Lessons learned from farmers' experience of soil carbon management practices in grazing regimes of Australia

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Abstract

Previous research on increasing soil carbon sequestration, through soil carbon management (SCM) has not integrated social components into the ecological system. To understand how experienced farmer's combine social and ecological components of soil carbon management practices we have used a social-ecological systems (SES) framework. This study examines the distribution and pattern of farmers' SCM practices, comparing and contrasting two farming cohorts based on inherent soil fertility in a rotational grazing regime of sub-tropical temperate grazing lands in Australia. Twenty five grazing farmers with land of low (n= 13) and moderate (n=12) fertility soils were interviewed about SCM and how they have maintained their grazing regime despite climatic constraints using the SES framework. Both farming cohorts (low-fertility farms and moderate-fertility farms) have shown resolve to continue their grazing regime because the benefits were manifold and affect whole-farm sustainability. Farmers with low-fertility farms highlighted a number of SCM outcomes but were less confident of achieving them. Farmers were focused on the agri-environmental benefits of SCM practices in a holistic manner, rather than a single goal of increasing soil carbon. The interviewed farmers reported a number of benefits that accrue from their grazing regimes, including improvements in production, soil moisture retention and soil health, even though some of these benefits were not measured. Farmers in more "stressed" environments, with low soil fertility also emphasised mental health and landscape aesthetics as outcomes of SCM. These features of the farmers' SCM provide important benefits that are not easily quantified, but are also instrumental for encouraging other farmers to manage their soil. Long-term practitioners of rotational grazing such as the farmers in this study can provide useful insights for a more targeted, customized and nuanced government policy that focuses on whole-farm sustainability, which can also improve soil carbon stocks in similar regions of Australia.

Keyword: Soil stewardship, Land capability, Carbon sequestration, Rotational grazing, Soil health

1. Introduction

Carbon sequestration in soil is controlled by a series of systematic processes that include the inputs and outputs of carbon (Rabbi et al. 2015). The maximum limit of the carbon input into soil is determined by the net primary productivity of plants, which is controlled by the factors of solar radiation, climate and the presence of water and nutrients in soil (Sanderman et al. 2009). The soil carbon pool is three times greater than that of atmospheric carbon (Post and Kwon 2000; Scharlemann et al. 2014) and twice that stored in terrestrial vegetation (Friedlingstein et al. 2019). Soil carbon management (SCM) in agricultural land has the potential to sequester 0.4 to 0.8 Pg carbon yr^{-1} in soil (Lu et al. 2011). SCM in agricultural lands is possible through a number of land and soil management techniques that ensure either reduced emissions of carbon from the soil to the atmosphere or sequestration of more carbon into the soil itself (e.g., Chang et al. 2021; Dumbrell et al. 2016; Kragt et al. 2016; Li Liu et al. 2016).

Several studies in various countries of the world, including Australia, have demonstrated that SCM practices such as no till, reduced tillage, stubble retention, crop rotation and permanent pasture have the potential to increase soil carbon (Lu et al. 2011; Luo et al. 2010). Whitehead et al. (2018) reviewed the role of several SCM practices in New Zealand grazing lands to understand the effect on soil carbon stocks such as application of external inputs (e.g. fertilizer application, manure and dairy effluent), grazing intensity management, addition of biochar, full inversion tillage and introduction of deep-burrowing earthworms and dung beetles, but suggested in soils with moderate to high soil carbon stocks there was limited scope to increase soil carbon stocks, and results so far were inconclusive. Minasny et al. (2017) suggested that regionally specific SCM efforts had the potential to sequester more carbon in the first 20 years of those specified practices, where initial stocks of soil organic carbon (SOC) were very low, but rates of soil carbon sequestration would slow down. Research has indicated the positive relationship between soil carbon sequestration and changes in land use and management (i.e. cropping to pasture, no tillage, stubble retention) in the semiarid and subhumid regions of Australia (Cotching et al. 2013; Page et al. 2013; Young et al. 2005). A recent study by Díaz de Otálora et al. (2021), in Spain, also showed evidence of a higher potential for soil carbon sequestration through regenerative rotational grazing compared with conventional set-stocked grazing.

Despite the mounting evidence of an increased potential for soil carbon sequestration using SCM practices, a considerable number of studies have also shown that rainfall and vapour pressure deficits have more influence than SCM practices on soil carbon storage (Cotching et al. 2013; Hobley et al. 2015; Hoyle et al. 2013; Rabbi et al. 2015). Despite the modest effect of SCM practices (i.e. conservation tillage in cropping and conversion to pasture from cropping) on soil carbon sequestration, it is considered to be largely driven by factors beyond the land manager's control, such as climate (particularly rainfall) and inherent soil properties (e.g. fertility) (Rabbi et al. 2015). The aridity and clay percentages were the dominant factors that influence SOC stock, and land use effect on SOC stock is higher than soil management. Rabbi et al. (2014) suggested that land use and soil management induced change of SOC stock needs to consider local environment and specific climatic situation. SOC could be increased through soil management when high organic matter input and slow decomposition ensued. Reduced or no till in a cropping system is estimated to sequester about 140 kg C ha^{-1} yr^{-1} in the upper 10 cm of soil; however, edaphic and climatic conditions in the Australian environment have led to an inconclusive result for the rate of carbon sequestration at the wider temporal and spatial scale (Conant et al. 2001; Lam et al. 2013). Li Liu et al. (2016) revealed that high temperatures strongly interact with stocking rate approaches to SCM and reduce soil carbon storage in the pasture system. According to Sanderman et al. (2009), the carbon sequestration potential through SCM is lower in Australia compared with the northern hemisphere countries due to constraints such as aridity and edaphic factors such as low soil fertility. Thus the interaction between farmers' SCM practices and the influences of climate and fertility is essential to optimise the potential for soil carbon sequestration. SCM practices managed inappropriately can impair soil carbon sequestration potential even under optimal conditions. Similarly, well managed soil can ensure that the sequestration potential could be enhanced despite a dry climate or less fertile soils is realised to the fullest extent possible.

The *4 per mille Soils for Food Security and Climate* initiative of COP21 aimed at increasing the soil organic carbon (SOC) stock by 0.4% per year to mitigate greenhouse gas (GHG) emissions globally from anthropogenic origins (Rumpel et al. 2018). In this regard, to sequester or avoid release of carbon from agricultural soils, Australia's Emission Reduction Fund (ERF) targets farmers and project proponents to undertake certain SCM practices (i.e. conversion of cropping to pasture, tree planting in pasture land, native vegetation establishment and grazing management) in areas previously not managed that way (Australian Government, 2020; Verschuuren 2017). However, compared with other types of 'carbon farming' (such as revegetation and abandonment, improving manure and animal effluent management, reducing ruminant emissions and increasing fertilizer efficiency), SCM initiatives have gained little interest from farmers, and even those farmers who signed up for a soil carbon project under ERF have been critical of the uncertainty of the policy and the processes (e.g. measurement of SOC changes) involved (Baumber et al. 2020; Kragt et al. 2016), such as payment of carbon credits for different types of farming (Amin 2022). SCM practices currently rewarded by the ERF are mainly focused on conversion to reduce tillage, cropping to pasture, organic amendment (e.g. bio-solids or compost) and grazing management (Climate Work Australia, 2021).

Fig. 1. Rotational grazing practices in the grazing regimes of New South Wales, Australia (source: Md Nurul Amin, 2020)

Approximately 33 million sq km is occupied by pasturelands which is 70% of the total agricultural land of the world, and is estimated, to a depth of 1m, to contain about 20% of the world's soil carbon stock (Conant et al. 2011). Thus, improved pastureland management is highly important for atmospheric carbon mitigation. Climate and soil conditions have the largest impact on soil carbon sequestration, however, grazing management can make a significant contribution of 148 to 699 megatons of CO_2e year^{-1}under the same biophysical and climatic conditions (Bai and Cotrufo, 2022). Grazing regimes cover more than half of Australia's land area (Fig 1) and have the potential for sequestering soil carbon, particularly in grasslands of the temperate regions with high summer rainfall (Díaz de Otálora et al. 2021; Waters et al. 2020). Grazing management such as rotational grazing (Liu et al. 2021) or sparsely grazed land (Chang et al. 2021) and stock management (Bork et al. 2020) could ensure improved soil carbon sequestration that can contribute to the emissions reduction target of the SDGs that relate to climate change and food security (2, 3, 6, 13, 12 and15) (Lal et al. 2021). Grazing lands in Australia have been identified as one of the important areas for soil carbon sequestration and achieving Australian government's ERF target (Climate Work Australia, 2021).

Livestock grazing is the largest agricultural enterprise by area in the Australian state of New South Wales (NSW). Consequently, altering grazing management would have potential to sequester carbon in soil of this area. Case study research has shown that farm business income can also increase in the 9–39 years after introducing pasture regeneration as an SCM technique in grazing enterprises of western NSW (Cockfield et al. 2019). Research evidence indicates a two-sided relationship in altering agricultural management for climate change mitigation (Chang et al. 2021; Solinas et al. 2021). For instance, by converting cropping lands into grazing lands, more carbon can be sequestered in the soil (Li et al. 2018), whereas unsystematically grazed lands with higher livestock numbers can create a source of GHG emissions (Chang et al. 2021). Systematic grazing techniques such as rotational grazing of livestock enhances soil carbon sequestration (Liu et al. 2021) and globally, both biophysical and socio-economic factors influence soil carbon stocks (Duarte-Guardia et al. 2020). Thus, the trade-off between potential soil carbon sequestration in agricultural lands and risks of GHG emissions from agricultural practices needs to be established. A framework that explores the social-ecological features that influence SCM could increase our capacity to develop effective climate policy (Amin et al. 2020).

