UNIVERSITY OF NEW ENGLAND

Understanding the Role of the Social-Ecological System Framework for Examining Australian Farmers' Capacity to Manage Soil Carbon

A dissertation submitted by

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Declaration of Originality

I, Md Nurul Amin, hereby declare that all research herein is entirely my own work. The work has not been submitted for any other degree or professional qualification. I certify that, to the best of my knowledge, I have acknowledged all the help I received and cited all the sources I used in this thesis. Although Chapters 2, 3 and 4 have joint authorship, the work contained in these chapters is solely my own. Co-authorship represents support in terms of comments, suggestions, advice and discussion aspects of the research.

Signed: [redacted]

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Abstract

Soil carbon is the largest terrestrial carbon pool, which is three times larger than atmospheric carbon storage. Soil carbon sequestration is considered to be one of the major means for climate change mitigation, and can ensure soil fertility, habitat conservation and reduced soil erosion. Grazing enterprises cover over 50% of Australia's land area (around 336 million hectares), and research evidence has shown a greater potential for being able to offset greenhouse gas (GHG) emissions on grazing lands, particularly in higher rainfall zones with greater vegetation retention. Thus, Australian grazing regimes could be a productive area for achieving Australia's carbon emission reduction targets. In Australia, a credit offset scheme (i.e. carbon trading with an authorised carbon price) was designed under the Emission Reduction Fund (ERF), and was the world's first national initiative to regulate the emission of carbon to the atmosphere from the agriculture and forestry sectors. The environmental conditions, land use and farming practices that improve carbon storage are considered to be known, in part from a series of government-funded programs in Australia during the late 2000s and early 2010s. However, the mismatch in priorities and knowledge expectations between farmers and scientists appears to be on how much and how quickly carbon can be built up in the soil profile. This knowledge gap has led to confusion as to what soil carbon management (SCM) approaches are best in Australian conditions. Carbon markets and SOC abatement potential fail to recognise that additional co-benefits of on-farm SCM because they are only rewarding the quantum of abatement. Irrespective of newly emerged carbon markets farmers have long recognised these co-benefits and managed for these (despite government investment in incentives, R&D). However, R and D effort from the review of literature showed a disproportionate emphasis on SOC for climate mitigation to inform government policy. In addition, the bulk of the past literature on SCM deals with the biophysical aspects of SCM rather than a holistic (socio-ecological) view. This study examined the SCM of long-term SCM practitioners in the grazing regimes of the Northern Tablelands and Upper Hunter regions of NSW using the novel approach of Ostrom's social-ecological system (SES) framework. The higher-level tiers of this framework were adapted to determine the particular features that are important for farmers' SCM practice.

The first part of the research was a two-stage systematic review of SCM in Australia. The first stage examined the progress made in SCM research in Australia, and the second stage focused on the use of the SES framework in SCM in both the global and Australian contexts. The study

then used both quantitative and qualitative assessment of articles to identify and synthesise research trends, challenges and opportunities for improved SCM (Chapter 2). The results provide a valuable insight into the SES components that have been examined, the methodological challenges experienced in the research into SCM that has been conducted over the last two decades and the research gaps. The review revealed that research has predominately focused on the ecological component of SCM in agricultural practices and has been conducted from a scientist's perspective. However, the sustainability of carbon-building soil management practices will require integration of the social components into future research, particularly from a farmer perspective. This research made the first attempt to develop a conceptual SES framework for SCM that can be used to identify and investigate the SES components in SCM in order to increase the process of offsetting GHG emissions as required by the United Nations Sustainable Development Goals (SDGs) 2, 13 and 15.

The second step (Chapter 3) of this study focused on understanding experienced farmers' current SES for SCM of grazing lands to identify the areas that affect their potential engagement in such policy initiatives. The mixed method approach used in this study included a network analysis that examined the connectivity of the SES features in SCM and estimated the strength of the connectivity among the SES features in the network. The network connectivity identified from the quantitative data was then validated by separately arranged farmer (n=2) and service provider workshops (n=2). The outcome was a consolidated SES causal loop map, which was produced by the system dynamic (SD) modelling platform STELLA. To understand the complex SES features in SCM, the farmer interviews were based on Ostrom's high-level categories of resource system, resource units, governance, actors (users) and interaction-output (interactions-outcomes). Interviews were conducted with experienced graziers (n=25) who were purposively selected. The selection criteria aimed to capture the perspectives of highly experienced graziers who had been undertaking two to three SCM practices for at least a decade, and represented both low-fertility and moderate-fertility farming cohorts. Utilising the categories of Ostrom's SES framework, 51 SES features of SCM were identified by the farm-level interviews. In the current SES of SCM, the connectivity among the SES features was 30%, which is relatively low compared with an ideal, fully connected social network. In stakeholder workshops, consensus was reached on the causal relationships (e.g. interactions, feedback loops) between the specific SES features that were considered to influence SCM. The SES had 10 critical feedback loops, with policy settings and instruments not positively affecting SCM practice.

In the third step (Chapter 4) of the research, grazing farmers in low-fertility and moderate-fertility soils were interviewed about their SCM and how they have persisted with their grazing regime despite obstacles such as drought. Both farming cohorts have shown resolve to continue their grazing regime because the benefits are manifold and affect whole-farm sustainability. Farmers were not familiar with the government initiatives for SCM under the ERF and the relevance to them and their SCM. As the studied farmers were focused on the broad agri-environmental benefits of SCM practices in a holistic manner, these long-term practitioners were unlikely to engage with soil carbon projects given their current structure and eligibility criteria. Farmers were focused on a number of benefits that accrue from their grazing regimes, including improvements in production, soil moisture retention and soil health. Farmers in more "stressed" environments also emphasised mental health and landscape aesthetics as outcomes of SCM. These features of the farmers' SCM present tangible benefits that are not easily quantified but were identified as important for farmers in managing their soil.

This study developed the SES for SCM based on farmers' practices in the Northern Tablelands and Upper Hunter of NSW, and explored the social-ecological relationships for SCM in order to improve farmers' capacity to engage with existing or future policy mechanisms in Australia. This study used a novel approach by operationalising Ostrom's SES framework to provide a tool for unpacking the SES relationships and exploring feedback loops in the grazing regimes. This approach can be applied to similar data-poor regions of the world. Unpacking the SES relationships in SCM can identify the gaps, challenges and needs of stakeholders, particularly farmers, and this information can be used to develop approaches that can help to achieve local, national and international objectives, such as SCM co-benefits, GHG emission offsetting, carbon sequestration targets and SDGs. The SES for SCM of long-term practitioners in rotational grazing needs to be considered in order to formulate more targeted, customised and nuanced government policy. 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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Acronyms

CFI	Carbon farming initiative
GHG	Greenhouse gas
ERF	Emission reduction fund
LLS	Local Land Services
NA	Network analysis
NSS	National soil strategy
NSW	New South Wales
SCM	Soil carbon management
SD	System dynamic
SDG	Sustainable development goals
SES	Social-ecological system
SLM	Sustainable land management
SNLC	Southern New England Landcare
SOC	Soil organic carbon

Table of Contents

List of Tables

List of Figures

Chapter 1

Introduction

1.1 Overview

Soil carbon sequestration through soil carbon management (SCM) is considered one of the potential measures for mitigating climate change and improving soil health. The ecological features of SCM are mostly understood through scientific studies, but less explored is how the social and ecological features of SCM interact with each other to influence the capacity of the farmers to manage soil carbon at the farm level. Understanding such interactions could inform policy and research to support SCM and help practitioners overcome the major impediments to sustaining SCM practices into the long term. These SCM practices are essential for achieving Australia's international commitments to reducing carbon emissions by 2030. This chapter discusses the role of soil carbon in climate mitigation and the social-ecological system (SES) framework and its role in SCM. The chapter also presents the problem statement, research questions, research approaches, rationale for selecting the study area and structure of the thesis.

1.2 Background to role of soil carbon in climate mitigation

Securing improvements in soil carbon stocks reduces soil erosion, ensures soil fertility and conserves habitat (Bossio et al., 2020; Wood et al., 2018). Soil carbon is the largest terrestrial carbon pool, three times larger than atmospheric carbon storage (Friedlingstein et al., 2019; Scharlemann et al., 2014), and small changes in this largest terrestrial organic carbon pool can significantly influence the concentration of carbon in the atmosphere (Johnston et al., 2009; Stockmann et al., 2013). Therefore, Soil carbon sequestration is considered to be one of the major means for mitigating climate change (Metz et al., 2007) and improving soil health (Lal et al., 2015). Soil carbon sequestration is defined as the capture and secure storage of atmospheric carbon in the lithosphere in a way that enhances the mean residence time and reduces re-emission (Lal et al., 2015). The other benefits of carbon sequestration include extended food and nutritional security, enhanced refurbishment of water quality, firming of elemental cycling and conservation of soil biodiversity (Lal, 2004; Lal et al., 2015).

Many agronomists and soil scientists agree that the carbon pool in agricultural lands represents a substantial sink for greenhouse gas (GHG) mitigation (Sanderman, 2012), and that a modest increase in carbon stock in agricultural soils can be achieved by introducing land management practices such as no tillage, grazing management, and the use of organic amendments (Lal, 2004; Sanderman et al., 2009; McKenzie et al., 2017). The '*4 per mille Soils for Food Security and Climate'* initiative of COP21 recognises that soil carbon sequestration is a saviour for-offsetting GHG emissions, and to globally mitigate the CO_2 emissions from human origins it aims to grow the soil organic carbon (SOC) stock by 0.4% per year in the 30–40 cm soil zone (Rumpel et al., 2018). Inherent and managed soil fertility and variations in land management influence soil carbon sequestration to varying degrees (Luo et al., 2020; Orgill et al., 2014). Conversely, prevalent research about the total potential and rate of carbon storage in soil, the stability of the carbon sinks, the efficacy of monitoring changes in soil carbon and the influence of climate and soil type over soil management at a larger spatial scale (Orgill et al., 2017; Rabbi et al., 2015; Stockmann et al., 2013) will influence landholders' capacity to choose management practices for improving SCM (Dumbrell et al., 2016).

