs.net.au.

Parton, W. J., Gutmann, M. P., Merchant, E. R., Hartman, M. D., Adler, P. R., McNeal, F. M., & Lutz, S. M. (2015). Measuring and mitigating agricultural greenhouse gas production in the US Great Plains, 1870-2000. *Proceedings of the National Academy of Sciences of the United States of America*, *112*(34), E4681–E4688. https://doi.org/10.1073/pnas.1416499112

Parton, W., Morgan, J., Smith, D., Del Grosso, S., Prihodko, L., Lecain, D., Kelly, R., & Lutz, S. (2012). Impact of precipitation dynamics on net ecosystem productivity. *Global Change Biology*, *18*(3), 915–927. https://doi.org/10.1111/j.1365-2486.2011.02611.x

Parton, W., Silver, W. L., Burke, I. C., Grassens, L., Harmon, M. E., Currie, W. S., King, J. Y., Adair, E. C., Brandt, L. A., Hart, S. C., & others. (2007). Global-scale similarities in nitrogen release patterns during long-term decomposition. *Science*, *315*(5810), 361–364.

Paustian, K., Lehmann, J., Ogle, S., Reay, D., Robertson, G. P., & Smith, P. (2016). Climate-smart soils. *Nature*, *532*(7597), 49–57. https://doi.org/10.1038/nature17174

Peel, D., Berry, H. L., & Schirmer, J. (2016). Farm exit intention and wellbeing: A study of Australian farmers. *Journal of Rural Studies*, *47*, 41–51. https://doi.org/10.1016/j.jrurstud.2016.07.006

Perceval, M., Ross, V., Kõlves, K., Reddy, P., & De Leo, D. (2018). Social factors and Australian farmer suicide: A qualitative study. *BMC Public Health*, *18*(1). https://doi.org/10.1186/s12889-018-6287-7

Power, S., Casey, T., Folland, C., Colman, A., & Mehta, V. (1999). *Inter-decadal modulation of the impact of ENSO on Australia*.

Power, S., Haylock, M., Colman, R., & Wang, X. (2006). The Predictability of Interdecadal Changes in ENSO Activity and ENSO Teleconnections. *Climate Dynamics* , *15*, 319–324. http://journals.ametsoc.org/jcli/article-pdf/19/19/4755/3799141/jcli3868_1.pdf

Rabbi, S. M. F., Tighe, M., Delgado-Baquerizo, M., Cowie, A., Robertson, F., Dalal, R., Page, K., Crawford, D., Wilson, B. R., Schwenke, G., McLeod, M., Badgery, W., Dang, Y. P., Bell, M., O Leary, G., Liu, D. L., & Baldock, J. (2015). Climate and soil properties limit the positive effects of land use reversion on carbon storage in Eastern Australia. *Scientific Reports*, *5*. https://doi.org/10.1038/srep17866

Rigby, R. A., & Stasinopoulos, D. M. (2005). Generalized Additive Models for Location, Scale and Shape. In *Source: Journal of the Royal Statistical Society. Series C (Applied Statistics)* (Vol. 54, Issue 3).

Rillig, M. C., Caldwell, B. A., Wösten, H. A. B., & Sollins, P. (2007). Role of proteins in soil carbon and nitrogen storage: Controls on persistence. *Biogeochemistry*, *85*(1), 25–44. https://doi.org/10.1007/s10533-007-9102-6

Risbey, J. S., Pook, M. J., McIntosh, P. C., Wheeler, M. C., & Hendon, H. H. (2009). On the remote drivers of rainfall variability in Australia. *Monthly Weather Review*, *137*(10), 3233–3253. https://doi.org/10.1175/2009MWR2861.1

Rowntree, J. E., Stanley, P. L., Maciel, I. C. F., Thorbecke, M., Rosenzweig, S. T., Hancock, D. W., Guzman, A., & Raven, M. R. (2020). Ecosystem Impacts and Productive Capacity of a Multi-Species Pastured Livestock System. *Frontiers in Sustainable Food Systems*, *4*(December). https://doi.org/10.3389/fsufs.2020.544984

Sanderman, J., Baldock, J., Hawke, B., Macdonald, L., Massis-Puccini, A., & Szarvas, S. (2011). *National Soil Carbon Research Programme: Field and Laboratory Methodologies*.