Ostrom's (2007, 2009) social-ecological system (SES) framework has been used for analysing sustainability of a particular system by examining the interactions and relationships between components (Page et al. 2013). SES frameworks examine the interrelationships between the social and ecological features and facilitate the examination of the sustainability goals across different levels and scales (Fischer et al. 2015). For example, SES frameworks have been used to assess the sustainability of food product systems (Marshall 2015), and to unpack the complexity of ecosystem services and human wellbeing at regional levels (Friedlingstein et al. 2019; Hossain et al. 2020b; Hossain et al. 2020a). Moreover, SES framework was also used to examine the sustainable management of fisheries and water resources (de Wet and Odume 2019; Galappaththi et al. 2019). Amin (2022) used Ostrom's SES framework to examine the factors that influence features of SCM in the studied grazing systems presented here at the farm level. Kröbel et al. (2021) suggested that sustainability of farming could be improved by farmers participating directly in scientific research to gain a deeper understanding of agri-environmental problems and to obtain the best management solution at the farm level.

Therefore, this research is examining long-term practitioners of rotational grazing who have continued to maintain a rotational grazing regime despite the land being subject to permanently limiting variables such as low clay content soil types with low land capability, which would make soil carbon improvement difficult. Researchers (Li Liu et al. 2016; Orgill et al. 2018) have found soil carbon stock declined with a change in grazing management or showed some slight improvement in soil carbon stock with rotational grazing compared to set-stocked land (Cowie et al., 2013). Our study examines the distribution and pattern of farmers' SCM practices, comparing and contrasting two farming cohorts based on inherent soil fertility in a rotational grazing regime using a SES framework. By understanding the way farmers' intentions and motivations interact with the biophysical landscapes of their farms and with the social and economic context in which their operations exist it may lead to insights about the limitations and opportunities for achieving carbon reduction goals for the well-being of current and future farming generations. This study focused on the following research questions:

- What is the distribution of farmers' SCM practices under a rotational grazing regime in a low and moderate soil fertility situation?
- Do particular SES features differ between farming cohorts under a low and moderate soil fertility situation?
- What are the lessons from farmers' experiences in customizing SCM interventions?

The detail of the methodology (Fig 3) is explained in section 2, before presenting the impacts of SCM practices by farming cohort (3.2), and distribution of SCM resource features and practices between moderate and low fertility farming cohorts is described. In section 3.3 network of SCM outcomes and farmers' SES of SCM is presented in detail. The impact of resource endowment on SCM practices and network features (4.1) and challenges and potential opportunities for current SCM practices (4.2) is discussed to reveal the lessons of farmers' experiences in customizing SCM interventions.

2. Methodology

2.1 Selection of study area

Grazing enterprises contribute 86% of the total value of the Northern Tablelands regions agricultural production, with wool (41.7%) and meat (44.5%) being the dominant products. The farms studied were predominantly beef and sheep producers with grazed perennial native pastures located in the Northern Tablelands and Upper Hunter regions of New South Wales (NSW), Australia (Fig. 2). In this area, 68% of the total land has been has been used for agriculture which is equivalent to 2.1 million ha. The yearly average minimum temperature in this region is around 7° C, with maximum temperatures usually not exceeding 30° C. The rainfall of this area ranges from 750 mm to 800 mm with 60% of the rain falling over summer. Seasonal drought is common and occurs every 3.5 years on average, and severe drought is predicted to take place every 10 years (Wilson and Lonergan, 2013). The relevance of this case study region is that 50% of Australia's land area is used for cattle and sheep grazing enterprises (Climate Work Australia, 2021), and areas of summer-dominated, high-rainfall grazing regimes with high vegetation retention have the potential to sequester more carbon in the soil (Díaz de Otálora et al. 2021; Reich et al. 2020; Rey et al. 2017). Under this climate regime and in times of grass production (reasonable rainfall and temperature for plant growth), this geographical area could have the potential (Baumber et al. 2020) to increase soil carbon sequestration.

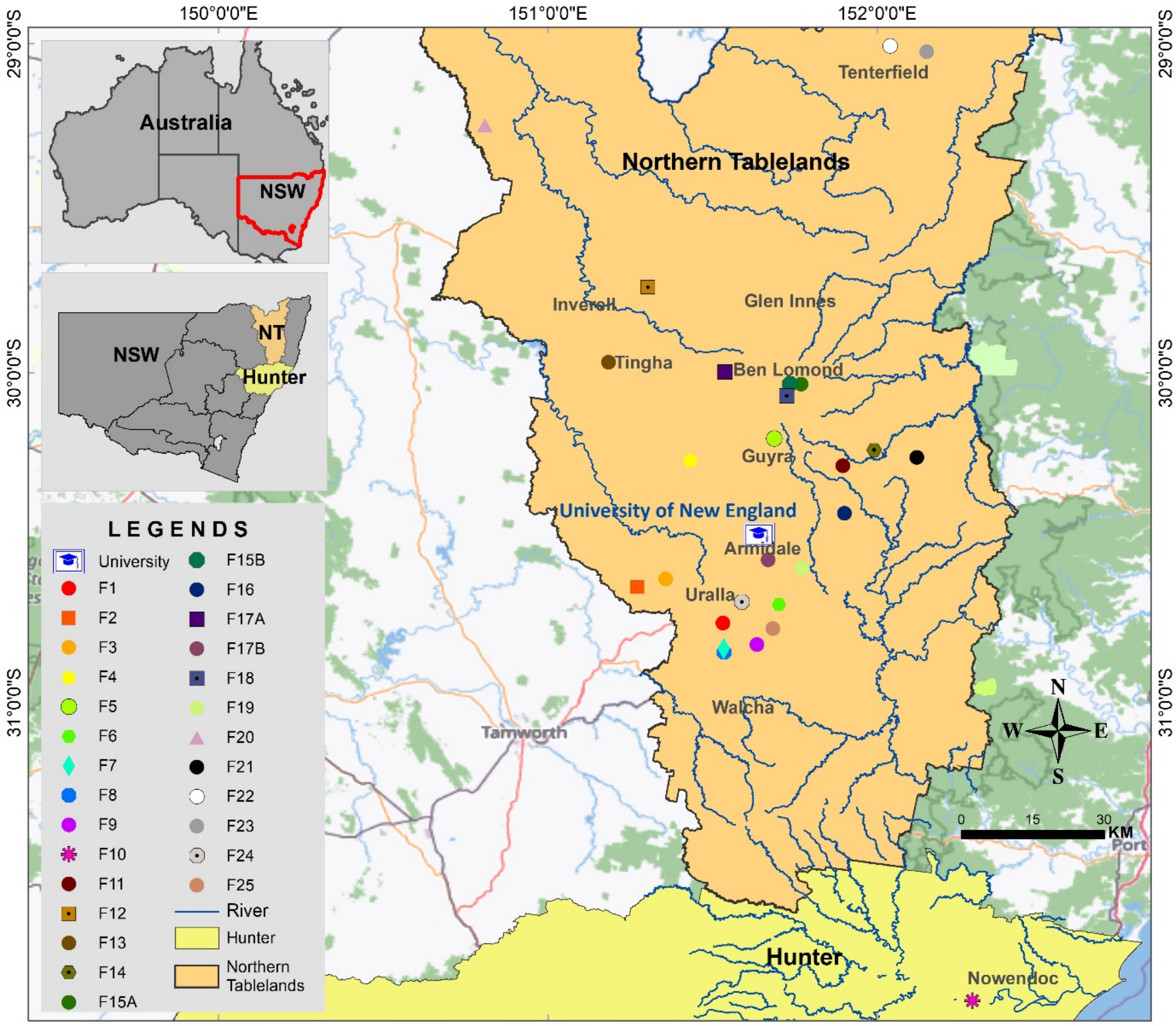


Fig. 2. Farm location in Northern Tablelands and Upper Hunter regions of New South Wales. Here, the identification numbers represent different farms (e.g., F1, F2) and a letter after the numbers represent farms owned by the same farmers (e.g., F17A, F17B).

2.2 Conceptual framework for understanding SCM practices

The SES framework is considered to be the most inclusive conceptual framework for studying a system's interrelationships and the outcome of those relationships to monitor the state of the sustained practices of a system (Pacheco-Romero et al. 2020; Partelow 2018). We studied the ecological and social features of current SCM in grazing regimes of the NSW Northern Tablelands and Upper Hunter, Australia, using Ostrom's SES framework as a conceptual lens to understand farmers' experience with SCM practices in grazing regimes (Fig 3). By providing a common classification system, Ostrom's SES framework (Ostrom 2007, 2009) can enhance our understanding of the complex management practices implemented to improve sustainability (Gurney et al. 2019; Pacheco-Romero et al. 2020; Seghezzo et al. 2020). Our study applied Ostrom's first-tier features of resource system, resource units, governance, actors and interaction-output (SCM outcomes) to analyse the use of SCM practices in the grazing systems of Australia. When using the higher category of Ostrom's SES features, the study focused on the size, productivity, location and predictability of the system as the resource system features, and the spatial-temporal status of the resources, economic value, growth rate and resource management systems were considered under the resource units. The governance system focused on government and non-government organizations, monitoring rules, policy, social networks and operational rules, and the actor category focused on relevant actors, trust and attitudes of the actors. The interaction-output (SCM outcomes) focused on the product of the social-ecological interactions of the features in the SES for SCM as efficiency (e.g. soil moisture) and sustainability (e.g. soil carbon content).