Climate change mitigation through soil-based initiatives and restoration of soil health depends on the restoration of SOC (Bradford et al., 2019), and is reliant on landholders adopting practices that will improve SOC. SOC is one of the five indicators of soil condition being measured by the state governments of Australia (Metcalfe and Bui, 2016). The SOC levels were measured in a number of government-funded programs, most notably commencing with the National Land and Water Audit conducted from 1998 to 2002. For example, when comparing samples from the same time period, the decline of SOC content in NSW is about 12.5% as a result of the conversion of naturally vegetated land to agricultural land (Sanderman et al., 2009). The current stock of carbon is lowest in the dryland areas of NSW due to the existing land management practices, climate and soil type (McKenzie et al., 2017; Wilson et al., 2011). Nevertheless, since those earlier programs, there has been no large-scale follow-up monitoring to gauge the level of SOC change and thus capture the rate of SOC change. The environmental conditions, land use and farming practices that improve carbon storage are considered to be known (Tongway and Hindley, 2000; Sanderman et al., 2009; Young et al., 2005), in part from the work of the National Land and Water Audit, Monitoring Evaluation and Research Program (MER) and the Soil Carbon Research Program (SCARP). Nonetheless in Australia, although model data on SOC are available from various projects, no follow-up data collection about regional change and farm-level change in soil carbon has been undertaken, and this information is therefore unavailable (Wang et al., 2022). In addition, adoption of SCM practices are influenced not only by ecological factors (i.e. climate, soil) and types of land management practices, but also by social factors of farm size, education, gender and attitude towards management (Rochecouste et al., 2017). Thus, practitioners, advisors and policymakers need to consider both the social and ecological features of management for successful SCM.

In Australia, agriculture contributes almost 16% of total national GHG emissions (Rochecouste et al., 2015), and grazing enterprises cover over 50% of Australia's land area (around 336 million hectares) (Climate Work Australia, 2021). Research evidence has shown a greater potential for sequestering GHGs on grazing lands, particularly in higher rainfall zones with greater vegetation retention (de Otálora et al., 2021; Rey et al., 2017; Australian Government, 2018b; Badgery et al., 2020). Thus, Australian grazing regimes could be a productive area for achieving Australia's carbon emission reduction targets for 2030. In Australia, a credit offset scheme (i.e. carbon trading with an authorised carbon price) was designed under the Emission Reduction Fund (ERF), and was the world's first national initiative to manage carbon emissions into the atmosphere from the agriculture and forestry sectors (Evans, 2018; Macintosh and Waugh, 2012; Van Oosterzee et al., 2014). Following the IPCC's fourth assessment report in 2007, in 2011 the Australian Government introduced a market-based carbon offset scheme under the ERF called the Carbon Farming Initiative (CFI), to which the federal government allocated an additional $2.55 billion for the continued purchase of low cost abatement of carbon, mainly through the use of SCM methodologies (Verschuuren, 2017). CFI started in 2011, but following the change in federal government (2013), and was modified to ERF with certain ERF methodologies (e.g. estimation of soil organic carbon sequestration using measurement and modelled method) (Australian Government, 2018a).

In 2014, the Australian Government approved the SCM methods that farmers can adopt if they want to participate in the CFI (Minasny et al., 2017; AgriProve, 2019). These methods are cropping with no till, mulching on bare soil, establishing areas of native vegetation, intercropping with perennial pasture, retaining stubble in situ, managing grazing and reducing the cropping area by increasing the area of pasture (Australian Government, 2018a; Dumbrell et al., 2016; Macintosh and Waugh, 2012). In the Australian context, co-benefits of soil quality improvement and soil erosion reduction were the most important benefits of SCM to the farmers according to some researchers (Dumbrell et al., 2016; Kragt et al., 2016). The most important reason proposed by Dumbrell et al. (2016) for farmers' lack of enthusiasm to enter into a carbon farming contract was the uncertainty around the carbon pricing policy, productivity gains and the profitability of carbon farming practices (Dumbrell et al., 2016; Simmons et al., 2021). Other research has shown that farmers' interest in SOC can also be driven by stewardship for better soil health and farm production sustainability (Gosnell, 2021; Gosnell et al., 2019; Ogilvy et al., 2018). However, mismatch in priorities and knowledge expectations between farmers and scientists appears to be on how much and how quickly carbon can be built up and retained in the soil profile (Ashworth et al., 2009; Allen et al., 2013; Sanderman et al., 2015), which has led to confusion as to what SCM approaches are best for Australian conditions.

1.3 Defining the social-ecological system (SES) framework and its role in SCM

The prescribed SCM practices allowed under CFI implicate both social (i.e. attitude to management change, education) and ecological features (i.e. climate and soil) that affect practitioners' decision-making on the choice of SCM practices and potential carbon storage. Thus, an integrated social-ecological approach such as the social-ecological system (SES) framework can be employed to analyse the interconnections of the complex social and ecological features that relate to SCM. Ostrom's SES framework (Fig. 1.1) was used in this study to understand the role of the social and ecological features of SCM that influence the capacity of the farmers to manage soil carbon at the farm level. The SES concept helps to enhance understanding of the interlinked dynamics of societal and environmental changes. It examines the sustainability process more comprehensively by emphasising human dependence on ecosystems, collaboration across disciplines and collaboration between science and society, and by providing policy frameworks that consider social-ecological interdependencies (Fischer et al., 2015; Ostrom, 2009). This study uses Ostrom's SES framework to examine the sustainability process of SCM at the farm level by probing the social and ecological features that influence how land management affects the environment.

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Fig. 1.1. Ostrom's social-ecological systems framework (Ostrom, 2009)

The SES concept was first introduced by Berkes et al. (2000) to delineate the biophysical and social systems and to understand the dynamics of a system in a common framework. The biophysical system in an SES comprises the interactions of living organisms with the different abiotic components (e.g. climate factors) of nature, whereas the social system incorporates human systems of interactions among individuals, communities and institutions (Hossain and Szabo, 2017; Ostrom, 2007; Sakai and Umetsu, 2016). An SES for SCM includes both the ecological and social features, where ecological features are the interactions of living organisms with different abiotic components (e.g. climate, soil types, soil organisms) that influence SCS, and social features are the interactions among individuals, communities or institutions that affect farmers' willingness to change their farming system to sequester more carbon in soil.

Ostrom's (2007, 2009) SES framework describes and explains the interrelationships among the features in a complex system (Fig. 1.1). The first-level core subsystems of an SES framework (Fig. 1.1) are the resource system (e.g. water system, wildlife), the resource units (e.g. the types of animals or amount of water flow), the governance system (e.g. the organisation or authority that manages the resource systems or the mode of management), the actors or users (e.g. the individuals who use the resource systems) and interactions-outcomes (used as interaction-output in this study) (McGinnis and Ostrom, 2014; Ostrom, 2007, 2009). All of the core subsystems consist of several second-level variables, such as the knowledge of the user about the resource systems and the availability of the resources (Ostrom, 2009). Ostrom (2009) considered both bio-physical and social interactions to present a general conceptual framework of SESs for the sustainable management process. The SES framework provided by Ostrom (2009) is suitable for studying a distinct focal SES such as wetland SESs in deltas (Hossain and Szabo, 2017) because it initiates a common variable set for conducting analysis of the distinct SES. The SES framework organises the empirical and theoretical variables to provide sustainable solutions to problems (Folke et al., 2009; Ostrom, 2007, 2009), and enhances the sustainability of public policy by identifying particular issues from parts of the SES framework that might influence policy (Ostrom, 2009). The types of variable and their classification in the SES framework depend on the type of system and the spatial and temporal scale. For example, a slow variable such as soil resources is affected by the regional scale of management and also stimulates a more rapidly changeable fast variable such as soil nitrate. Slow variables are those that change slowly from one state to another, such as SOC, while fast variables are those that change rapidly within the system process and management, such as soil nutrients. Changes in both fast and slow variables eventually alter the social and ecological system (Folke et al., 2009).

Lescourret et al. (2015) provided a conceptual framework of an SES based on the dynamic interactions of diverse services delivered by sustainable agro-ecosystem management. This SES framework is consistent with Ostrom's SES framework, and consists of a social system and diverse ecosystem services in an interconnected ecological system that forms a distinct agricultural system in practice. In this conceptual framework, the ecological structures (e.g. soil, water and biodiversity), ecological processes (e.g. cycling of nutrients in nutrient, plant and animal growth), social structures (e.g. farmers, extension agents and researchers) and social processes (e.g. consultation, quality of product and resources, management regime) are the main components (Lescourret et al., 2015). Lescourret et al.'s (2015) study stated that SESs in agriculture are understudied and have not been examined as a mutual system (social-ecological) where there are actors with varied interests in the management system (i.e. extension agent, scientist, farmers) and an ecology of multiple services from the agricultural paddock (i.e. pollination, bio-pest control, soil moisture) (Egerer et al., 2018; Lescourret et al., 2015). In reality, for management of multi-services in an agriculture environment, the relationship between the management system and the ecology of the agricultural land is critical.

Identifying this relationship is also essential for developing robust and relevant policy guidelines and instruments for improving farmers' capacity and system sustainability. Therefore, understanding slow variables such as soil carbon storage using the SES framework approach is a prerequisite for improving farmers' capacity and system sustainability in SCM at the farm scale.

1.4 Research problem statement and research questions

Most land in Australia is privately managed, so any improvements to land management are in the hands of private land managers. Lobry de Bruyn and Andrews (2016) showed that rather than taking an evidence-based approach to management using extensive physical evidence (i.e. soil testing), land managers mostly depend on financial records and observational records of soil health. However, land managers acknowledge that sharing knowledge can enhance the capacity of the farmers to improve land management and sustainable soil use (Lobry de Bruyn et al., 2017). Communication of soil carbon science to farmers needs to consider attributes such as the credibility, salience and legitimacy of the complex SCM system (Ingram et al., 2016). In this regard, there is growing appreciation for how analysis that is based on an SES framework can ensure a comprehensive understanding of the system and safeguard the legitimacy of the procedure. Our interest in farmers' capacity is grounded in the knowledge that without their actions and adoption of SCM, not much will be achieved. Recent research evidence shows that farmers' capacity is integral to sustainable land management decision-making and is essential for the success of policy instruments (Hou et al., 2020; Kröbel et al., 2021).