Sanderman, J., Hengl, T., & Fiske, G. J. (2017). Soil carbon debt of 12,000 years of human land use. *Proceedings of the National Academy of Sciences of the United States of America*. https://doi.org/10.1073/pnas.1706103114

Sherren, K., Hodbod, J., MathisonSlee, M., Chappell, E., & King, M. (2022). Adaptive multi-paddock grazing and wellbeing: uptake, management practices and mindset among Canadian beef producers. *Agroecology and Sustainable Food Systems*, *46*(9), 1304–1329. https://doi.org/10.1080/21683565.2022.2107597

Spratt, E., Jordan, J., Winsten, J., Huff, P., van Schaik, C., Jewett, J. G., Filbert, M., Luhman, J., Meier, E., & Paine, L. (2021). Accelerating regenerative grazing to tackle farm, environmental, and societal challenges in the upper Midwest. In *Journal of Soil and Water Conservation* (Vol. 76, Issue 1, pp. 15A-23A). Soil and Water Conservation Society. https://doi.org/10.2489/jswc.2021.1209A

Stanley, P., Spertus, J., Chiartas, J., Stark, P. B., & Bowles, T. (2023). Valid inferences about soil carbon in heterogeneous landscapes. *Geoderma*, *430*. https://doi.org/10.1016/j.geoderma.2022.116323

Stewart, C. E., Paustian, K., Conant, R. T., Plante, A. F., & Six, J. (2007). Soil carbon saturation: Concept, evidence and evaluation. *Biogeochemistry*. https://doi.org/10.1007/s10533-007-9140-0

Stockmann, U., Adams, M. A., Crawford, J. W., Field, D. J., Henakaarchchi, N., Jenkins, M., Minasny, B., McBratney, A. B., Courcelles, V. de R. de, Singh, K., Wheeler, I., Abbott, L., Angers, D. A., Baldock, J., Bird, M., Brookes, P. C., Chenu, C., Jastrow, J. D., Lal, R., … Zimmermann, M. (2013). The knowns, known unknowns and unknowns of sequestration of soil organic carbon. In *Agriculture, Ecosystems and Environment* (Vol. 164, pp. 80–99). Elsevier B.V. https://doi.org/10.1016/j.agee.2012.10.001

Wiesmeier, M., Urbanski, L., Hobley, E., Lang, B., von Lützow, M., Marin-Spiotta, E., van Wesemael, B., Rabot, E., Ließ, M., Garcia-Franco, N., Wollschläger, U., Vogel, H. J., & Kögel-Knabner, I.

(2019). Soil organic carbon storage as a key function of soils - A review of drivers and indicators at various scales. In *Geoderma*. https://doi.org/10.1016/j.geoderma.2018.07.026

12. Appendix

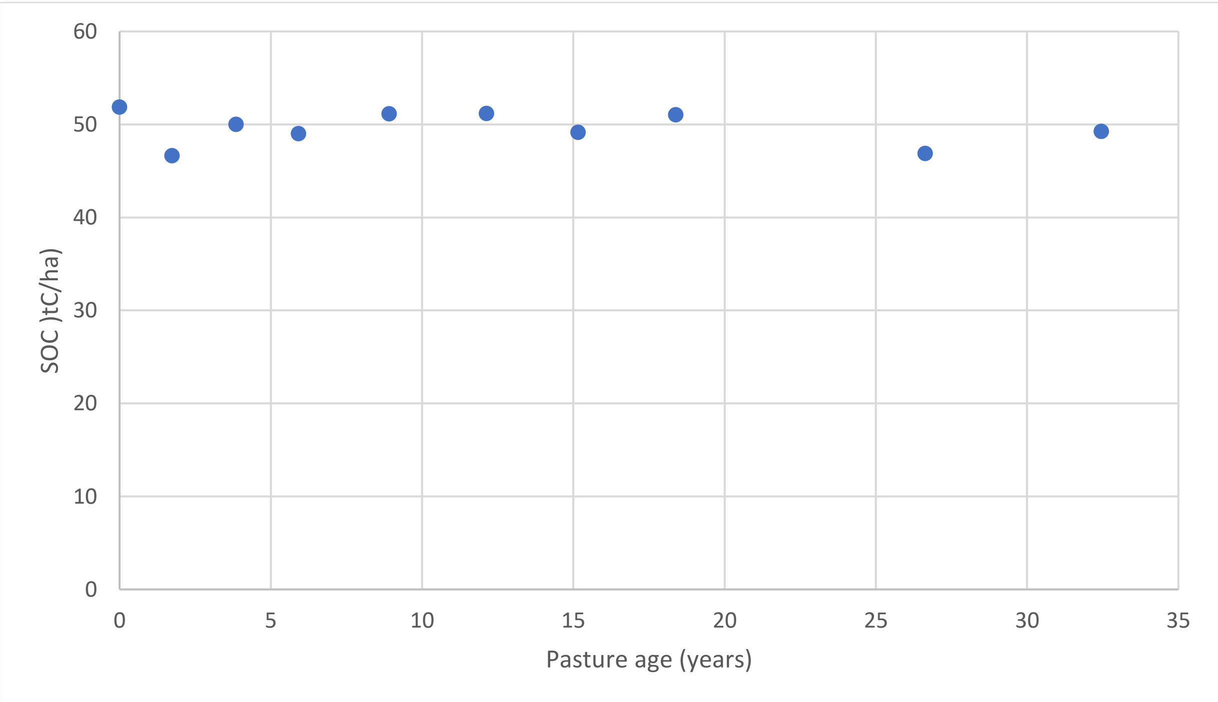
12.1 The conversion of forest to pasture