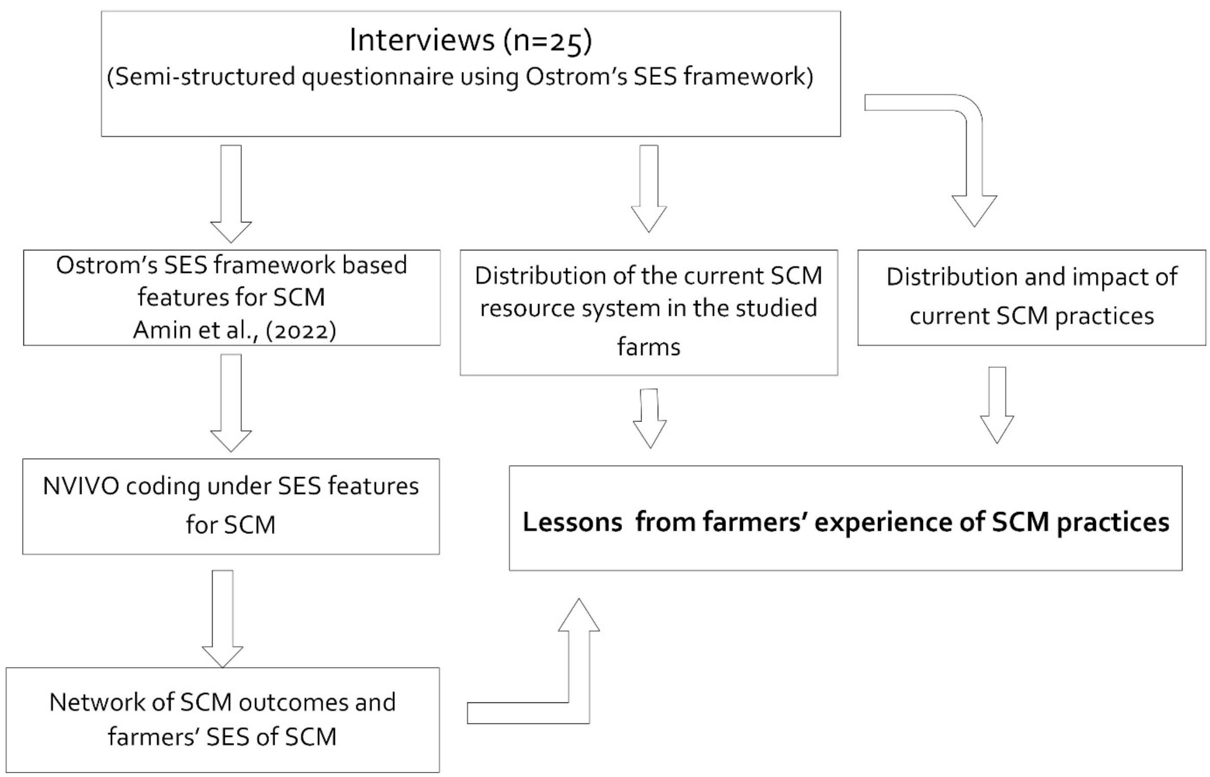


Fig 3. Flow chart of the conceptual framework for study methodology

2.3 Farmer interview protocol and content analysis

The first step in our information collection was face-to-face interviews using a semi-structured question schedule between November 2019 and February 2020. The interview participants were initially selected based on having at least five years' experience in practicing at least two SCM practices that were known to have a positive impact on soil carbon stock (e.g. Díaz de Otálora et al. 2021; Dumbrell et al. 2016; Li Liu et al. 2016). The interviewed farmers were selected with the assistance of two organizations, Northern Tablelands Local Land Services, which is a government organization, and Southern New England Landcare, which is a local non-government organization. The farmers were purposively or deliberately chosen because they were long-term practitioners of SCM practices. The majority of the study participants are leading graziers who are highly motivated by land stewardship. All landholdings are subject to periods of recurring drought, exacerbated in some instances by inherent low fertility soils with low land capability. The interviewed farmers (n=25) were of mixed ages (40–79 years) and highly experienced, having undertaken SCM practices for several decades (Table 1). Among the interviewed farmers, more than half (68%) were highly educated (Bachelor to PhD), with around half of them having a university degree and around one third of them having an MSc or PhD. The face-to-face interviews lasted up to 90 minutes. The interviews were recorded and later transcribed by a transcription service. The human ethics approval of this study was granted by the University of New England, Australia (approval number HE19-149).

The aim of the interview was to understand the distribution and pattern of current SES features of SCM in order to identify the potential for soil carbon sequestration through sustained use of SCM practices on grazing lands (SI Table 1). The interview questions covered information about current SCM practices at farm level, as well as questions relevant to Ostrom's SES first-tier features of resource system, resource units, governance system, actors and interaction-output (McGinnis and Ostrom 2014; Ostrom 2007, 2009). The interview questions covered three aspects: first, farmer socio-demographic data ; second, questions on farm data (e.g. types of SCM, economic aspects, governance systems, relevant actors) and their relationships in the current SCM system; and third, co-benefits for social and ecological features.

The SES features were determined from interview data with 25 highly experienced rotational graziers who were long term practitioners of practices associated with SCM. The transcribed interviews were coded to themes under Ostrom's first-tier SES categories using NVivo12 (SI Table 1). NVivo is a software that enables the researcher to efficiently code comments and insights in interview transcripts into themes, as well as organising coded segments for analysis and retrieval for each SCM feature data was coded from the farmer interviews under each SES higher-level category. For example, where farmers explained about the support of government or non-government organizations it was coded under the 'governance system' category. Given the importance of soil fertility and land capabilities for SCM, we confirmed the soil type and land capabilities of the farms examined through the NSW Government's online land capability and soil mapping service eSPADE version 2 (Office of the Environment and Heritage 2018). Locations of the farms was georeferenced to determine the dominant soil types (underlying granite, sedimentary and basalt geology) and land capability eSPADE (Office of the Environment and Heritage 2018) (a database of 80,000 soil profiles for NSW, April 2020). The interviewed farmers were comprised of two cohorts, one with moderate-fertility farms and the other with low-fertility farms. In addition, SCM features (SI Table 1) were analyzed to explore the distribution and patterns relevant to the SES categories according to soil fertility potential. . The patterns of SCM practices were visualized in a one-mode network diagram (Section 4.3.3) for both low- and moderate-fertility farms using the i-graph package of RStudio. The perceived influence of the SCM practices was visualized in a stacked bar chart using the ggplot2 package of RStudio to identify differences between the farm cohorts. From the farmer interviews under Ostrom's first-tier features, the challenges of and potential solutions to the sustainability of current SCM practices were collated and visualized in a Sankey network graph using the network3D package of RStudio.

2.4 Network map

A one-mode network represents the connectivity of one set of features with another set of features. A one-mode network was employed to visualize the SCM under both situations - 'moderate-soil fertility farms' and 'low- soil fertility farms'. This network visualizes the influence of SCM outcomes and the resources unit features (i.e. SCM practices, SCM cost, change of income and agri-environmental benefits) on other features of SCM. The responses of each farmer were coded by assigning a number as a weight (1 and 0), where '1' represented a positive response and '0' represented a negative response about the influence of SCM output or resource unit features on other SES features (SI Table 3). The resource system features that determined the farm status, such as the size of the farm, farming type, proprietorship and loan status were represented as a numeric relationship with the SCM outcome and resource unit features in the network (SI Table 3 and 4). In the network diagram, each feature is represented as a circle (e.g. SCM cost, trust) and connections from one feature to another are 'lines'. The width of the line indicates the number of positive responses for each connection.

3. Results

The distribution of the SCM features was examined based on the underlying soil fertility of the farm. Soil fertility, which is based on soil texture and underlying geology, is a variable that relates strongly to the processing and storage of soil carbon, and is a defining characteristic of land capability due to its stable nature over time. The results from these two cohorts (i.e. moderate-fertility and low-fertility farms) are presented to examine their ability to sustain SCM practices over an extended period and also to identify the particular SES features that have allowed them to do so, given that those on land of lesser fertility and land capability would be considered more vulnerable and less likely to improve soil condition.

3.1 Distribution of SCM resource features and practices between farming cohorts

The distribution of the SCM resource system features were identified from farmer interviews (n=25) and categorized according to underlying fertility and land capability, with almost equal division between moderate and low soil fertility (Table 1). The majority of farms were sheep grazing enterprises with livestock for meat (n=21, SI Table 2), and a few also had cattle and sheep breeding. A few of the farms (n=4) were mixed farming with grazing and limited cropping (mainly fodder crops) for livestock feed. Our study revealed that the distribution of SCM practices between the farm types were broadly similar, although in a few instances, differences were apparent. The soil fertility status was identified by the farmer and further corroborated by the information from eSPADE on land capability (Table 1). The debt status for low-fertility farms was mostly moderate (62%) and a smaller proportion had high debt levels (15%), whereas more than half of the moderate-fertility farms were under no financial obligation (59%) or had moderate debt (33%) (Table 1). The distribution of farm size was similar for both cohorts, with more than half of the farms being large farms (>500 ha) for both moderate-fertility farms (58%) and low-fertility farms (62%) (Table 1). Human capital was similar for both cohorts in terms of farmers' age (around 60 years old) and farming experience in the area (23 years) (Table 1). A large proportion of farmers (80%) manage only one property and a smaller proportion (20%) manage between two to four properties.

Table 1. Distribution of the current soil carbon management resource system in the studied farms (n=25)

Resource system features	Distribution criteria of Resource system features	Farm type resource status	
		Low-fertility farm (n =13)	Moderate-fertility farm (n =12)
Land Capability (Percentage)	Slight but significant limitation	0	67
	Moderate to severe limitation	0	33
	Severe limitation	54	0
	Very severe limitation	46	0
Debts (Percentage)	None	23	59
	Moderate	62	33
	High	15	8
Farm Size (Percentage)	Small farm <500 ha	38	42
	Large farm >500 ha	62	58
Human Capital (Year)	Age	59	63
	Farming experience in locality	26	21