Farmers' capacity can be affected by a range of factors, such as their personal goals or motivations and their ability to make decisions. The latter is affected by particular feedback loops such as their level of prior knowledge of system conditions and how they are able to understand changes in these conditions (Rougoor et al., 1998). Overall, capacity factors (e.g. trust building, learning, ecosystem stewardship, behaviour change) have different dimensions from the social, biophysical, technical and institutional perspectives (Rougoor et al., 1998). The capacity factors considered in this project were related to the farmers' level of sustained practice of SCM and the support they received to establish SCM practices. SES framework approaches can assess the impact of land use planning on different parameters, and can assist farmers in developing sustainable land use practices (Karimi and Hockings, 2018; Lescourret et al., 2015).

Increasing the soil carbon stock in many Australian landscapes will be challenging because of the constraints of the climate and soil properties (Rabbi et al., 2015), and its success will depend on the landowner's ability to implement soil management measures like minimum tillage cropping and grazing management regimes (McKenzie et al., 2017). A wide range of investment in low-emission technology is occurring at present, but a study suggested that in Australia, many people are unaware of carbon dioxide capture and storage, and that there is a more investment in technical programs than in communication activities , which may have contributed to this lack of awareness (Ashworth et al., 2009; Kragt et al., 2017). Successful capture and storage of carbon requires not only a risk analysis to identify the benefit-loss of carbon storage, but also trust-building through clear and proactive communication (Ashworth et al., 2009; Evans, 2018). In reality, the interconnectedness of society affects the rate of change in the management processes, for example, the level of interconnectedness can affect how quickly information about outputs from particular projects can spread to other countries of the world (Ashworth et al., 2009).

Sustainable carbon management in soil requires clearly articulated and accessible information on the associated benefits and costs of change in SCM. The exact extent of carbon abatement and co-benefits delivered from the different methods used in the carbon projects need to be well communicated. Moreover, the information on the financial return associated with various carbon prices, variations in the carbon yields in different soil types and impacts of carbon storage on productivity are also important in influencing farmer adoption of soil carbon storage practices (Ashworth et al., 2009; Dwyer et al., 2009; Evans, 2018). Another important issue is the source of information, which affects the trustworthiness of the message to landholders. Effective communication of information requires these trustworthy messengers to increase awareness of SCM practices and encourage their adoption by farmers (Evans, 2018).

Improving farmer capacity for SCM requires policy certainty in Australia (Dumbrell et al., 2016). Landholders seek social and ecological co-benefits from farm-level SCM projects, such as protection of biodiversity, improved soil, and shade and shelter for livestock (Baumber et al., 2019; Kragt et al., 2016). In general, co-benefits from soil carbon projects need to be incentivised, monitored and well communicated rather than relying on the prospect of carbon credits (Dumbrell et al., 2016; Evans, 2018; Kragt et al., 2016). In the case of carbon farming in Australia, policy uncertainty and complexity are the main factors for the low adoption rates (Evans, 2018). Proponents of current carbon projects funded under the Australian Government's ERF are able to register for co-benefit credits (i.e. monetising the soil biodiversity increase), but empirical evidence on carbon farming co-benefits is very low (Baumber et al., 2019). Also, practice-orientated schemes (i.e. practice-oriented carbon pricing and monitoring) for allocation of carbon credits were recently introduced in the ERF; however, no clear directions and mechanisms for the process for different areas and practices were stated. A recent online initiative to identify SCM best practices in Australia invited expressions of interest from the different stakeholders and services to provide evidence of various existing SCM practices at the farm level (Australian Government, 2021). This information revealed three lessons: SCM needs to focus on achieving ecological benefits (i.e. carbon sequestration, soil health), social benefits (i.e. credit gain, carbon market) and increased participation of farmers who have the capacity to manage soil carbon at the farm level.

This study examined the SCM of long-term practitioners of the grazing regimes employed in the Northern Tablelands and Upper Hunter area of NSW using a novel application of Ostrom's SES framework. This novel application involved adapting the higher-level tiers to determine the particular features that are important for farmers' SCM practices. The main aims of this study were to develop an SES framework for SCM based on practices in the Northern Tablelands and Upper Hunter of NSW and to explore the social-ecological relationships at work in SCM. This information can then be used to improve farmers' capacity to engage with existing or future policy mechanisms in Australia. The research was framed around the following research questions, which were first explored in a systematic review of SCM in Australia (Chapter 2), followed by an in-depth qualitative study of long-term grazing practitioners in the Northern Tablelands of NSW and Upper Hunter, Australia (Chapters 3 and 4):

1. What are the current research trends in Australia's SCM and in the use of a social-ecological system framework to examine farmers' capacity to manage soil carbon? (Chapter 2)
2. What are the social and ecological features within the SES of SCM that influence farmers' capacity to manage soil carbon? (Chapter 3)
3. How are the social-ecological features interrelated? How do these relationships affect SCM and farmers' capacity to manage soil carbon in the grazing regimes studied? (Chapter 3)
4. What are the social-ecological relationships that are critical for enhancing farmers' capacity for SCM in grazing regimes? (Chapter 3)

5. What is the distribution and pattern of SCM practices based on long-term practitioners' SES for SCM in the grazing regimes studied? (Chapter 4)
6. What are the implications for policy and practice related to farmers' sustained SCM of the studied SES for SCM in grazing regimes? (Chapter 5)

The overall approach to operationalising the SES for SCM at the farm scale in the grazing regimes of Australia comprised four steps: (i) reviewing the existing literature to understand the trends, gaps, methodological challenges and future research directions for SCM in Australia and the role of the SES framework for examining farmers' capacity to manage soil carbon (RQ1); (ii) exploring the SES features for SCM and unpacking the relationships (interactions and feedbacks) of these features in order to enhance farmers' capacity to sequester soil carbon in the grazing regimes of Australia (RQ2, RQ3 and RQ4); (iii) analysing the distribution and pattern of SCM practices based on long-term practitioners' SES for SCM in moderate-fertility and low-fertility grazing farms to utilise farmers' experience for customising interventions in SCM at public policy level (RQ5); (iv) synthesising the research findings and extracting implications for policy and practice in relation to sustaining farmers' SCM (RQ6).

1.5 Case study area: Rationale for selection and brief description

Livestock grazing is the main agricultural practice in Australia, occupying half of Australia's land mass (Government of Australia, 2021). According to de Otálora et al. (2021), Reich et al. (2020) and Rey et al. (2017), high-rainfall grazing regimes with high vegetation retention have a superior potential to sequester soil carbon. High-rainfall grazing zones with modified pastures occupy 71 million ha in Australia (Australian Government, 2021), and thus there is a large proportion of Australia where soil carbon levels can be improved under certain forms of land management. To understand what an SES framework approach might tell us about Australian farmers' capacity to manage soil carbon, this study focused on farms located largely in the Northern Tablelands and Upper Hunter region of New South Wales, Australia (Fig. 1.2). The findings of this research will have broader relevance to other similar areas where grazing is dominated by summer rainfall (Fig 1.2).

The Northern Tablelands is an area of 3.12 million ha, located between latitudes 29° 00' south and 32° 00' south. In the study region, there is an area of 2.11 million ha of agricultural land with an estimated agricultural commodity value of AU$217.8 million. Livestock grazing contributes 86% of the total value, with wool (41.7%) and meat (beef and lamb; 44.5%) the dominant products (Alford et al., 2003). The major geological parent materials of the soils are granites, greywackes and tertiary basalts (Alford et al., 2003). The soils of the study area are characterised by low fertility and poor physical condition with a greater limitation in land capability (Office of the Environment and Heritage, 2018). The studied region is located at an altitude of 750–1200 m above mean sea level. This region is a temperate climatic zone (Lodge and Whalley, 1989), and mean annual temperature minimum is 7° C. The area experiences seasonal drought every three years (Fig. 1.3) and severe drought one in every 10 years (Lodge and Whalley, 1989). Average rainfall is around 750– 800 mm with a dominant summer rainfall pattern (Fig. 1.4B). Maximum temperatures (Fig. 1.4A) in this region usually remain below 30° C (Lodge and Whalley, 1989).

Fig. 1.2. Study area in the Northern Tablelands and Upper Hunter, New South Wales, Australia. The administrative boundary is from GADM (2021)

Conventional farm during the mega drought 2019, pictures captured in December 2019 by author M N Amin

Rotational grazing after the mega drought 2019, pictures captured in March 2020 by author M N Amin

Fig. 1.3. Climate stress situation in a conventional farm during the mega drought of 2019 in Inverell, NSW, and rotational grazing after the mega drought in Tenterfield, NSW.