The conversion of forest to pasture in the Brigalow Catchment Study is shown in the Figure below. When expressed on an Equivalent Soil Mass (ESM) basis, SOC stocks of pasture soil showed no significant change with time (see the attached sheet) (Dalal *et al.,* 2021).

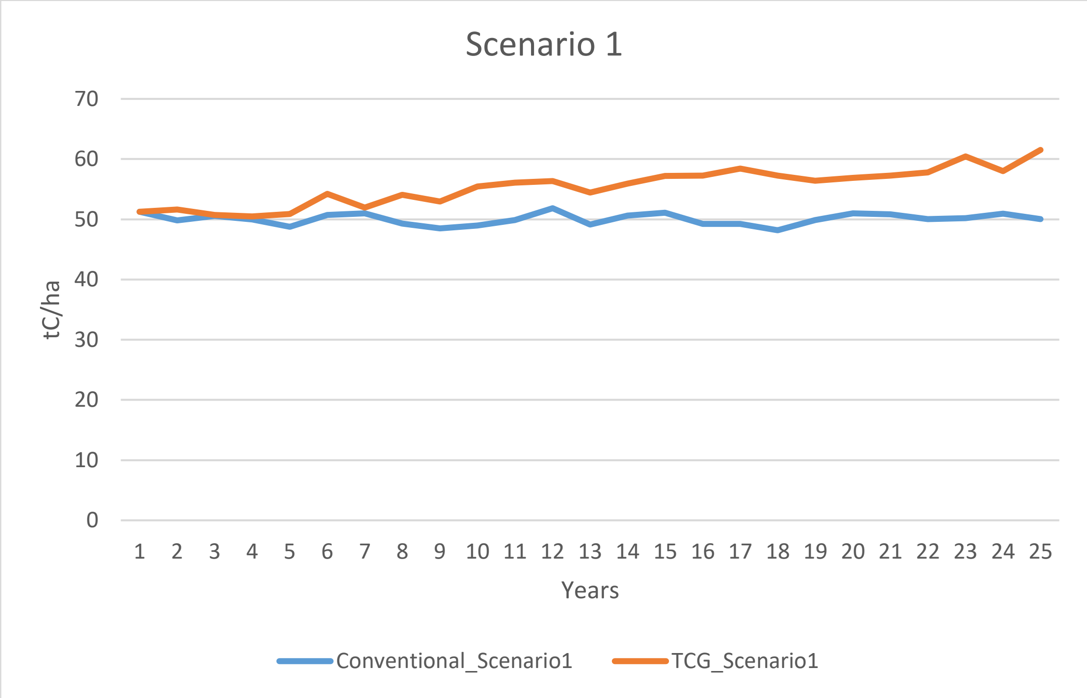
The Brigalow Catchment Study is a long-term trial commenced in 1965 in the Brigalow Belt bioregion, located near Theodore, Central Queensland (24.818°S, 149.808°E). The catchment area was cleared and converted into cropping and grazed pasture systems in 1982 with some remaining native forest. The pasture site was sown to Buffel pasture in November 1982. Grazing of the pasture commenced a year later and the animal stocking rate was adjusted to maintain ground cover >85 % or about 1000 kg ha^{-1} of aboveground pasture biomass during the experimental period (1983–2014) (Radford et al., 2007). This pasture catchment area is dominated by Vertisols as described by the USDA classification (Soil Survey Staff, 2022) with a mean maximum temperature of 33.1°C in January, a minimum temperature is 6.5°C in July and 720 mm of mean annual precipitation (Cowie et al., 2007). Soil samples were collected in 1981 (baseline, 0 y), 1983, 1985, 1987, 1990, 1994, 1997, 2000, 2008 and 2014 at three monitoring locations within each of the three sites of native forest, pasture and cropping (Dalal et al., 2021).