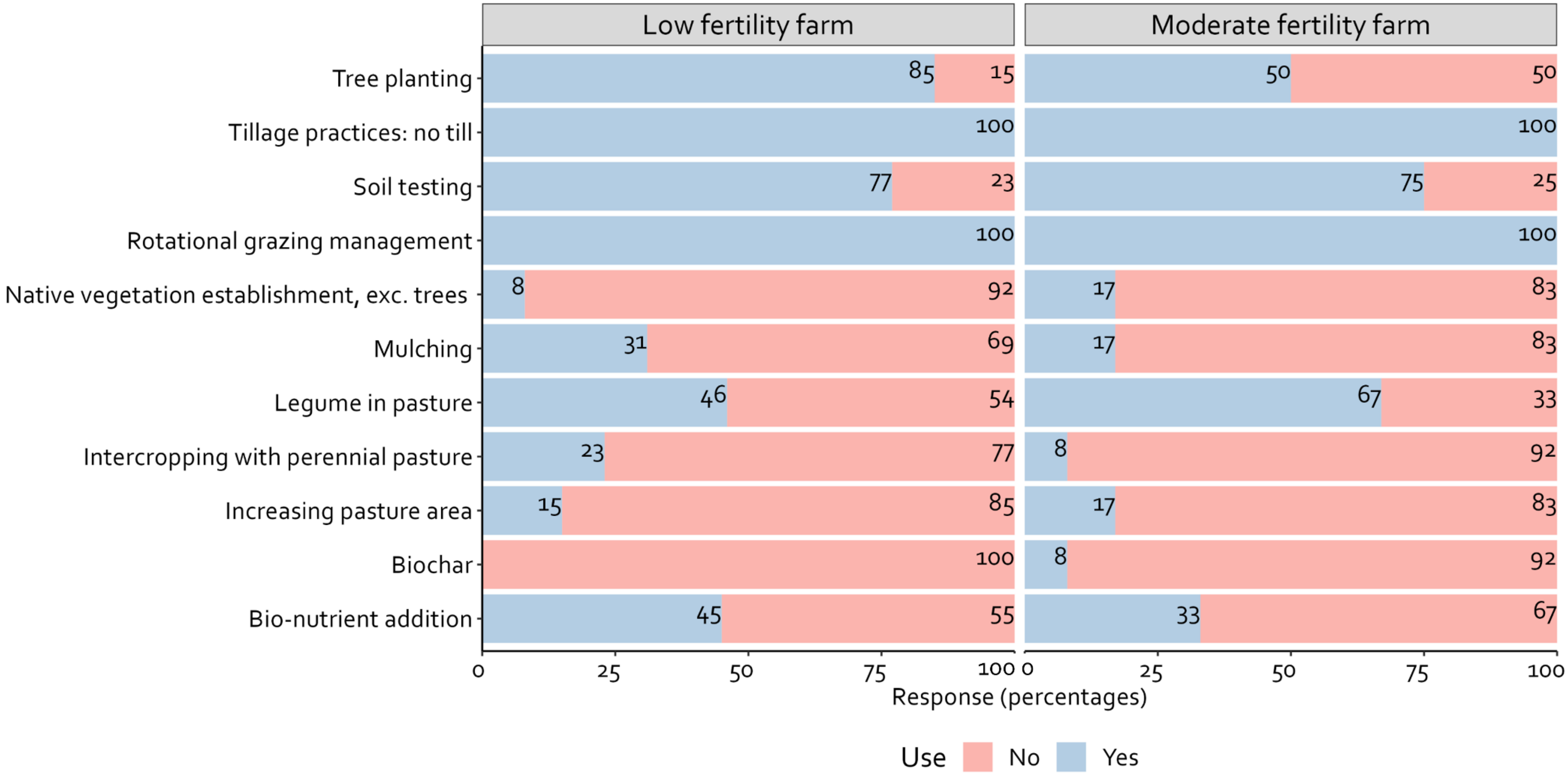


Fig 4. Application of the current soil carbon management practices (in percentage) in low- and moderate-fertility farms (n=25)

All of the interviewed farmers (100%) were undertaking rotational grazing, although farmers referred to it differently (SI Table 2). Other than rotational grazing practices, no-till for sowing of introduced pasture species, legumes in pasture and tree planting were the most frequently used SCM practices in the farms studied. A few farmers were using intercropping with perennial pasture, usually in limited trials to understand the future potential for their farm (e.g. F19, F24).

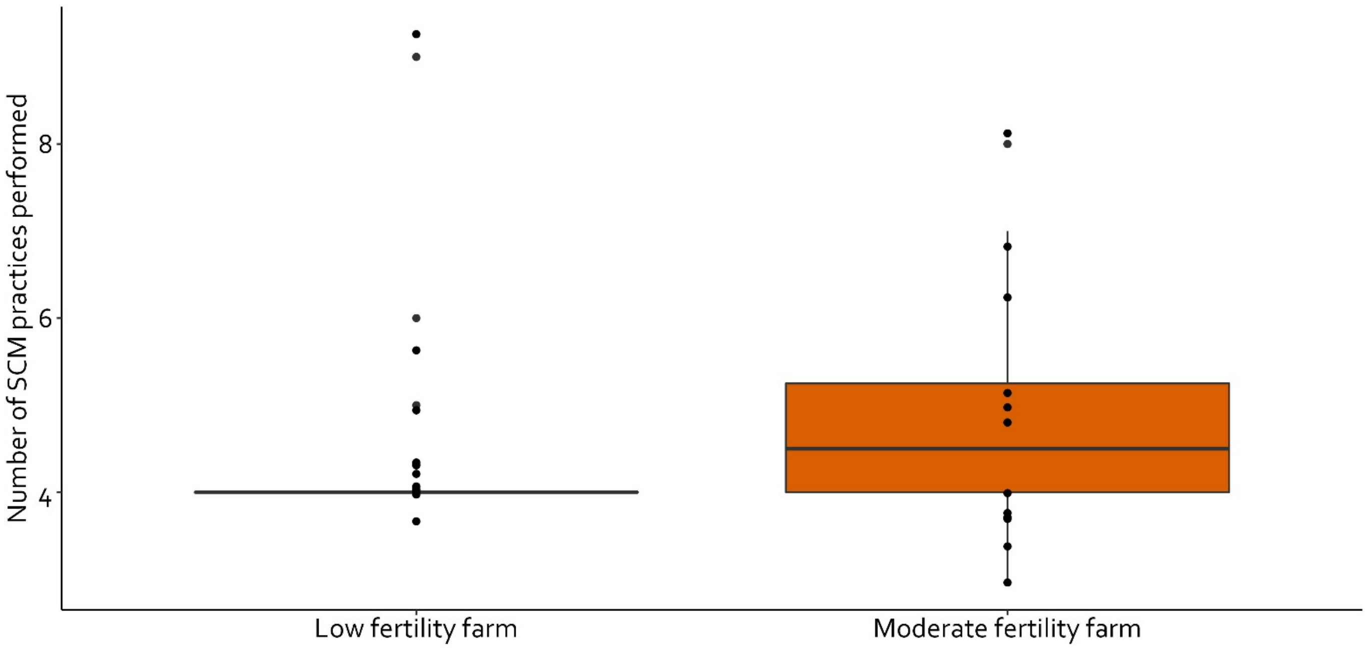


Fig. 5. Distribution of soil carbon management practices (n=11) between the low-fertility and moderate-fertility farms in the grazing regimes of the Northern Tablelands and Upper Hunter (n=25)

Up to four different types of SCM practices were used by 77% (n= 10) of the low-fertility farms and 50% (n= 6) of the moderate fertility farms (Fig. 5). Conversely, more than four SCM practices were used on 50% of the moderate-fertility farms and 23% of the low-fertility farms Fig 5). However, one low-fertility farm (F4) practiced the highest variety of SCM practices (n=9) (Fig 5). The distribution of SCM practices varied between the farming cohorts depending on fertility or land capability (Fig 5). A point of difference in distribution of SCM practices was that farmers with low-fertility farms were undertaking tree planting at a higher proportion (85%) compared to the farmers with moderate-fertility farms (50%) (Fig 4). The SCM practice of establishing native vegetation (e.g. grass) other than trees (8% to 17%) was low for both farming cohorts and depended on the level or type of existing vegetation on the studied farms. The distribution of bio-nutrient use (i.e. nutrients that have bio-active properties) was similar for both farmer cohorts (Fig 4). Usually, the addition of nutrients to the soils was in the form of manure, compost and biodynamics (i.e., holistic, spiritual and ecological approach to treat soil fertility, plant growth and livestock) but this practice was undertaken by less than 30% of those interviewed (Fig 4). More than half of the farmers with moderate-fertility (67%) and low-fertility farms

(55%) did not apply additional nutrients, although a few farmers were using balanced chemical fertilizers after soil testing (Fig 4). Three-quarters of the farms (~75%) that had been soil tested were tested either before or after starting the SCM practices (Fig 4). A quarter of both farming cohorts had not undertaken soil testing at all.

In both farming cohorts, the main goal for undertaking SCM was sustainable farm production. According to the practicing farmers sustainable farm production related to conservation of soil health that ensures continuous production even during adverse climatic condition (e.g., prolonged drought). Precipitation was perceived in both cohorts as being very important for soil carbon storage and pasture production of the farms. Regardless of underlying soil fertility, both cohorts of farmers perceived that favourable climatic conditions improve grass production. Thus, the farmers' main focus was on adapting to the current climatic situation by applying holistic livestock grazing management and regenerative agricultural practices (Box 1).

3.2 Observation of outcomes of SCM practices by farming cohort

We studied the common and contrasting outcomes of SCM practices on the low-fertility and moderate-fertility farms. The majority of farmers experienced increased or optimized income throughout the season after the long-term application of SCM practices, although in the short term, the investment for installing water management infrastructure and fencing represented a substantial impact on the farm income. SCM infrastructure along with other SCM costs such as soil testing, manure, fertilizer and compost were typical concerns when starting the specialized SCM practices for both the moderate-fertility and low-fertility farms.

Both types of farming cohorts explained in their interviews similar agri-environmental benefits after adopting SCM practices, such as high levels of ground cover throughout the year, even during severe drought periods, less water erosion and increased soil moisture retention in grazing lands. Farmers from both cohorts believed that farm production (i.e. pasture and livestock production) had increased regardless of underlying soil fertility (Fig. 6). A high proportion (85%) of the low-fertility farms were tree planting (Fig. 4), with a greater proportion of farmers indicating an increase in shelter for livestock (77%) compared with the moderate-fertility farms (42%), where tree planting was practiced on 50% of farms (Fig. 6). Moderate-fertility farms (58%) reported a decrease in the use of additional nutrient applications after introducing SCM practices. More than 50% of the low-fertility farms and 42% of the moderate-fertility farms reported an increase in soil pH (i.e. became more alkaline) after introducing SCM, which indicated an improvement in soil condition where soils were normally acidic. A higher proportion of farmers (92%) in the low-fertility farms indicated improvements in soil moisture retention and soil structure as these SCM outcomes were associated with higher plant production (Fig. 6). Similarly, for the moderate-fertility farms, 58% of farmers suggested an increase in soil moisture, and 83% of farmers also suggested an improvement in soil structure. Similar to soil moisture retention, farmers assumed with higher plant growth and soil moisture retention it would have a positive effect on soil biodiversity, which was also considered to have improved, more so, in the low-fertility farms (92%). The other benefits mentioned during the interviews were improved mental health even in adverse climatic events such as drought, minimized soil erosion, maximized water cycling and maximized nutrient cycling. Enhanced sustainability and good soil health reduced farmers' anxiety about adopting SCM practices in both cohorts. The farmers' belief in positive changes in soil condition after introducing SCM reflects the association of multiple benefits with undertaking SCM practices.