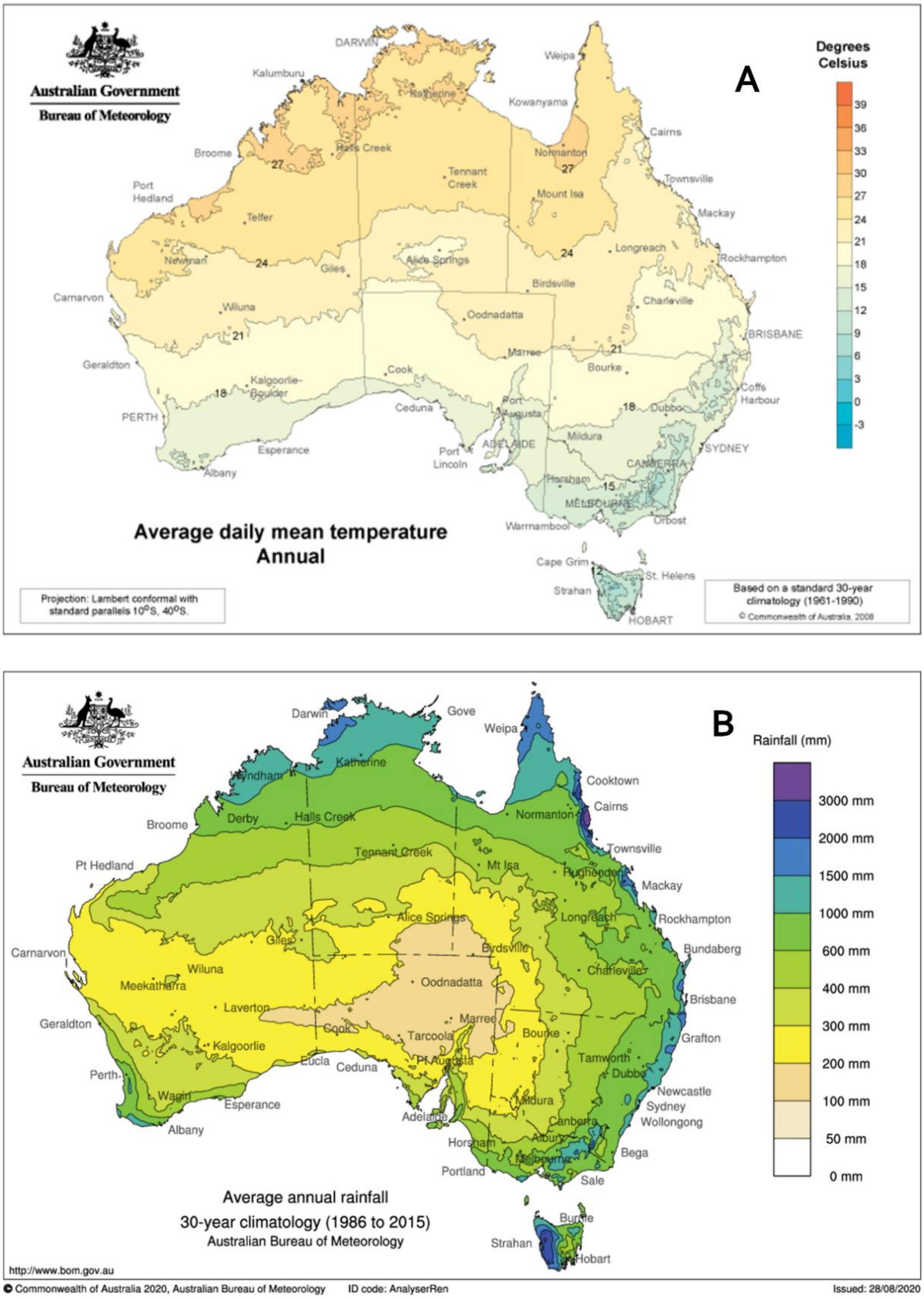

Fig. 1.4. (A) Average daily mean temperature (1961–1990) and (B) average annual rainfall (1985–2015) (Bureau of Meteorology, 2021)

1.6 Thesis structure

Following the University of New England's guidelines for a higher degree research thesis by publication, this thesis consists of three research chapters that were prepared in the form of papers for publication and which examine the research questions outlined earlier. Fig. 1.5 shows the relationship of the three papers to the overarching goal of operationalising the SES approach for SCM at the farm level in the grazing regimes of Australia. Prior to the research chapters, Chapter 1 has provided the context of the research and the background to the SES framework. It also discussed the imperative to improve soil carbon, especially in the Australian agricultural environment and presented the research aim and questions. The chapter that follows the research chapters (Chapter 5) synthesises the research presented in three research chapters (Chapter 2, 3 and 4) and draws out the implications for policy and practice related to sustained SCM of the studied SES for SCM in farmers' grazing regimes. All co-authors involved were PhD supervisors. The percentage of co-authorship statements presented at the end of each chapter (Chapter 2, 3 and 5).

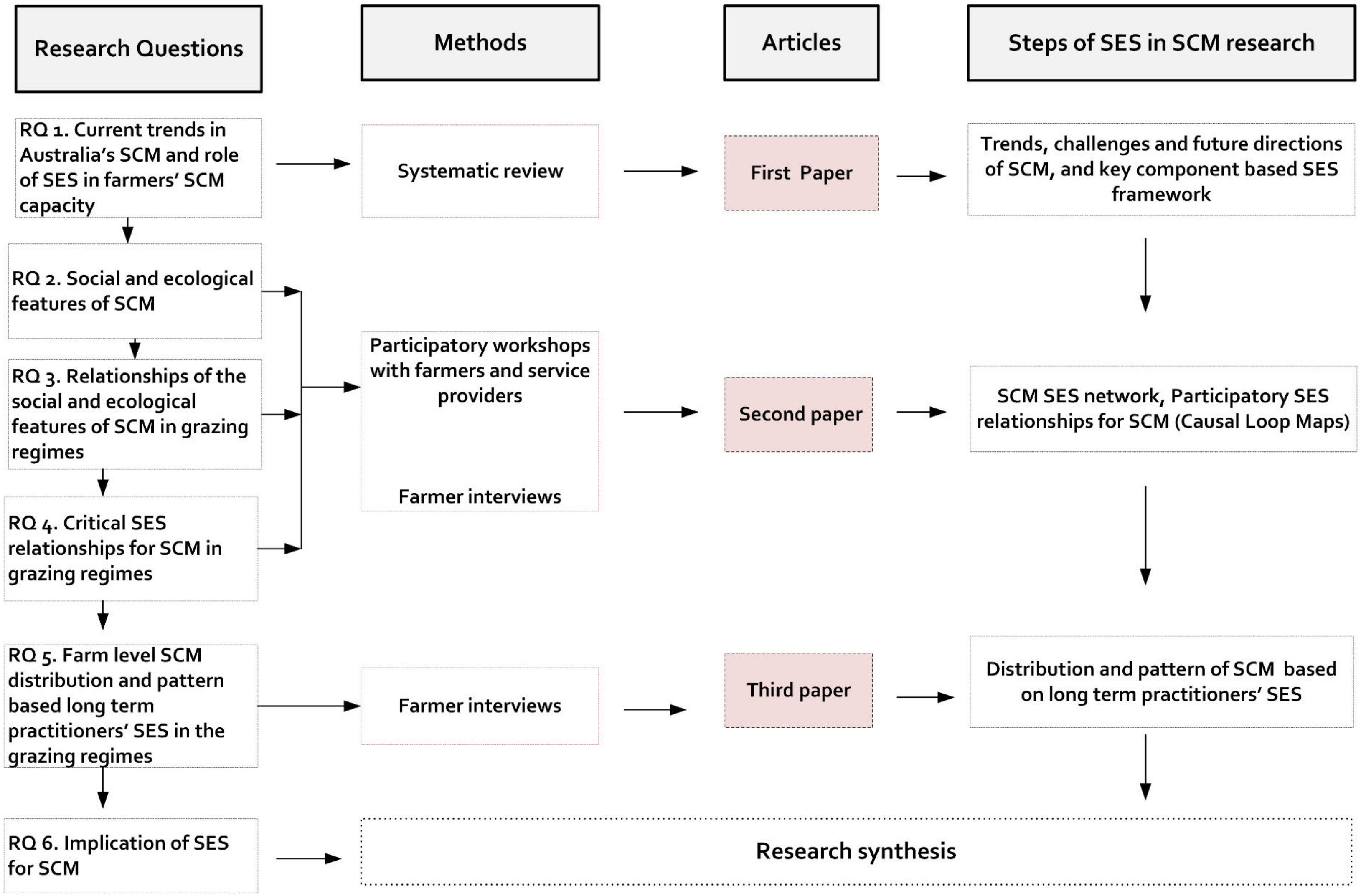

Fig. 1.5. Flow diagram of the thesis showing the relationships between the research questions, methods, articles and steps of the SES in SCM research, culminating with research synthesis.

1.6.1 Chapter 2: Current trends in SCM and the role of SES

This first paper focuses on the trends in SCM in Australia and the extent that the social and ecological features are used in SCM research in Australia. This paper reports a systematic review that was carried out in two stages: (i) a review of articles on SCM in Australia and (ii) a review of articles that use the concepts of SCM and SES (Fig. 1.5). The challenges, trends and gaps in SCM in Australia were explored in the existing literature, as well as farmers' participation in SCM research and the influence of farmers' capacity to implement SCM in Australia. The review also examined the presence of the SES concept in SCM research globally and the need for an SES framework for SCM. . It is proposed that the key components that form the basis of an SES for SCM should be the subject of further study (Fig. 1.5).

1.6.2 Chapter 3: SES relationships in SCM

This chapter operationalises Ostrom's SES framework to identify the current SES features of SCM in the grazing regimes of the studied region of New South Wales. Both quantitative and qualitative methods were used to answer the research questions. First, the social and ecological features of SCM that help or hinder farmers' ability to manage soil carbon at the farm level were identified using data from semi-structured interviews with farmers (n=25). Ostrom's higher-level categories (e.g. resource system, resource units, governance system, actors and interaction-output) were used to organise the underlying features. Then, the relationships between and among these SES features were presented at farmer (n=2) and service-provider (n=2) workshops to organise the set of social and ecological features for SCM in the grazing regimes studied (Fig. 1.5). SES relationships (i.e. interactions, feedback loops) for SCM were also examined in the participatory workshops (Fig. 1.5). The interview data were analysed using social network analysis in RStudio. The consolidated SES for SCM was depicted on the system dynamic modelling platform STELLA. Unpacking the critical SCM SES relationships in the grazing regimes revealed policy gaps and challenges in the current SCM system in the grazing regimes of Australia (Fig. 1.5).

1.6.3 Chapter 4: Farm-level SCM distribution and pattern based on SES

In this third paper, the farm-level distribution and pattern of SCM practices were analysed based on interviews (n=25) with long-term practitioners of SCM in the grazing regimes studied. Qualitative analysis was used in this study. Ostrom's high-level categories (e.g. resource system, resource units, governance system, actors and interaction-output) were used to analyse the distribution and pattern of practices inherent in this SES. The distribution and pattern of

SCM practices of two farming cohorts were compared (i.e. moderate-fertility farms and low-fertility farms). The SCM comparison between the two farming cohorts is presented as a network map for each situation. The challenges and opportunities for SCM in these two farming cohorts are presented using a Sankey plot. Finally, by analysing the approaches of the long-term practitioners, some lessons that are relevant for customising public policy interventions in SCM are extracted.

The overall structure of the thesis is illustrated in Fig. 1.5, including the main research questions and the linkage between the articles and the steps of the SES in SCM research. The challenges, limitations and future research directions are discussed in each paper. The synthesis chapter (Chapter 5) summarises the findings and contributions of the study, keeping in mind the key audiences of SES researchers, farmers, public policymakers and extension support agents, with the final section presenting overall future research opportunities.