A non-significant change in soil organic carbon (SOC) over time in pasture was considered the most likely outcome under conventional management systems (scenario 1 below). However, this does not rule out the possibility that SOC levels were actually declining at the paired sites studied under conventional management (scenario 2 below).

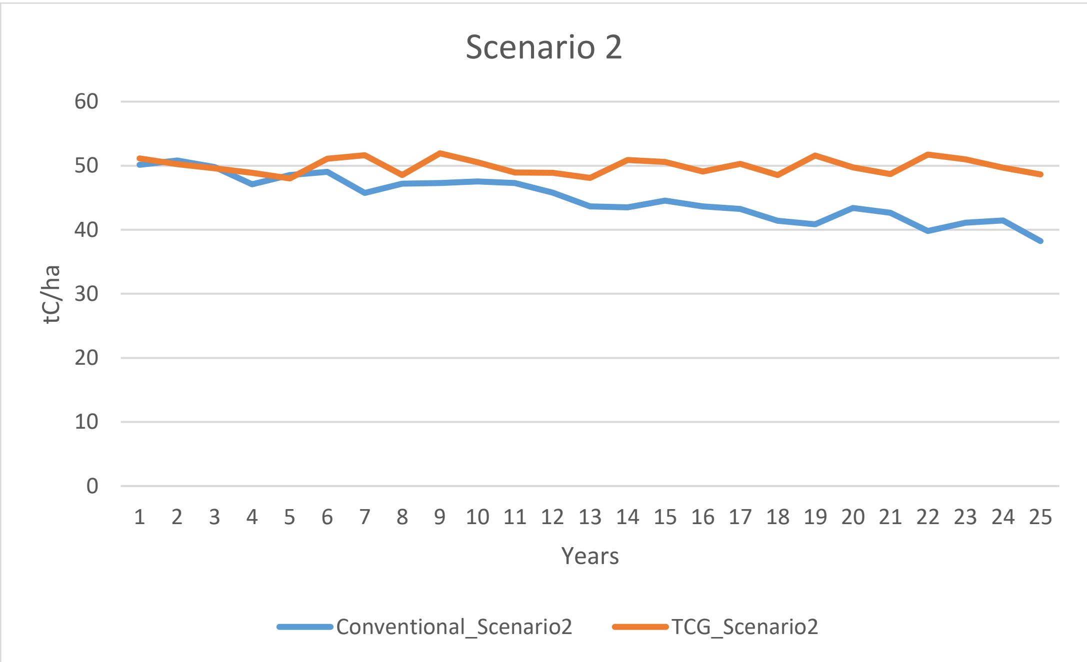
Measured SOC (0-30 cm) in forest to pasture conversion in Brigalow Belt



Scenario 1: conventionally grazed sites show stable SOC stocks over time (as in Brigalow study above)



Scenario 2: Conventionally grazed sites show a decline in SOC over time



12.2 The advantage of the flux tower approach

Flux towers are crucial instruments in the study of atmospheric and ecosystem interactions, particularly for measuring carbon sequestration. These towers use eddy covariance methods to monitor the fluxes of carbon dioxide (CO_2), water vapor, and energy between the ecosystem and the atmosphere. Here are some of the key advantages of using flux towers for this purpose:

1. Continuous Data Collection

Flux towers operate continuously, providing real-time monitoring of carbon fluxes. This allows researchers to capture diurnal and seasonal variations in CO_2 uptake and release, offering a comprehensive picture of ecosystem dynamics across different time scales.