Both farming cohorts suggested after the introduction of SCM, especially rotational grazing, there was an increase in grass production with higher levels of ground cover all-year-round (Fig. 6). They understood that an increase in grass production, and coverage would also lead to greater below ground biomass, leading to improvements in water retention in situ (i.e less runoff). Thus by undertaking the current SCM practices, farmers in both cohorts, observed greater plant production, and associate such improvements with soil health (which could include soil pH, soil organic carbon, and soil structure) (Fig. 6). Despite not precisely measuring changes in soil condition after introducing a SCM practice, farmers understood such positive changes in plant production would improve overall soil health (Fig. 3), as reflected in this quote from F8: "*Making the soil a better soil is one big thing, and therefore, we're able to hold more moisture, we're able to grow more grass …. …[O]n top of that, we're getting the reward through that system of storing the carbon.…[T]he carbon then helps to make it more productive as well.…[O]ur trees…in some of those areas … seem to be healthier than they used to be. So, it's through the management system we're improving this land".*

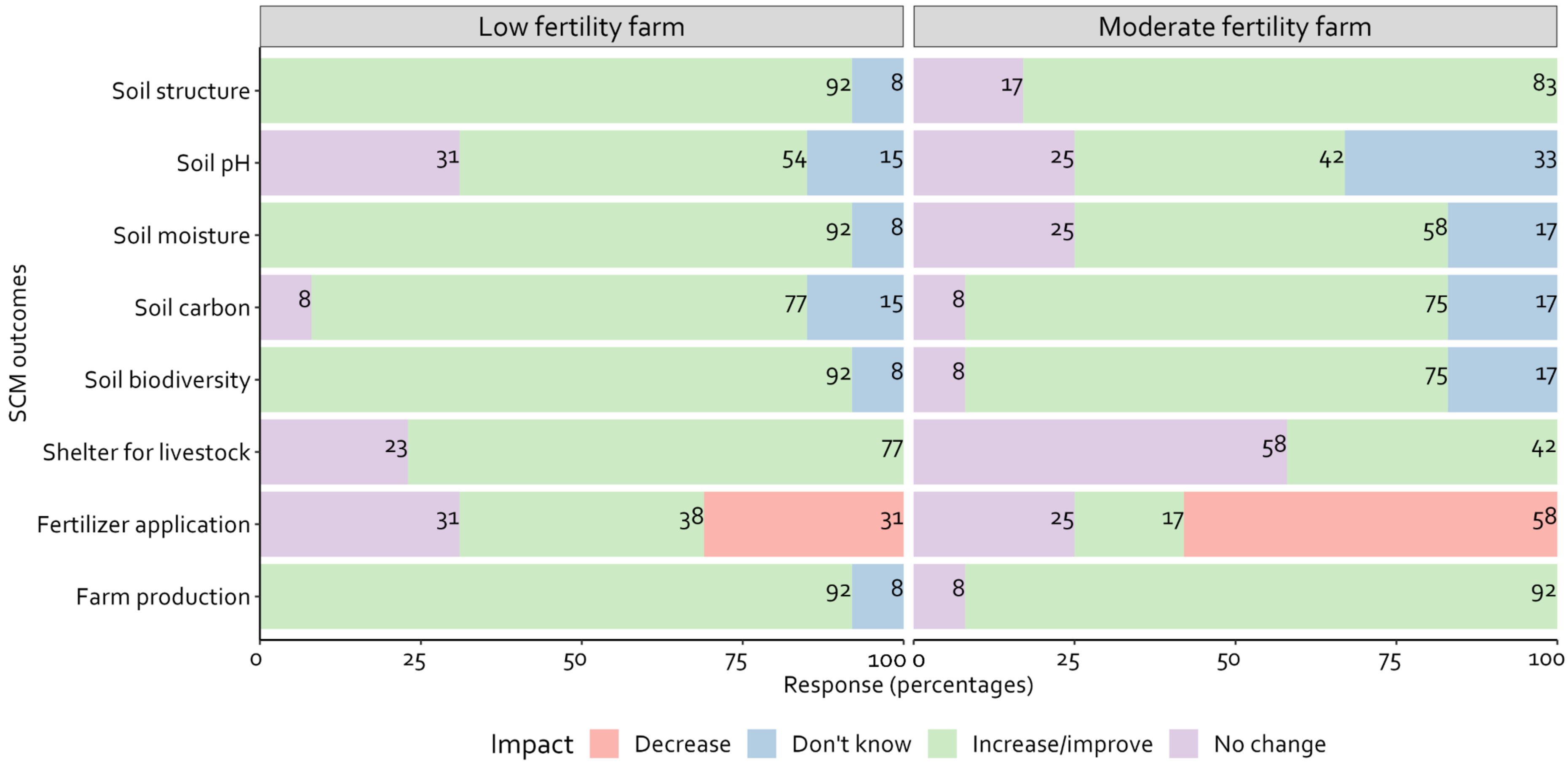
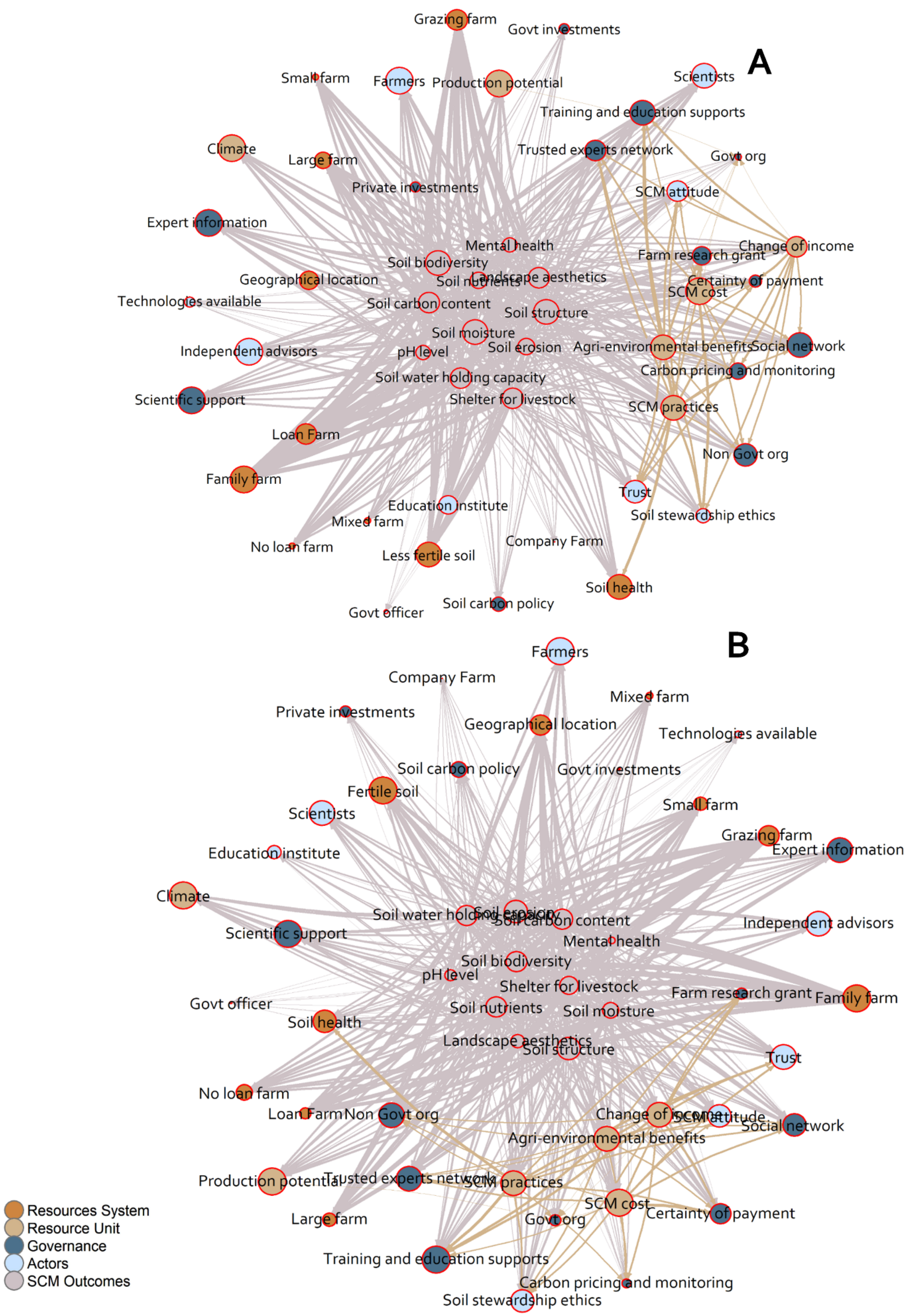


Fig. 6. Farmers' judgement of soil carbon management outcomes in the low-fertility farms and moderate-fertility farms of the Northern Tablelands and Upper Hunter under rotational grazing regimes (n=25)

3.3 Network of SCM outcomes and farmers' SES of SCM

Using network figures (Fig. 7), we visualise the influence of the SCM outcomes and resource unit features (SCM practices, SCM cost, change of income, agri-environmental benefits) on the other SES features (resource system, governance system, actors) for moderate-fertility and low-fertility farms. The network figures show the degree of connectivity (weak or strong) between the SES features (Fig. 7). What is immediately noticeable is the complexity of the diagrams, which reflects the complexity of the processes at work in social-ecological systems (Fig. 7). There are many relevant factors of interest (the features shown as circles) and these interact with multiple other features. Next, it is possible to observe that some features are more important in the farmers' estimation than others, indicated by larger circles. Some features interact more frequently with other features, indicated by the number and thickness of lines radiating out of the feature circle. For both farming cohorts the connectivity between the SES features indicated by the circle sizes were for the most part similar (Fig. 7). In particular for the soil health, independent advisor, social network and SCM attitudes features were similar in circle size (i.e. similar in importance in the network) for both farming cohorts. However, a small number of features differed in importance, as shown by the circle size of the feature, between the moderate-fertility and low-fertility farms, and these are discussed in the following section.