This study applied both qualitative and quantitative approaches. The farmer interviews were based on Ostrom's high-level categories (Fig. 1.1) to understand the complex SES for SCM. Ostrom's SES approach describes and explains the existing interrelationships in a system, which provides clues to solutions for sustainability problems. Interview participants for this study (n=25) were purposively selected, with the selection criteria aimed at capturing the perspectives of highly experienced graziers who have been undertaking two to three SCM practices for at least a decade. The interviewed farmers were widely distributed throughout the Northern Tablelands and Upper Hunter areas and represented both low-fertility and moderate-fertility farming cohorts of this grazing regime. The interviews captured the lived experience of farmers who are practising SCM. The mixed method approach of this study includes a network analysis, which examined the connectivity of the SES features of SCM and estimated the strength of the connectivity among the SES features in the network. This network connectivity was based on quantitative data, and was then validated by separately conducted farmer (n=2) and service provider workshops (n=2). Two workshops for each group ensured saturation of information and minimised redundancy. These groups were selected to maximise the understanding of the SES in the study area. The workshops for the farmers and service providers were held separately to ensure that the perspectives of the service providers did not dominate or overshadow the farmers' deliberations. The approach used in this study is novel and can be applied to other similar data-poor regions of the world.

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Chapter 2

A systematic review of soil carbon management in Australia and the need for a social-ecological systems framework

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It is presented here with the original contents (published materials) in MS Word version, with figure and table numbering adapted to suit the context of the thesis.

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2.1 Abstract

Research efforts on soil carbon management in agricultural lands over the last two decades have sought to improve our understanding in order to increase soil productivity and soil carbon sequestration and to offset greenhouse gas emissions. This systematic review aims to identify the research gaps and future direction of soil carbon management in Australia. We explored and synthesised the use of social-ecological systems (SESs) both in the global and Australian context before making the first attempt to develop a conceptual SES framework for soil carbon management. Both quantitative and qualitative assessment of articles were used to identify and synthesise research trends, challenges and opportunities for improved soil carbon management. The results provide valuable insight into the SES components examined, the research gaps and the methodological challenges for research into soil carbon management conducted over the last two decades. The review revealed that research has predominately focused on the ecological component of soil carbon management in agricultural practices and has been conducted from a scientist's perspective. The sustainability of carbon-building soil management practices will require integration of social components into future research, particularly from a farmer perspective. The proposed conceptual SES framework is designed to identify and investigate SES components in soil carbon management in order to increase the process of offsetting greenhouse gas emissions as required by Sustainable Development Goals 2, 13 and 15.

Keywords: Agriculture; Soil carbon; Ecological components; Social components; Carbon sequestration

2.2 Introduction

Secure storage of atmospheric carbon in the soil is considered to be a potentially effective and enduring climate change mitigation strategy (Yang et al., 2019). The Conference of Parties (COP21) approved a mitigation scheme for climate change, limiting global warming to a 2°C increase on the pre-industrial level through the 'Paris Agreement' of 2015 (Yang et al., 2019). As part of this agreement, the attending parties launched an aspirational program called '*4 per mille Soils for Food Security and Climate'*. This program's goal was to increase soil organic matter (SOM) stock by 0.4% per year in order to offset the emission of greenhouse gases (GHG) to the atmosphere from human induced sources (Arrouays and Horn, 2019). In Europe, participating stakeholders committed to a voluntary plan of action to introduce prescribed farming practices that have been shown to increase carbon stocks in agricultural soils. Soil carbon management is also a key recommendation for achieving the United Nations (UN) Sustainable Development Goals (SDGs) 2, 13 and 15 (Hamidov et al., 2018) through the increased adoption of practices that improve soil carbon sequestration (Lal, 2018). Increased soil carbon storage through soil carbon management in terrestrial ecosystems also has wider benefits through biodiversity protection, enhanced food security and mitigation of climate change (Hamidov et al., 2018).

Agriculture contributes almost 16% of total national greenhouse gas emissions in Australia, and the cropping sector alone is responsible for 2.5% (Rochecouste et al., 2015; Young et al., 2009). Australian research on soil carbon management in agricultural lands has attempted to understand how agriculture can contribute to reducing net emissions of carbon through carbon sequestration (McHenry, 2009a; Morán-Ordóñez, 2017). Following the fourth assessment report of the IPCC in 2007, the Australian Federal Government introduced market-based carbon offset schemes including the Carbon Farming Initiative (CFI) in 2011, the Emission Reduction Fund (ERF) and more recently the Climate Solutions Fund (2019), investing an additional $2.55 billion for the continued purchase of low cost abatement of carbon, principally through agricultural land management change. The Climate Solution Fund's goal is to provide farmers and landholders with access to carbon markets for the reduction of net carbon emissions using prescribed soil carbon management methodologies (e.g. no tillage, bio-char application, mulching on bare soil) (Verschuuren, 2017). Carbon credits are purchased through a reverse auction process, and by the end of 2018, six auctions had taken place with an estimated 191 million tonnes of emission reduction (Government of Australia, 2018). In addition to the offsetting of carbon emissions, this scheme also claimed several co-benefits, including improved biodiversity, income and employment for local communities.

There is broad agreement among scientists and policymakers that terrestrial carbon stored in agricultural land represents a substantial potential sink for GHG mitigation through modest increases in carbon stocks (Lal et al., 2007; Sanderman et al., 2009). However, there are a number of factors that seem to be responsible for the limited adoption of practices that are specifically designed for soil carbon management. These include poor communication of the co-benefits of practices or measures for soil carbon management, uncertainty about the carbon pricing policy, and uncertainty about the productivity and profitability of carbon farming practices (Rochecouste et al., 2017). Moreover, it appears that the farming community is not motivated to manage soil carbon for the sole purpose of climate change mitigation (Evans, 2018).

Adoption of soil carbon management practices is influenced by socio-economic, cultural, psychological and farm variables (e.g. farm size, farmers' age, gender, and education) that affect farmers' decision-making (Kragt et al., 2016; Rochecouste et al., 2017). Prescribed land management practices for soil carbon management therefore consist of both social (e.g. attitude to change, farm size and farmer demographics) and ecological (e.g. climate and soil properties) variables that affect the decision-making environment of stakeholders and the potential for carbon storage, respectively.

Research relating to soil carbon management in Australia has typically focused on empirical measures of soil carbon accumulation (e.g. Badgery et al., 2014; Bajgai et al., 2014; Chappell and Baldock, 2016; Luo et al., 2016; Preece et al., 2015; Rabbi et al., 2015; Rabbi et al., 2014; Wang et al., 2013; Wilson et al., 2010), with poor integration of social and ecological variables that could influence soil carbon management. To include all variables (social and ecological), the concept of the social-ecological system (SES) has received growing attention across the world (Hossain et al., 2018; Willcock et al., 2016). In general, the SES concept provides the opportunity to integrate and analyse the complex social and ecological components of soil carbon management as an interconnected system (Hossain and Szabo, 2017).

An SES in soil carbon management would consist of ecological variables such as climate, soil type and land use, while social variables might include individuals, communities or institutions and their willingness to change their farming system to store more soil carbon. The social and ecological components of soil carbon management are interrelated and feedback loops could drive the dynamics of the SES. By understanding the influence of the variables acting within and between the ecological and social components of an SES, there is greater potential to manage soil carbon with a consideration of all these variables. In an SES, exogenous system controls such as climate and global markets affect the slow control variables (e.g. soil carbon, cultural ties to the land) that in turn stimulate the more rapidly changeable fast variables (e.g. soil nitrate, community income) (Folke et al., 2009).

Therefore, to study such an SES, the use of an SES framework is required to examine the relationships between variables operating at different spatial and temporal scales in order to seek a better understanding of how the system works and what can be done to manage it more sustainably (Marshall, 2015). For example, SES frameworks have been applied to regional sustainability (Hossain et al., 2017a; Hossain et al., 2020), determining the impact of ecosystem services (Hossain et al., 2017b) and climate change adaptation, fisheries and water management (Aguirre et al., 2019; de Wet and Odume, 2019; Galappaththi et al., 2019). However, the use of an SES framework in soil carbon management is as yet unknown.

A systematic review was conducted on soil carbon management research and how it may influence farmers' capacity to manage soil carbon in Australia. The review focused on the following research questions within the context of soil carbon management and farmers' capacity to manage soil carbon in Australia:

1. What are the current trends in soil carbon management research?
2. What are the research gaps and opportunities for further improvement in soil carbon management research?
3. To what extent has the concept of SES been used in reviewed studies?
4. What are the implications for soil carbon management using a conceptual SES framework?

Section 2.2 details the methodology of the study in terms of searching for and reviewing articles, before describing current trends (Section 2.3.2), SES components (Section 2.3.3) and knowledge gaps and methodological challenges (Section 2.3.4) in soil carbon management research. Sections 2.4.1 and 2.4.2 introduce the SES components of soil carbon management and propose a conceptual SES framework, before discussing the future research direction for soil carbon management research in Australia.

2.3. Methodology

2.3.1 Search terms and article selection approach

Our systematic review followed a two-stage process (Appendix A, Fig. 2.1). In Stage 1, the systematic review focused on the progress made in soil carbon management research (RQ 1 & 2) in Australia and Stage 2 focused on the use of the SES framework in soil carbon management (RQ 3) across the world**.**

The scientific literature was examined through Scopus and Web of Science databases using a fixed set of inclusion criteria: articles published in English and limited to journal articles and book chapters. The literature search was undertaken between August and November 2018 using the search terms provided in Appendix A, Table 2.1. The search terms were first tested for effectiveness using search engines such as Google Scholar. In this review, our scope was to consider total organic carbon (TOC) as we are considering the carbon storage potential and a measure of soil carbon that is tested by farmers (Lobry de Bruyn and Andrews, 2016).

The search terms were further refined and limited to Australia, resulting in a total of 274 articles in Scopus and 306 in Web of Science. All bibliographic details were imported into EndNote to eliminate any duplicates. The deleted files were verified manually to ensure no potential articles were removed accidentally. The number of duplicate articles from Stage 1 of the search was 104. After applying the exclusion-inclusion criteria (e.g. key words, years 2000–2018 and types of literature) and examining each article's title, abstract and keywords, irrelevant articles were excluded. The number of potentially usable articles was 97 (Appendix A, Fig. 2.1).