2. High Temporal Resolution

With the ability to record data at high frequencies (measurements captured every 3 seconds), flux towers enable detailed analysis of how carbon sequestration rates change in response to environmental conditions and management.

3. Area Coverage

Although they measure data at a point, flux towers effectively represent larger areas by capturing the integrated signals of air moving over the landscape. This gives a good estimate of the carbon fluxes for extensive areas, depending on the uniformity of the ecosystem and tower height.

4. Direct Measurement of Ecosystem Exchange

Flux towers directly measure the net ecosystem exchange (NEE) of CO_2, providing an accurate assessment of whether an ecosystem is a net source or sink of carbon.

5. Versatility

Flux towers can be equipped with various sensors to measure additional ecological and meteorological parameters such as temperature, soil moisture, light intensity, and more. This capability allows for a holistic understanding of the ecological processes influencing carbon dynamics.

6. Long-Term Monitoring

Flux towers can be used for long-term monitoring, which is essential for assessing the impacts of management, climate change, and other ecological disturbances over time.

7. Comparative Studies

The standardized data collected from flux towers worldwide allow for comparative studies across different ecosystems and climatic zones. Such studies are vital for global modelling of carbon sequestration and climate forecasting.

8. Contribution to Global Networks

Flux towers often contribute data to global networks such as FLUXNET. This collaboration enhances the understanding of global patterns and controls of carbon dioxide exchange, helping to refine climate models and improve predictions of future climate scenarios.

12.3 Tower Outputs: Key Indicators

Productivity

Gross Primary Productivity (GPP): Towers measure plant productivity by capturing photosynthesis via CO2 drawdown, representing the total carbon entering the system. This carbon is stored as above-ground biomass (AGB: pasture shoots), below-ground biomass (roots), and soil organic carbon (SOC) through the transfer of organic material to the soil.

Partitioning Biomass: By measuring cumulative AGB at key points during the season, we can partition total Net Primary Productivity (NPP) from flux tower data into above-ground and below-ground components, allowing for daily tracking of pasture (shoot) biomass growth.

Predicting Root Growth: Combining shoot data with root-to-shoot ratios from soil coring helps predict root growth. Subtracting the biomass of shoots and roots from total NPP provides insights into soil carbon storage and carbon use efficiency.

Carbon

Net Ecosystem Productivity (NEP): NEP reflects the balance between CO2 entering through photosynthesis and leaving via ecosystem respiration. Ecosystem respiration includes autotrophic respiration (from plants) and heterotrophic respiration (from microbial breakdown of carbon).

Partitioning NEE: Net Ecosystem Exchange (NEE) can be partitioned to distinguish CO2 stored in pasture shoots and roots, and soil carbon.

Water

Water Inputs and Outputs: Towers measure water input through rain gauges and output through evapotranspiration (ET), which includes both ecosystem transpiration and evaporation. Soil moisture probes connected to the towers measure plant-available water content in the soil.

Rainfall Efficiency (R/ETr): The ratio between rainfall input and ET output (R/ETr) indicates how much rainfall infiltrates the soil and is used by plants, versus how much is lost to surface runoff or deep drainage below the root zone. Overgrazed pastures with shallow roots tend to have low R/ETr, while deep-rooted legumes have higher R/ETr.

Rainfall Efficiency in Biomass Production: Comparing NPP with rainfall helps calculate how many kilograms of biomass are produced per millimetre of rainfall. Overgrazing or shallow-rooted pastures can reduce this efficiency by limiting water access deeper in the soil profile or increasing runoff.

Water-Use Efficiency (WUE): WUE, the ratio between ET and NPP/NEE, reflects how much water is lost per kilogram of carbon grown or sequestered. High WUE is associated with optimal plant growth stages and sufficient ground cover, while low WUE can result from large areas of bare soil or plants in non-optimal growth stages (e.g., stage 1 or stage 3).

Data processing

Data from the flux towers was automatically ported through the TERN analysis pipeline into a centralised database. This not only has the advantage of generating real-time (daily) fully processed data through TERNs six QC levels, but also ensures outputs confirm to national and international best practice, linking to both the national Ozflux and international Fluxnet networks.