A
Grazing farm
Govt investments
Small farm
Farmers
Production potential
Scientists
Training and education supports
Climate
Large farm
Trusted experts network
Govt org
Private investments
SCM attitude
Expert information
Mental health
Change of income
Soil biodiversity
Farm research grant
Geographical location
Landscape aesthetics
Certainty of payment
Technologies available
Soil carbon content
SCM cost
Soil structure
Soil moisture
Independent advisors
pH level
Soil erosion
Agri-environmental benefits
Social network
Carbon pricing and monitoring
Soil water holding capacity
Scientific support
Shelter for livestock
SCM practices
Loan Farm
Non Govt org
Family farm
Trust
Education institute
Soil stewardship ethics
Mixed farm
No loan farm
Company Farm
Less fertile soil
Soil health
Soil carbon policy
Govt officer
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Farmers
Company Farm
Mixed farm
Private investments
Geographical location
Technologies available
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Grazing farm
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Scientific support
Mental health
Soil biodiversity
pH level
Shelter for livestock
Farm research grant
Family farm
Govt officer
Soil nutrients
Soil moisture
Soil health
Landscape aesthetics
Soil structure
Trust
No loan farm
Loan Farm
Non Govt org
Social network
Agri-environmental benefits
SCM practices
SCM cost
Certainty of payment
Large farm
Govt org
Training and education supports
Carbon pricing and monitoring
Soil stewardship ethics
Resources System
Resource Unit
Governance
Actors
SCM Outcomes

Fig. 7. Soil carbon management features connectivity network based on the influence of SCM outcomes (in centre) and resource unit features (SCM practices, SCM cost, change of income, agri-environmental benefits) for (A) Low-fertility farms and (B) Moderate-fertility farms. The circle size relates to the importance of the feature for SCM. The lines represent connectivity between features. The complete list of social-ecological system features is provided in SI Table 1.

3.3.1 Comparing and contrasting farming cohorts relationships between SES features

Change of income in relation to SCM was found to be slightly less important in the low-fertility farms compared with the moderate-fertility farms despite SCM cost, SCM practices, agri-environmental benefits and production potential influencing SCM equally for both farming cohorts. This is shown in Figure 7 by the slightly smaller circle for 'change of income' in item A (low-fertility farms) compared with B (moderate-fertility farms), while the other resource unit features were similar in circle size. For both cohorts, farmers experienced higher costs when initiating SCM practices that lessened over time, and income improved as SCM practices became more established. The network map also revealed that SCM outcomes were similar in both farming cohorts for soil water-holding capacity and soil carbon content (Fig. 7). The positive outcomes resulting from SCM in relation to mental health, landscape aesthetic, soil moisture, soil biodiversity and soil acidity level were more pronounced in the low-fertility farms (as indicated by the larger circles for these features in item A) than the moderate-fertility farms, whereas soil erosion control was considered to be a more important outcome of SCM for the moderate-fertility farms (i.e. a larger circle for this feature in item B of Fig. 7). The main contribution of current SCM practices was sustained farm production throughout the year (e.g. pasture, livestock and wool), which in turn was favourably linked to the mental health of the practicing farmers. Farmers from both cohorts reported improved farm outcomes compared to conventional farmers during adverse climatic events such as prolonged drought (the interviews were conducted during the 2019 drought and bushfires). By retaining soil moisture and improving soil structure, farmers from both cohorts have maintained high levels of ground cover throughout the year, even in adverse seasons. The positive mental health benefits for farmers practicing SCM is reflected in the quote from F1: "*[T]he big [benefit] is mental health because you're never stressed out about anything, so we're completely destocked at the moment but the drought has absolutely zero impact on my mental health.… [W]hat you're doing is reducing soil erosion, you're fixing up other types of degradation in the system*".

3.3.2 Relationships between governance and actors in SES of SCM

The features in the SCM governance and actor categories exhibited a similar pattern of importance to both farming cohorts (Fig 7). Of the 13 governance features mentioned by farmers (n=25), from most to least common influences on SCM were: training and education support (96%, n=24), social network (80%, n=20), soil carbon policy (56%, n=14), and carbon pricing and monitoring (48%, n=12). Of the eight actor features mentioned by farmers (n=25), from most to least common influences on SCM were:

other farmers (100%, n=25), independent advisors (96%, n=24), soil stewardship ethics (68%, n=17), and government officer (12%, n=4). The complete list of governance and actor features appears in SI Table 1. The most to least important features (indicated by size of circle) in these two categories were social network, independent advisors, expert information, trusted expert network, non-government organization, scientific support, education and training support, government organization and government officer. However, governance features such as government investment were minor contributors (i.e. smaller circles) for both cohorts, with moderate-fertility farmers not seeking government investment on their farms after introducing SCM practices (Fig. 7). The majority of farmers from both cohorts undertook their current SCM without any support from government organizations, although a few had received some financial support from state government organizations such as Local Land Services. Independent advisors were an important source of advice for most interviewed farmers in both farming cohorts, especially on soil testing or making choices about SCM practices. Moderate-fertility farms (50%, n=6) were less involved than low-fertility farms with educational institutions for technical know-how (85%, n=11). Farmers from both cohorts believed they were successful in building trust among other farmers in the same network and motivating them to adopt SCM.

Another difference (albeit smaller) between the two cohorts in the network map (Fig. 7) was technology, with low-fertility farms experiencing a higher need for available technologies than moderate-fertility farms. A similar proportion of the interviewed farmers (88%) from both cohorts had received funding for small on-farm projects, which they used for fencing, soil testing and water management infrastructure. Farmers from both cohorts would like to have more support to conduct on-farm research in the form of grants or soil testing from the government or flexible financing from private sources. Farmers in both farming cohorts believed that government allocation of funding is general and not specific to different soil and farm types, which is essential when considering SCM. Farmers from the low-fertility farm cohort emphasized a need for more on-farm research grants compared with moderate-fertility farms.

The network map showed that farmers with moderate-fertility farms would be more confident than the farmers with low-fertility farms about receiving payments for the SCM practice from the government (i.e. a larger circle for this feature in item B of Fig. 7), although the feature was less important compared to other governance features. Farmer confidence in the certainty of payment for SCM from the government was less pronounced in the low-fertility farms compared to the moderate-fertility farms, even with improvements (i.e. improved soil moisture, improved soil biodiversity) associated with SCM. This is because certainty of payment for SCM is singularly focused on soil carbon content, and farmers from both farming cohorts suggested similar changes in carbon content on their farm soil but with different levels of effort required. Carbon pricing and monitoring were more important for the farmers in the low-fertility farm cohort compared with the farmers in the moderate-fertility farm cohort, but overall, it was poorly connected to other features of SCM (i.e. a larger circle for this feature in item A, and more lines connecting these features, but not necessarily to other features of the network in Fig. 7). Only a few of the farmers (16%, n=4) expressed an awareness of the carbon pricing and monitoring mechanism under the Australian Government's ERF. Those who were aware or are participating in the ERF remain uncertain about the outcomes of the government policy. The quote from F2 demonstrates the mixed messages around soil carbon sequestration and distance from policy initiatives. "*I understand that you can do carbon offsets….[A]nd I understand that you can have a covenant for 100 years or something to, for example, take all the cattle off and look after my native vegetation only. So that would be a change in farm enterprise. And I'm not interested in those initiatives because I'm not interested in being involved with the government policy that I feel can change when the government changes….[I]t seems that there's no long-term planning and I don't have any faith in the system. I'm going to be dead before 100 years probably, so… it just doesn't seem like a very sensible approach, given that I have no confidence in the government being able to provide a responsible and long ranging policy around carbon".*

A majority of the farmers (84%, n=21) were attracted to the possibility of location-specific scientific information from the experts on SCM through a trusted expert network. Most of the farmers were highly motivated and had adopted their current management practices after completing courses such as holistic management and seeking out information from different experiences such as field days, seminars or workshops. Most of the farmers self-funded their participation in courses that were co-incidentally related to SCM but more closely related to whole-farm management. Most of the interviewed farmers were interested in further training and educational support to understand the trajectory of their current SCM. All the interviewed farmers emphasised the role of their social network, and in a majority of the cases the motivation to undertake SCM originated from the local social network.