During the initial screening of articles, it became clear that the SES framework has not been used in Australian soil carbon management research. Thus, Stage 2 of the systematic review focused on the extent to which the SES framework has been used in soil carbon management across the world. In Stage 2, a total of 45 articles from both databases (Scopus and CAB Abstract) were identified. After applying exclusion-inclusion criteria (e.g. keywords, year 2000–2018 and types of literature) and examining the article's title, abstract and keywords, the total number of potentially usable articles was four (Appendix A, Fig. 2.1). The list of articles used in the review are included as supplementary materials in Appendix A with full bibliographic details.

2.3.2 Quantitative and qualitative analysis

We conducted the review with NVivo12 Plus, which allows for quantitative and qualitative analysis, traceability of coding decisions and creation of coding rules. After exporting the articles from EndNote to NVivo12 Plus, each article was categorised into a source classification with bibliographic information and other categorical data such as research focus, research methodology, spatial scale of research (national, regional or local or farm) and the social, ecological or social-ecological component addressed. Categorisation of each article allowed for quantitative and qualitative analysis. Source classification data could then be further coded under themes (e.g. future research gaps, trends in soil carbon management research, key research focus, policy implications, and potential co-benefits of soil carbon management). After further reading of all articles, emerging themes were identified (e.g. components of SES).

To scope the keywords of articles during Stage 1 of the systematic review, a word frequency query in NVivo12 Plus was undertaken (Fig. 2.1). The word frequency query corroborated the main ‘search terms’: soil carbon, carbon sequestration, agriculture, management and climate. Moreover, other words representing particular farming practices, factors of carbon management and co-benefits were also found to be present in the word cloud, but less frequently (Fig. 2.1).

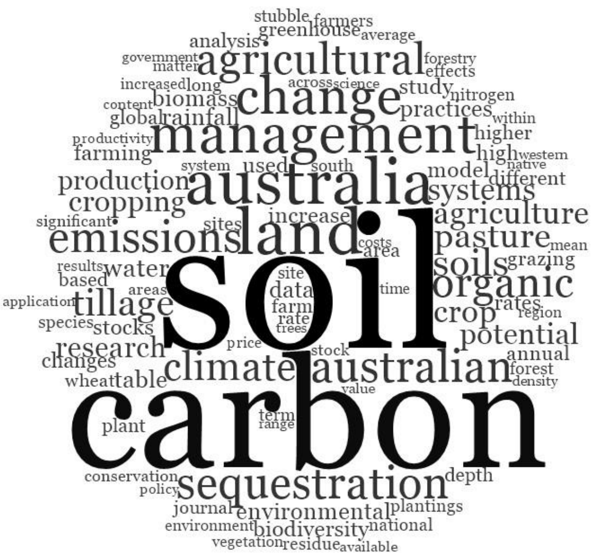

Fig. 2.1. Representativeness of scientific literature in relation to the study theme using NVivo12 Plus word frequency query. This word cloud shows the clear representation of the search terms used in Stage 1 of the systematic review (Appendix A, Table 2.1).

After all articles were imported into NVivo12 Plus, they were categorised under their dominant component: ecological, social, or social-ecological. Potential ecological components in an article included examination of biophysical variables such as climate and soil properties. Social components included articles that examined socio-economic variables such as governance and policy, carbon markets, demographics and social norms. Finally, articles categorised as a social-ecological component were those that examined social-ecological aspects together, such as aspects of a farming practice or land use change under soil carbon management.

The spatial scale was categorised as either national, regional or local or farm level for each article. Articles categorised as national level examined soil carbon management research across Australia with no mention of specific localities (e.g. Australian wheat farmers). Articles categorised as regional level examined soil carbon management research at multiple locations within or across state boundaries (e.g. 11 sites in Victoria) or broad regions such as northern New South Wales. Articles categorised as local or farm level examined soil carbon management research at (usually) one location on a research station or farm (e.g. the Wagga Wagga Agricultural Research Institute).

The other forms of analysis enabled by NVivo12 Plus were matrix coding queries and crosstab queries. These functions allowed examination of interactions between the articles' source classifications and a coded theme. The relationship between the source classification "SES component" and the "soil carbon management co-benefits" theme was examined using matrix coding queries. The crosstab query function was used to explore the number of articles that examined each spatial scale soil carbon management co-benefit (theme), as well as the type of perspective. The matrix coding query function was used to synthesise the coded themes qualitatively for different sections of the article. For example, the matrix coding query separated the 'research focus' of the articles according to spatial scale and identified the associated research focus under those spatial scales (Section 2.3.2).

2.4 Results

2.4.1 Summary of soil carbon management research

This part of the review focused on the 97 articles examining soil carbon management in Australia: 17 papers were reviews and 80 were primary research articles. Examining the spatial scale of the articles, 51 articles were focused on the regional level, 32 articles were focused on the national level, 12 articles were focused on local or farm level, and two articles had no specified level. The highest number of articles for agricultural soil carbon management was at the regional level (Fig. 2.2). Much of the research was initiated at a regional level after the establishment of 57 regional organisations, such as Catchment Management Authorities in 2003 across Australia under the National Action Plan for Salinity and Water Quality. This review identified very few articles that examined soil carbon management at the local level (i.e. farm level) (Fig. 2.2).

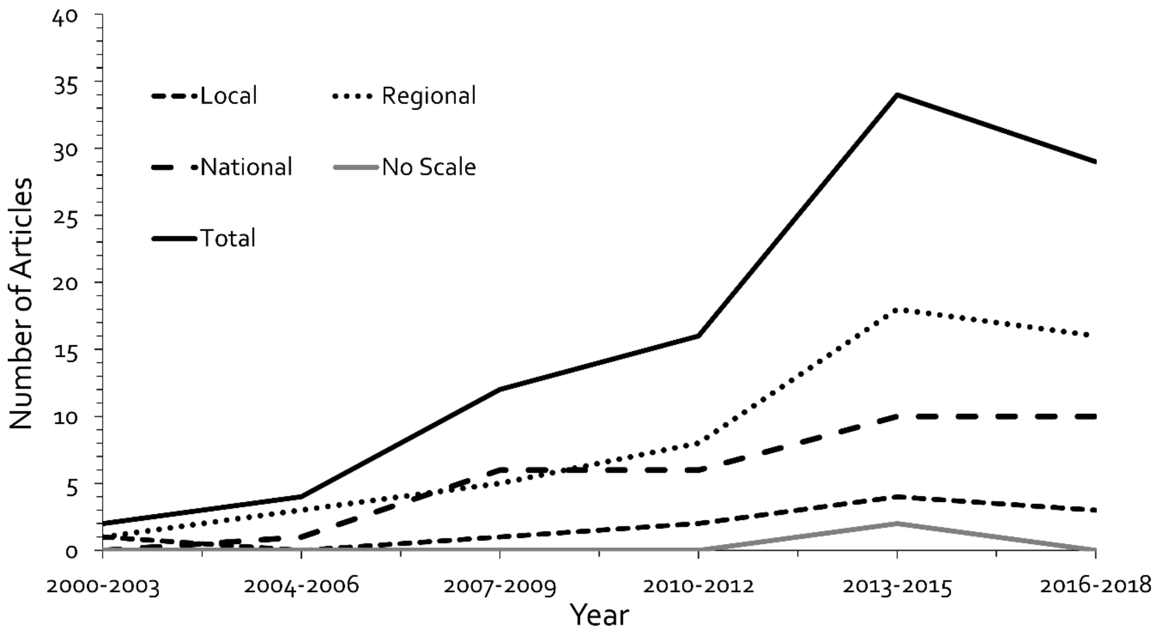

Fig. 2.2. Since 2000, the spatial management levels and temporal distribution of soil carbon management articles from Stage 1 of the systematic review.

Prior to 2011, there were under three articles on research into soil carbon management per annum. After 2011, coinciding with the introduction of the CFI, the number of soil carbon management articles increased to nine per annum. However, research output declined slightly from 2015 after the incorporation of CFI into the ERF (Fig. 2.2). This slight decline in research output might be due to changes in research funding under the ERF and its implementation in 2015 (Fig. 2.2).

2.4.2 Current trends in soil carbon management research

Our systematic review examined the trends in soil carbon management research in Australian agriculture. During the exclusion-inclusion process of our review, we noticed that soil carbon management research in Australia commenced in the early 1970s and was at that time focused largely on defining soil organic matter (SOM) levels in soil. However, the present trends in soil carbon management research are focused on either land use studies or soil management studies in agriculture.

Land use studies were the most prevalent form of soil carbon management research (66 of 97 articles), and consisted of research that focused on particular land use types and the effect of land use activities (e.g. grazing and cropping), policies, and to a lesser extent the influence of socio-economic conditions on soil carbon (Appendix A, Table 2.2). These studies revealed that management practices were less influential than environmental variables (e.g. climate and soil type) on soil carbon stock; however, under long-term management, increases in soil carbon are likely (Chappell and Baldock, 2016; Rabbi et al., 2015). Modelling and auditing of soil organic carbon using the Agricultural Production System Simulator (APSIM) model, Rothamsted Carbon Model (RothC), Agro-C and Full carbon Accounting Model (FullCAM) in order to simulate SOC content in agricultural lands was the most researched topic (21 of 66 articles) (Appendix A, Table 2.2). Australian soil carbon storage practices are focused almost exclusively on agricultural land use and, more rarely, the potential soil carbon storage following reforestation in agricultural lands (e.g. Paul et al., 2016). This type of research assessed the co-benefits of carbon farming and community values on climate change mitigation through soil carbon sequestration in agricultural soils. Other related research on land use studies focused on carbon farming policy, trade-offs and synergies of carbon farming, agricultural production and biodiversity conservation, but to a much lesser extent than other research topics (Appendix A, Table 2.2). Studies on carbon farming revealed that farmers had strong preferences for stubble retention and no till practices as strategies to increase soil carbon (Dumbrell et al., 2016). Australian carbon farming policy needs to focus on carbon farming co-benefits to ensure greater farmer adoption (Evans, 2018), as discussed further in Section 2.3.3.