Turbulent fluxes were measured using a LI-COR LI-7500DS CO_2/H_2O infrared gas analyser, Gill WindMaster Pro and LI-COR SmartFlux 3 unit Turbulent fluxes of water vapour, virtual heat and carbon dioxide were processed using a modified version of PyFluxPro (previously OzFluxQC). Turbulent flux results were intermittently validated against EddyPro for agreement. Half-hourly covariances were calculated from the fast (initially at 10Hz and later 20Hz) measurements following spike removal. Time-lag between the instruments was corrected using covariance maximisation in a predefined window for the scalar covariances. Further QA/QC followed to exclude periods of station downtime, during site visits, where instruments reported diagnostic warning flags or the instruments reported implausible measurements. Flux towers measured the key metrics of net ecosystem exchange (NEE) and evapotranspiration (ET).

12.4 Credit issuances from the Australian Carbon Credit Unit Scheme

Credit issuance by the Clean Energy Regulator (CER) from soil carbon projects, including 2024 issuances not part of the original analysis (which focused on 2023). The annualised SOC accumulation rates for these projects were inferred based on the number of credits issued over the Carbon Estimation Area (CEA), after accounting for deductions. Since the CER does not directly provide measurement periods, these were estimated based on the time between project registration, credit issuance, and available media reports.

Project ID	Project registration	ACCUs	tCO_{2e}	t C	CEA (ha)	t C/ha	Measurement period (years)	t C/ha/yr
ERF108333	25/01/2017	94666	189332	51589	3885	13.3	5	2.7
ERF105067	12/01/2017	85262	170524	46464	2621	17.7	5	3.5
ERF102074	9/10/2015	66050	132100	35995	2876	12.5	5	2.5
ERF104527	4/11/2016	12486	24972	6804	578	11.8	5	2.4
ERF169446	4/03/2022	5623	11246	3064	335	9.1	2	4.6
ERF169439	4/03/2022	3591	7182	1957	255	7.7	2	3.8
ERF143770	12/06/2020	3559	7118	1940	393	4.9	2	2.5**
ERF168644	1/03/2022	3176	6352	1731	334	5.2	2	2.6
ERF168650	1/03/2022	2976	5952	1622	250	6.5	2	3.2
ERF162497	29/01/2021	2110	4220	1150	93	12.4	2	6.2
ERF104781	28/10/2016	1904	3808	1038	100	10.4	5	2.1
ERF158470	21/08/2020	1362	2724	742	506	1.5	2	0.7
ERF159853	16/10/2020	641	1282	349	217	1.6	2	0.8
							Average	**2.9**

**The area of CEAs was calculated using spatial files provided by the CER. However, in cases where the spatial file was unavailable, the CEA was estimated using the project area map, deducting any obvious exclusions such as trees, buildings, roads, and steep slopes.*

***The project developer reported rates of 4.4 ACCUs/ha/yr = 1.2 t C/ha/yr.*

12.5 The three main phases of vegetative growth and the relationship with grazing

	PHASE I	PHASE II	PHASE III
Characteristics:	Below about 1000 kg green DM/ha of a moderately dense pasture	Between about 1000 - 3000 kg green DM/ha of a moderately dense pasture	Above about 3000 kg green DM/ha of a moderately dense pasture
Positive aspects:	• Grazing enables control of unwanted species • Grazing enables reduction of litter prior to germination of desirable species • High digestibility	• High yield of high quality pasture • Grazing pressure will delay onset of flowering • Rapid pasture growth • Good livestock weight gain • High yields of feed • Good use of soil water • Good protection from runoff	• Replenishes energy reserves of perennial species • Allows seed set and replenishment of seed reserves in the soil • Low risk of runoff and erosion
Negative aspects:	• Slow pasture growth rate • Long term grazing threatens plant survival - root reserves of perennials not adequately replenished • Increased runoff and soil erosion risk • Poor use of soil water • Low livestock weight gains	• May not allow desirable pasture species to seed down	• Low pasture quality • Slow pasture growth rate • Suppression of companion species in pasture • Low livestock weight gains • May inhibit germination of annuals the following season • Poorer use of soil water
	Yield: low **Quality: high**	**Yield: good to high** **Quality: good to high**	**Yield: high** **Quality: low**

Source: Prograze Manual