Again, the features under SCM actors of similar importance in both farming cohorts were SCM attitudes, independent advisors, scientists, farmers and trust. The influence of soil stewardship ethics on SCM was more pronounced for the moderate-fertility farms than the low-fertility farms (i.e. a larger circle for this feature in item B of Fig. 7). In this study, farmers defined soil stewardship ethics as instilling a sense of soil conservation responsibility from the currently practicing farmers to other farmers in the community through SCM. Most farmers (88%) argued that government was considering paying farmers for increasing "storage of carbon in soil"; however, the farmers' main aim is to restore soil health for better production, which is a process that would not necessarily increase soil carbon levels. Improving soil carbon in soil is one part of their soil health management agenda, but their agenda also involves pasture and animal management. According to most of the farmers (87%), soil carbon is not their sole focus, as reflected in this quote from F2: *"It had nothing to do with the price of soil carbon….[T]he price of carbon is so low that it's laughable at the moment, but we didn't do it to store carbon. What we did was to make the landscape as resilient as we could possibly make it, and as* *productive as we could possibly make it, and if we built any soil organic matter or soil organic carbon as a result of that, then that was good".*

4. Discussion

4.1. Impact of resource endowment on SCM practices and network features

The SES approach was used to understand the distribution and pattern of farmers' SCM practices in grazing regimes of moderate-fertility and low-fertility farms of the NSW Northern Tablelands and Upper Hunter regions, Australia. This approach is also used in relation to level of resource endowment in a low fertility farm where there are inherent limitations to soil carbon sequestration. This study thus revealed the current farm-level SES dynamics in terms of soil fertility of the grazing regimes in sub-tropical temperate grazing lands of Australia. This study finding also suggested that moderate-fertility farms have adopted diversified practices for improving soil health and production at the farm level (Fig. 5). There were generally more SCM practices used in moderate-fertility farms than low-fertility farms. Even though, low-fertility farms chose fewer interventions (e.g. two to four SCM in most of the farms) (Fig 5), the farmers reported more SCM outcomes (Table 1). The higher prevalence of tree planting practice on the low-fertility farms, which had areas that were unsuitable for grazing production, and therefore by planting trees they are gaining other benefits such as shade and shelter for livestock and landscape aesthetics. Farms with hills and ridges with shallow stony soils might be better off planted to trees in order to prevent soil erosion, improve amenity value and provide shade and shelter for stock. Subsidies for the costs of tree planting, would make it more attractive to implement, even with in-kind labor contributions by farmers. However, the farmers with moderate-fertility farms may not be prepared to forego production, and the land is too valuable to exclude grazing unless accompanied by other substantial benefits.

The farmers who own the moderate-fertility farms reported less use of additional nutrients after introducing the SCM practices, which might be because of the inherently higher soil fertility with less constrained land capability of those farms (Table 1). Low-fertility farms were less likely to reduce fertilizer applications (Fig. 5), and the land had inherently low capability. Farmers from both farming cohort perceived similar importance for climate and other non-climatic features (e.g. production potential, soil health, SCM cost) (Fig 7), which is in contrast to local studies (Rabbi et al. 2015) and reflects the farm level implications of farmers SCM in the grazing regimes. In relation to management-induced changes in SOC it was clear from the review of the literature that the scale of measurement was at a regional or state level where the recognised drivers of SOC are mainly climate, soil type and land use, but as the scale becomes more fine-grained, to a farm-scale, then land management can have a greater impact where climatic and soil type conditions are similar. The majority of interviewed farmers accept the consequences of climate change but by introducing SCM practices, such as rotational grazing they can be more resilient to its impacts. The influence of soil stewardship ethics on SCM was more pronounced for the moderate-fertility farms than the low-fertility farms because we hypothesize that the moderate-fertility farms have inherently better land quality and more time to consider the wider issues of soil stewardship. For example, farmers with moderate-fertility farms use multiple SCM practices (Fig. 4), while low-fertility farms do not, allowing the former to experiment with SCM options for soil health improvement with a minimum risk of farm production loss. Regardless of resource endowment, all farmers considered their social networks to be a platform for sharing their experiences related to the challenges and opportunities of certain SCM practices to the wider community.

Understanding the features that motivates farmers to adopt a particular form of agricultural management (e.g. climate smart agriculture) can ensure sustainable policies, support materials and incentives are designed appropriately (Gosnell, 2021). In our study, for both farming cohorts, the outcomes (i.e. soil moisture, farm production) of SCM practices were the main motivating factor for persisting with SCM. SCM outcomes such as mental health, soil moisture, biodiversity and pH were more highly connected to the SCM practices of the low-fertility farms compared with the moderate-fertility farms. Farmers from both cohorts were in favour of financial support and incentives in the form of training and education support, and for maintaining the social network for information on SCM. High reliance on independent advisors was common among the farmers from both cohorts when choosing SCM management practices (Fig. 7). The interviews revealed that these independent advisors were one of the most substantial influences on farmers' decisions and behaviours in relation to SCM practices for both types of farms. An individual adviser supports farmers to adopt SCM practices and often becomes the main sources of information for understanding the techniques of practices, and achieving sustainable benefits (Nettle et al. 2018). Government organizations had less influence as actors, whereas private organizations and an individual's own stewardship ethics were more influential compared with any other actors in the current SCM system. All of the farmers had medium-to-extensive experience (Table 1) in the existing practices of land management, but there were few instances of systematic long term monitoring of soil change, through soil testing, with the implementation of an SCM practice, even though a high proportion of farmers had undertaken soil testing at some point. Despite this lack of documented evidence, our study showed that the overwhelming experience of farmers was positive in terms of SCM co-benefits and improving soil health (Fig. 5). Irrespective of farming cohort, soil carbon stock and the successful outcome of the current SCM practices were captured by "good soil health". The majority of farmers believed that the reward of their current SCM is agri-environmental benefits such as improved soil health and soil pH changes, even if they cannot quantify these benefits in precise terms. Regardless of negative climatic events and physical constraints such as low soil fertility in the study area long-term capacity to maintain certain level of stocking densities, would help better understand the "real" impact of approaches that farmers apply as SCM. Compensation or incentives for storing carbon was just one of the numerous benefits of the SCM practices and one area of government policy most farmers were not cognizant of. Farmers valued real or perceived environmental benefits over soil carbon storage.

This study found that grazing farmers from both farming cohorts have observed improvements in plant and animal production that have persisted with their grazing management despite socio-economic and environmental constraints. Farmers from the two farming cohorts experienced varying levels of confidence in achieving their goals when undertaking the SCM practices, with low-fertility farmers less confident of the outcomes. Our study also showed farmers in the studied grazing regimes are focused on a number of outcomes from SCM, including improvements in soil health and farm production of pasture, wool and meat. Most farmers focus on the agri-environmental benefits of SCM practices by increasing soil carbon in a holistic manner, more than knowing the actual amount of soil carbon held in the soil. Therefore, soil carbon credits as a policy lever may not be useful to individual farmers nor have much influence on their management activities especially for early adopters that are prepared to undertake SCM without any soil carbon payment.

4.2. Challenges and potential opportunities for current SCM practices

The interviewed farmers identified 13 challenges and potential opportunities for future adoption by other farmers of the current SCM practices (Fig. 8). A Sankey diagram is used to visually highlight the commonalities and/or differences in the SES features on the basis of the farm's dominant soil fertility. The key challenge within the resource system is drought, and challenges within the governance system are carbon trading, finance for labor, fertilizer price and carbon pricing (Fig. 8). In the resource unit and actor systems, there were more challenges for low-fertility farms than moderate-fertility farms. The challenges for farmers in the resource unit features were related to soil and land management, such as implementation of rotational grazing techniques and financing for fencing and water management infrastructure. Investing in SCM was challenging for farms with low land capability given the uncertainty of how long the return on investment with improved farm production would take. Thus, farmers suggested that flexible financing and funding could address this challenge. The motivation for other famers to adopt a new practice depends on proof of concept; however, it is extremely challenging to demonstrate gains on low-fertility farms. Thus, the practicing farmers suggested showcasing their day-to-day changes in SCM approaches via field days and leveraging their social networks (Fig. 8).

Farmers in both farming cohorts (n=6) nominated water and fencing infrastructure development and drought as major challenges for SCM through rotational grazing (Fig. 8). This is because rotational grazing requires investment in fencing to create smaller paddocks and providing each paddock with a watering point, and the interview period also was during the mega-drought of 2019 in Eastern Australia. Low-fertility farmers struggle more than the moderate-fertility farmers to influence other farmers' attitudes towards a change in grazing management (Fig. 8). However, a third of farmers in both farming cohorts believed that demonstrating successful SCM and building scientific support around their grazing management might motivate other farmers to take up rotational grazing practices. Farmers in the moderate-fertility farms (42%) considered it more difficult to participate in carbon trading and access a price on carbon compared to the low-fertility farms (23%) (Fig. 8). This difference in perception between farming cohorts might be related to the moderate-fertility farms, after several decades of rotational grazing, have reached a new soil carbon equilibrium and unlikely to increase their soil carbon stocks further (Badgery et al. 2020).

For a system to function effectively, actors usually interact with resource unit features directly or indirectly under the governance system (Petursdottir et al. 2020). However, SCM policy interventions by government, either at federal or state level, are very weakly connected to the studied grazing regimes, with negligible interaction with farmers' trusted sources of information or advisors. Most of the interviewed farmers thought that carbon is currently priced very low, with other studies corroborating that there is poor understanding and uncertainty about the carbon trading mechanism in Australia amongst stakeholders (Badgery et al. 2020; Kragt et al. 2016). The potential opportunities proposed by the farmers from both farming cohorts to resolve these challenges were introducing practice-oriented schemes e.g., practice-oriented carbon pricing and monitoring mechanisms for particular SCM approach such as rotational grazing on low-fertility farms and alternative settings for carbon pricing (Fig. 8). For instance, the practice-oriented schemes and pricing could include allocation of carbon credits and schemes depending on farmers' current practice length, farm soil condition, and the type of current and previous practices in terms of soil carbon sequestration potential (Martin and Lawson, 2022). The current scheme in Australia is not considering the SCM currently being practiced and its effect on soil carbon level; therefore, for these farmers to participate in the scheme they need to acquire new land. In addition, the potential opportunity proposed to overcome farmers' reticence to participate in carbon trading was to allocate credits for the co-benefits of SCM (Baumber et al. 2019), and soil carbon sequestration would then occur as an indirect consequence of practice change.

The particular set of challenges experienced by a small proportion of the low-fertility farms (31%), and were not considered by moderate-fertility farms were lack of knowledge on best management practices, conversion of cultivable lands to pasture or abandoning agriculture and training on grazing-based land management such as rotational grazing (e.g. cell grazing, time control grazing, holistic grazing) (Fig. 8). Farmers with the moderate-fertility farms were more agile in adopting a diversified SCM approach because the inherent land capability of their farms allowed them greater choice of land management techniques. Thus, they could experiment more in the SCM approach without compromising their farm production. Securing finance for additional labor was a particular challenge for moderate-fertility farms, whereas fertilizer price was a particular challenge for the low-fertility farms (Fig. 8). The potential solutions proposed by most farmers were the provision of flexible financing (52%) by banks and other financial organizations and using the SCM approach (56%) with a smaller proportion of farmers suggesting increased training and educational support (8%). A new initiative into the Australian soil carbon scheme would be funding loans based on improvements to natural capital resulting from farmers' current management practices, and this could be achieved through a participatory discussion with the farmers' social networks such as landcare groups or collectives as how best to proceed (Skaalsveen et al. 2020) (Fig. 8).