Soil management studies were less prevalent (35 of 97 articles) and were more focused on the effects of specific soil management practices (e.g. no till, stubble retention, stubble burning, and nitrogen fertiliser) to promote macro-aggregate formation for soil carbon storage (11 of 35 articles) (Appendix A, Table 2.2). For instance, the effect of combined management practices on soil carbon stock, changes in tillage practices and their effect on soil carbon levels, effects of the cropping system or effects of biochar on soil carbon (Appendix A, Table 2.2). Studies on grain cropping systems revealed that the marginal economic value of SOC depends on the crop type and cropping zone, and this economic value was sensitive to fertiliser price (Petersen and Hoyle, 2016; Young et al., 2009). Young et al. (2009) suggested that soil carbon stock may accumulate under a number of years of healthy pasture rotated with no till cropping. However, in the same research in dryland areas with annual rainfall less than 700 mm under continuous cropping, soil carbon stock is unlikely in the short term. Drake et al. (2015) suggested that biochar was found to significantly increase the soil carbon stock (by 15%) in low carbon soils. Over more than 10 years of cotton-wheat rotations with minimum tillage and residue retention (Luo et al., 2016), soil carbon stock increased (Hulugalle, 2008).

We synthesised the research focus of the reviewed articles on soil carbon management associated with certain spatial scales using matrix coding queries (Section 2.2.3). Our review revealed that farm-scale soil carbon management research focused on emission reductions through revegetation (Longmire et al., 2015), tillage and crop rotation effect on carbon sequestration (Hulugalle, 2008) and the importance of management practices, cover crops and pasture for storing carbon (Bajgai et al., 2014; Chan et al., 2011). Regional-scale soil carbon management research focused also on soil management (e.g. zero tillage, conservation tillage), organic amendments (e.g. biochar) (Drake et al., 2015; McHenry, 2009a) and socio-economic and policy variables (e.g. trade-offs between carbon farming and agricultural development, carbon credit and economic return, adoption variables of carbon farming) (Sinnett et al., 2016; Thamo et al., 2013). Regional-scale research also focused on the effect of environmental variables (e.g. soil properties, climate) on soil carbon storage (Rabbi et al., 2015), influencing variables of conservation tillage adoption, farmers' perception of opportunities and constraints to carbon offsets, farmers' valuation of farm ecosystem services and public willingness to pay for carbon farming (D'Emden et al., 2008; Rochecouste et al., 2017). At the national scale, soil carbon management research focused on the effect of native vegetation on Indigenous land across Australia (Renwick et al., 2014), native regrowth and agricultural practice effects on biodiversity (Bradshaw et al., 2013).

2.4.3 SES components in soil carbon management research

The type of research identified in the systematic review mostly concentrated on the ecological component of soil carbon change. The main variables considered were soil type only (48% of articles), climate and soil type together (16% of articles), land use (23% of articles) and climate only (4% of articles) (Appendix A, Fig. 2.2A). The dominant land uses of interest in terms of managing soil carbon levels were cropping (29% of articles), crop and pasture (10% of articles), pasture only (11% of articles) and woody regrowth or forestry (16% of articles). However, land use type was not specified in more than 33% of articles (Appendix A, Fig. 2.2B).

The ecological variables identified in the reviewed articles that limited the amount of soil carbon sequestered under different land uses were soil texture, climate and topography, geographic location, water availability, micro-climate, vegetation types and land use practices (Appendix A, Table 2.3). This review found that these ecological variables dominated the published research on soil carbon management. Many of the variables under the ecological component were examined explicitly by the majority of articles (58). Only 16 articles raised the importance of social variables (Appendix A, Table 2.3), but did not examine these variables in detail and how they were connected to or interacted with ecological variables. The types of social variables that were considered to influence adoption of soil carbon sequestration measures in agriculture were typically policy instruments, farmers' attitudes towards climate change, preference for land use change, farm characteristics, opportunity cost of land use change, financial cost and benefits of soil carbon management, and information on soil carbon management benefit from trusted sources (Appendix A, Table 2.3).

Under half (43%) of the reviewed articles identified the co-benefits of soil carbon management (Fig. 2.3). The co-benefits examined in those articles were from a scientist's perspective (40 articles), and only two articles examined the co-benefits of soil carbon management from a farmer's perspective. Thus, the co-benefits of soil carbon management in Australian agriculture are oriented by a scientific agenda rather than understanding the views and knowledge of farmers (Fig. 2.3). Farmer participation in research was low with only 10% of articles gathering information directly from farmers (eight articles) or using information provided indirectly through use of farmers' fields for sampling (two articles) (Appendix A, Fig. 2.3A). Similarly, 68% of articles examined did not consider farmers' capacity needs (resources, knowledge and skills) when examining soil carbon management (Appendix A, Fig. 2.3B). The ecological and social-ecological components of potential co-benefits of soil carbon management were examined mainly from the scientific perspective, while a farmer's perspective was largely ignored (Fig. 2.4). Of the 43% of research that examined the co-benefits of soil carbon management, most were at the regional level (22 articles) and national level (18 articles), whereas studies undertaken at local or farm level were uncommon. Given that few studies (two articles) involved farmers, the dominant perspective was that of scientists. Thus, the crosstab analysis showed that the co-benefits of soil carbon management did not take into consideration the perspective of farmers in soil carbon management research as limited research has occured at their level (Fig. 2.4), and the results of research conducted at the national and regional levels would be difficult to scale to the level relevant for local application.

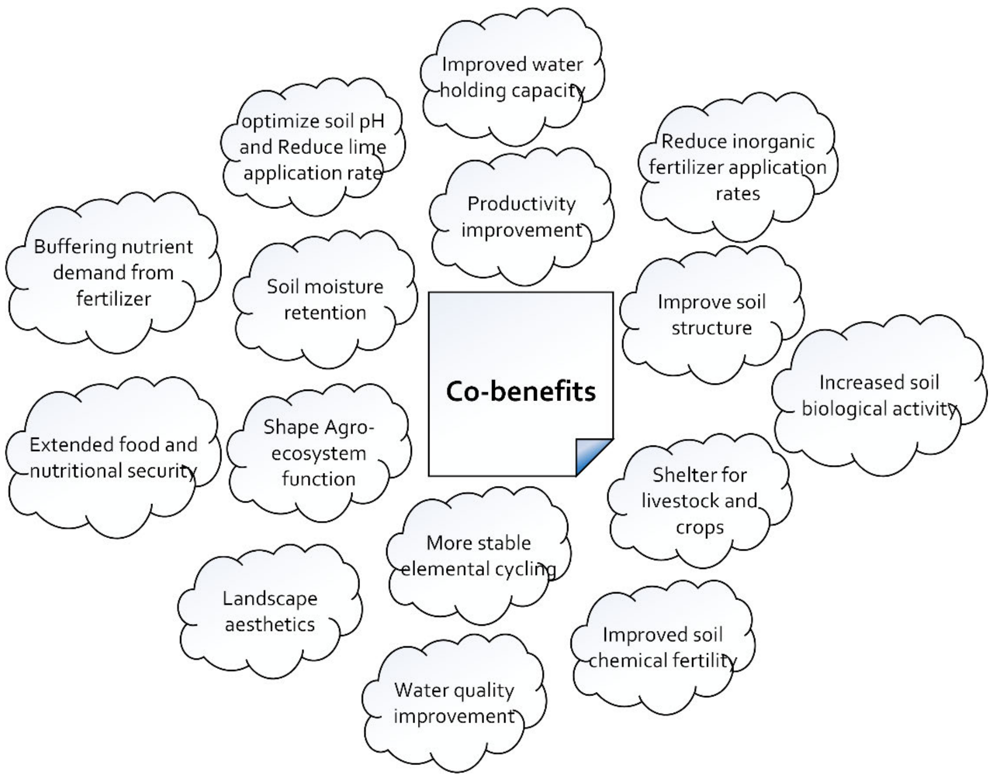

Fig. 2.3. Identified co-benefits of the soil carbon management in Australia from Stage 1 of the systematic review (n=97)

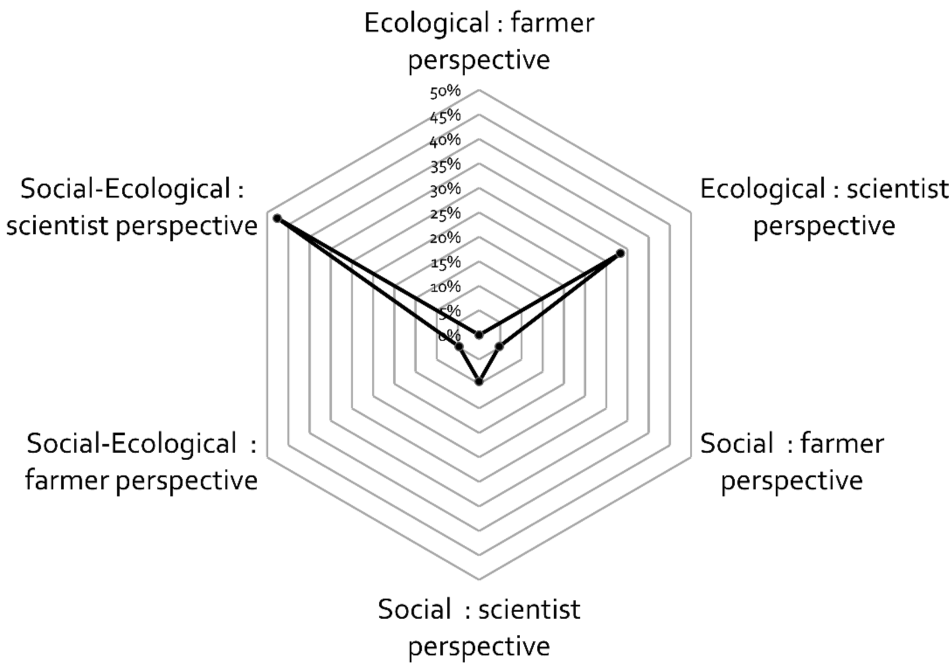

Fig. 2.4. The relationship between a farmer's and scientist's perspective with social-ecological component (ecological, social and social-ecological) in articles identified as examining potential co-benefits of soil carbon management

2.4.4 Knowledge gaps and methodological challenges in soil carbon management research

We identified some important knowledge gaps in soil carbon management research in Australia. There is limited insight into economic benefits after the expenditure of specific carbon management practices (under the CFI), and poor understanding of the cost and benefits of revegetating agricultural land by farmers in relation to carbon storage (Longmire et al., 2015; Rochecouste et al., 2015). Research in Australia on soil carbon management has been initiated for many reasons that are not solely restricted to understanding soil carbon sequestration. For example, research into minimum tillage and fertiliser application focuses more on improvements in soil organic matter levels for soil fertility or erosion control rather than measuring the influence of the practice on carbon stocks in soil (Dean et al., 2012; Wang and Dalal, 2006). Many knowledge gaps regarding the way carbon management practices influence soil carbon storage have meant that there is no consistent or easily generalised statement that can then be communicated to farmers or land managers (such as duration of pasture establishment, forest plantation time) in estimating soil carbon storage potential (Luo et al., 2014; Maraseni et al., 2008).