Although the farmers have experienced weak connections with government organizations in the current SES, there is an opportunity for governments to contribute via economic incentives or further education. The experience repeatedly shared by the farmers in the moderate-fertility farms was that the peer support and trust in their SCM increased after observing the co-benefits of improved soil health, farm production and ground cover during the recent drought period of 2019–2020 (Figs 5 and 6). Farmers in both farming cohorts have relied more on independent advisors and organizations such as Landcare rather than government, and yet have retained a sense of optimism that they can overcome the impact of drought through their SCM practices with the support of flexible financing (Fig. 8). Farmers from both farming cohorts (low-fertility farm, 77%; moderate-fertility farm, 33%) believed that other farmers' negative attitudes towards a change in grazing management could be resolved by sharing their SCM successes through the farmers' social networks (e.g., neighbours, regenerative agriculture group or landcare group).

The results highlighted the distinctive characteristics of farmers in both the moderate-fertility and low-fertility farms who have sustained SCM, largely through grazing management, for a number of decades. The reality that the practices that enabled these farmers to sustain their SCM were largely self-taught with little external support is instructive for policymakers when considering wider engagement of landholders in climate change mitigation at the farm level in Australia. Farmers were either unaware of the details of current initiatives, presumed that government policy was difficult to navigate and were uncertain about its targets and outcomes. From the farmers' point of view, future potential emissions reduction mechanisms need to be focused on the whole farming approach to address soil carbon sequestration at the farm level.

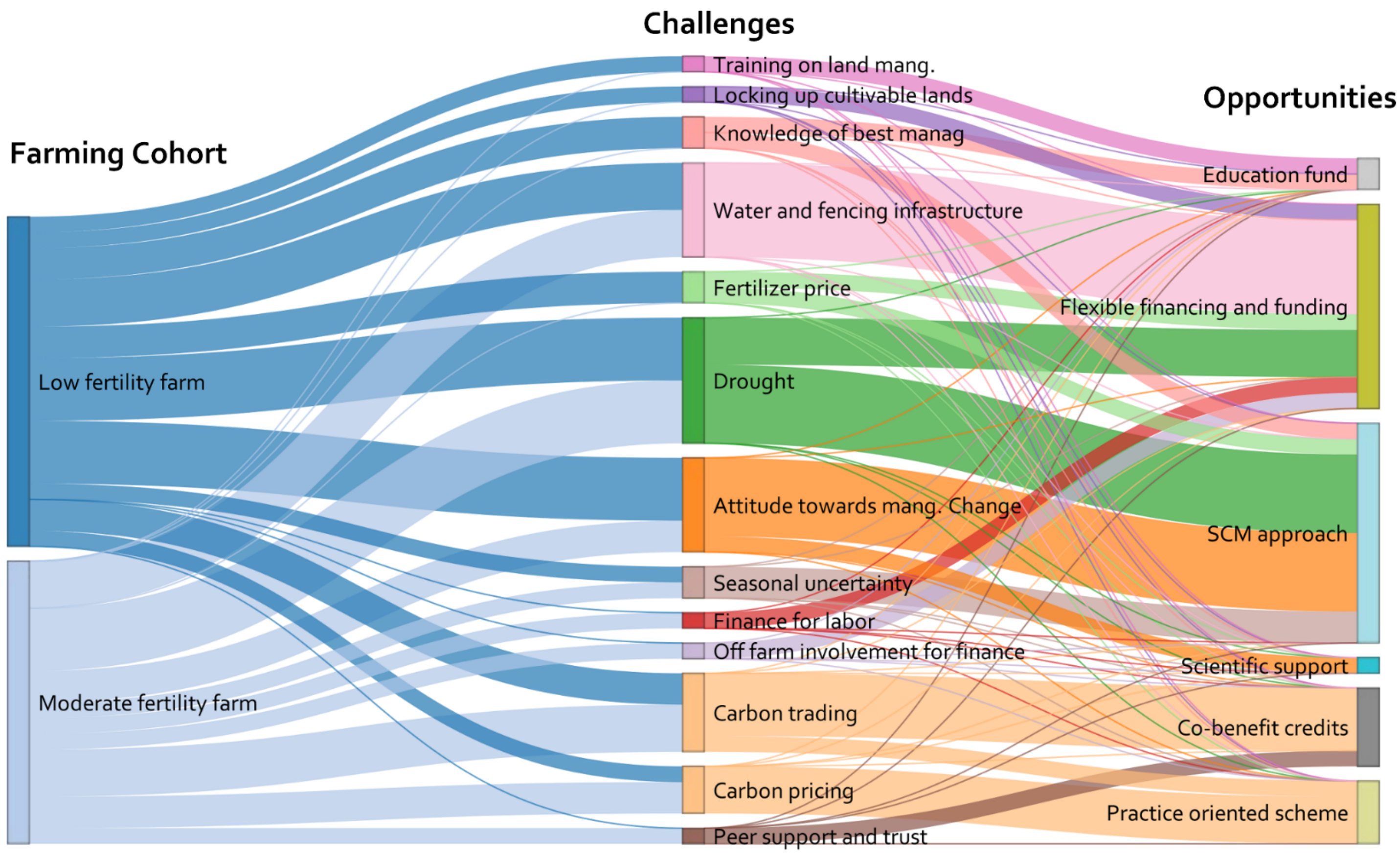

Fig. 8. Challenges experienced by farmers from low-fertility and moderate-fertility farms (n=25), and proposed potential opportunities under the existing SCM practices in grazing regimes categorized according to farm type. Here the weight or thickness of a line indicates the level of connection to other aspects, with thicker lines indicating stronger connections, and a single line "no connection" between related challenges and opportunities for each SES feature. The color on the extreme right of the Sankey highlights the individual opportunities (right panel) to address challenges of SCM (centre panel) as suggested by the farmers from both farming cohorts (left panel).

This study found that grazing farmers, especially those with low-fertility soils and low land capability have persisted with their grazing management despite the obstacles because they have observed improvements, mainly in grass production and animal health. Even though soil carbon sequestration and improvement are considered more challenging in low-fertility soils (Abaker et al. 2018), these famers have maintained a high level of commitment to their grazing regimes. This study revealed that farmers from both farming cohorts have shown resolve to continue their grazing practices because the SCM co-benefits are manifold and benefit whole-farm sustainability. Farmers were focused on a number of benefits they believe accrue from SCM under their current grazing regime, namely soil health, improved productivity, soil moisture retention, nutrient cycling and increased soil biodiversity (Amin et al. 2020; Baumber et al. 2019). These SCM co-benefits were similar for both farming cohorts with the additional focus for those in the more "stressed" SES of mental health and landscape aesthetics. Although these important SCM co-benefits are not easily quantified compared to other outcomes such as soil pH, they are particularly important for a resilient SES for SCM in these grazing regimes.

Although the SES is the based on a small subset of farmers, they represent highly skilled and long-term practitioners of rotational grazing who have been largely self-taught. The SES under consideration represents those farmers current SCM in grazing regime of sub-tropical temperate grazing lands in Australia. Even though it may not reflect the wider community of graziers not presently engaged in SCM, it could assist them through providing a farmers' perspective on what contributes to SCM and what does not help them in their current system. Future research could examine the longitudinal impacts of grazing management on soil carbon with more investment in long-term research and working with long-term practitioners of rotational grazing as well as less experienced ones. This evidence-based approach would then parameterize the anecdotal benefits of SCM that farmers have identified primarily through observational records on soil moisture, pasture production and financial records, rather than by soil testing, which has been shown to have a low uptake (Lobry de Bruyn and Andrews 2016). This study focused on farmers' perceptions of various aspects of agriculture, including resource quality and socio-economic capacity, within the context of grazing strategy, SCM, and societal attributes. Future studies also need to calibrate farmer's perceptions of resource quality, economic capacity against actual measurements.

5. Conclusion

Farmers from both farming cohorts persisted with their SCM despite the socio-economic and environmental challenges, even though for the low-fertility farming cohort their level of confidence in reaching their goal of improved farm production was found to be lower compared to the moderate-fertility farming cohort. Despite the lower confidence levels in achieving improved farm production for the low-fertility farming cohort they had a more optimistic assessment of SCM outcomes compared to the other farming cohort. Importantly, the majority of the studied farmers focused on holistic benefits or whole farm system improvement by managing soil carbon rather than knowing the actual soil carbon level they had achieved. This study revealed that SES for SCM of long-term practitioners in rotational grazing needs to be considered for a more targeted, customized and nuanced government policy, and what may attract less experienced farmers to undertake rotational grazing. Also the experience of farmers who have managed to sustain their SCM through challenging times needs to be communicated to younger and less experienced farmers, so that the broader system dynamics that sustain farming and contribute to improvements in soil carbon sequestration can be addressed.

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Conflict of interest

The authors declare no competing interests.

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Consent for publication

All authors have approved and have agreed to submit the manuscript to this journal.

Consent to participate

The authors affirm that human research participants provided informed consent for publication of collected information.

Ethics approval

The human ethics approval of this study was granted by the University of New England, Australia (approval number HE19-149).

Data availability statement

The datasets generated during and/or analyzed during the current study are not publicly available but are available from the corresponding author on reasonable request.

Code availability

The codes (Rstudio) generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Authors Contribution

Md Nurul Amin: Conceptualization; Data curation; Formal analysis; Methodology; Visualization; Roles/Writing - original draft. Lisa Lobry de Bruyn: Supervision; Methodology; Writing - review & editing. Md Sarwar Hossain: Supervision; Writing - review & editing. Andrew Lawson: Supervision; Writing - review & editing. Brian Wilson: Supervision; Writing - review & editing.

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