The funding initiatives for soil carbon storage in Australian agriculture have not considered variation in individual's attitudes to climate change or other demographic characteristics (Evans, 2018; Grundy et al., 2016); however, these attitudinal variables (e.g. how farmers perceive how soil management and climate change interact with carbon flows) need to be considered for the adoption of soil carbon sequestration measures by farmers (Page and Bellotti, 2015).

Another major gap in soil carbon management research in Australia is the level of stakeholder involvement in experimental examination of ways to improve soil carbon storage (Kragt et al., 2012; Longmire et al., 2015; Morán-Ordóñez, 2017). Carbon models like FullCAM need to be validated for local-level application, different plant species and local environmental conditions (George et al., 2012). In reality, such models make numerous assumptions (some not validated), which might not reflect the reality of the farm (Kragt et al., 2012; McHenry, 2009a; Sarker et al., 2018).

The lack of stakeholder involvement is a reflection of research methodology. The dominant method was ecological (including field experiments, soil sampling and laboratory analysis, and modelling), with 82 articles, while methods employing social techniques (e.g. survey and interviews) only numbered 12 articles. Research was also categorised according to spatial scale of application. Research conducted at local or farm level using only social methods was represented by one article. For ecological methods, the research results focused on regional and national level spatial scale implications. For example, research based on field experiments was dominated by regional and national level studies (45 articles). Modelling was used in 12 articles, which focused on data collected and presented at the regional and national level. Overall, the emphasis on local-level studies, and therefore results relevant to farmers on soil carbon management, is low.

One of the major methodological challenges identified from the articles reviewed was the difficulty in demonstrating the impact of CFI-prescribed soil carbon management practices on the accumulation rate of soil carbon. SOC was measured under a range of long-term agricultural experiments (15–34 years) in Southern New South Wales (Conyers et al., 2015). This research showed the accumulation rate of SOC under permanent pasture only increased modestly, while zero tillage and retention of crop residue resulted in no significant gains (Conyers et al., 2015). Modelling research on the contribution of above-ground biomass through woody re-growth found variations between stand age and density, but they could not identify a difference in soil carbon stock (Dwyer et al., 2010). In addition, the ability to explain the drivers of SOC variations at a regional level are often hindered by lack of historical land management information (Macdonald et al., 2013).

The mechanism for accounting for soil carbon sequestration in any carbon mitigation payment scheme is highly challenging because rates of sequestration depend on several edaphic and climatic variables acting at various spatial and temporal scales. Geographic Information System (GIS), Remote Sensing (RS), Soil Spectroscopy and Digital Mapping are tools that can be used to model and predict the potential carbon storage across the landscape. However, all of these approaches were used to examine the ecological components alone and their interactions aimed at building soil carbon, and did not include the influence of social variables such as level of adoption (Page et al., 2013; Sarker et al., 2018; Scarlat et al., 2019). Moreover, the adoption of tillage practices is governed by socio-economic variables again working on various spatial and temporal scales (D'Emden et al., 2008; Maraseni and Cockfield, 2011). The methods of measuring and comparing the monetary value of non-traded co-benefits are unavailable and therefore not included in auditing or trading of carbon credits (Kragt et al., 2016). Farmers in Australia are, on average, in their late 50s (Dumbrell et al., 2016) and interested in carbon farming initiatives. However, farmers having an interest in adopting these prescribed practices and making contact with those undertaking them did not necessarily translate into implementation (Dumbrell et al., 2016). Thus, the adoption of carbon farming initiatives for long-term income generation is challenging. The adoption of appropriate carbon farming practices and auditing methodologies that are low cost and socially acceptable is necessary if changes to current farming systems are to be made in order to improve soil carbon management (Verschuuren, 2017).

2.4.5 Use of the SES concept in soil carbon management research

From Stage 1 of the systematic review, we found only one article that discussed the importance and need for an SES for soil carbon management in Australia. Van Oosterzee et al. (2014) argued that an SES can be a useful tool to manage slow variables such as soil carbon at a landscape spatial scale for an integrated management approach. This article also highlighted the need to consider the components of the SES and their influence on the whole system. We extended our systematic search to Stage 2 where we considered the conceptual SES framework and its use in soil carbon management research across the world (Appendix A, Table 2.1). Our systematic review revealed that SES and soil carbon management is still an unexplored area of research, and only four articles were found that met our search criteria. Indeed, these articles merely identified the need for a conceptual SES framework and did not themselves analyse soil carbon management using both social and ecological components and the variables within them. However, these articles did cover comprehensively the variables of soil carbon management identified through this review (Table 2.1). Guto et al. (2012) investigated two soil management practices – tillage and crop residue retention – in a continuous cropping system as socio-ecological niches, where soil organic carbon content was one of the measures of soil fertility. The remaining three studies focused on the interactions between physical and human variables such as co-operative management of shade trees and its effect on soil carbon, land degradation (e.g. soil erosion) through land use, context of crop residue biomass and smallholder livestock system (Karamesouti et al., 2015; Méndez et al., 2009; Tittonell et al., 2015).

Table 2.1. Social-ecological systems components, key variables and example of potential indicators of soil carbon management

System component	Key variables	Potential indicators	References
Ecological	Climate	e.g. Temperature, precipitation, humidity	(Gray et al., 2015; Rajput et al., 2017; Xu et al., 2017)
	Soil Properties	e.g. Clay fraction of soil, soil type, soil pH	(Angst et al., 2018; Davy and Koen, 2013)
	Soil Biodiversity	e.g. Vegetation type, soil biota e.g. earth worm	(Angst et al., 2018; Davy and Koen, 2013)
Social	Governance and Policy	e.g. Subsidies for production loss, assurance of payments	(Dumbrell et al., 2016)
	Carbon Markets	e.g. Agri-environmental payments, economic return for carbon management, cost of land conversion, carbon pricing	(Kragt et al., 2016)
	Society and Culture	e.g. Individual behaviour and attitude, socio-cultural values, soil carbon management of individuals	(Dumbrell et al., 2016)
Social-Ecological	Land Use	e.g. Cropping, mixed cropping, agroforestry, native forest	(Forouzangohar et al., 2014; Renwick et al., 2014)
	Ecosystem Benefits	e.g. Water holding capacity, plant productivity, enhanced nutrient availability for plants	(Grace et al., 2010; Maraseni, 2009)
	Soil Carbon Management	e.g. Incorporation of residues, crop rotation, biochar, changing tillage practices	(Rochecouste et al., 2015)

2.5 Discussion

2.5.1 Opportunities for soil carbon management research

Soil carbon sequestration potential in Australian agricultural soil is difficult to document because of the time frame over which soil carbon changes (Hoyle et al., 2013) and our limited understanding of how actions at the local level can influence soil carbon sequestration. Despite these challenges, determination of a specific target for carbon storage in a global context is crucial. The science would suggest that not all sequestered carbon has the same stability, and the variables of SOC also vary at a local, regional and national level (Macdonald et al., 2013). This complexity is further compounded by a lack of understanding of the quantity of carbon that is stored in soil and how rapidly it can be stored under modified land management practices at the local level. Because of the uncertainty of carbon sequestrations, determining the co-benefits of soil carbon sequestration is important for improving adoption of soil carbon management by farmers. The narrative around carbon sequestration is that farmers are motivated by production benefits and that taking action on soil carbon has the potential to improve system profitability. Consequently, the crucial gap in soil carbon management research is identifying what the social and ecological variables are and their interactions (cross-scale and cross-level) to capture the complexity of the interactions between the social and ecological components that are critical to soil carbon management in the agricultural field. Furthermore, understanding how these interconnections in an SES affect soil carbon management and farmers' capacity to manage it could help farmers to manage soil carbon.

Future research questions would be: What are the practical ways to quantify the market value of co-benefits? How does the provision of information influence social-ecological variables to improve farmers' capacity to manage soil carbon? The next major challenge is therefore the availability or accessibility of farm-level social and ecological data. Soil carbon data and its relationship with social information needs to be more fully developed to clarify its influence on agricultural and environmental variables (Sarker et al., 2018). For example, few articles examined the social component and variables in carbon payment (for increasing carbon storage in the soil) in order to understand better the mechanism and its likelihood of success. Research needs to focus on those farmers already involved in implementing farming practices, particularly within carbon farming initiatives or emission reduction fund schemes, and the impacts on soil carbon and farming system resilience.

Uncertainty about the carbon farming policy, reliable information about soil carbon storing potential of certain soil carbon management practice, and more importantly, lack of good scientific extension of carbon sequestration co-benefits leads to a lower rate of adoption of prescribed soil carbon management in Australian agriculture (Evans, 2018; Rochecouste et al., 2017). Overcoming the above major challenges and effective adoption of carbon management practices at the farm level leads to other questions: What would be the conceptual SES framework in relation to soil carbon management in Australia? What tools are available to change soil carbon management practices in Australia? Future proposed approaches to soil carbon management in Australian agriculture will require effective policy formulation that understands the farmer demand-based incentives for sequestering carbon, which in turn can be supported by research, development and extension on those practices (Longmire et al., 2015).

2.5.2 SES components and underlying variables for soil carbon management

In our proposed SES framework, the system components are social, ecological, and ecological and social as defined in the methodology, with ecological and social components as the focus of soil carbon management (Fig. 2.5). The framework was influenced by the original concept of Ostrom (2007, 2009). The ecological and social components both interact with the centre panel of the social-ecological component of the framework (Fig. 2.5). In this SES framework, the components have key variables that influence soil carbon management in Australia (Fig. 2.5). Key variables are the high-level drivers of soil carbon management that were identified in our systematic review and are aligned under the relevant component but also interact with other variables in the SES framework (Fig. 2.5). We have provided some example indicators that could be measured to determine the influence of these key variables on soil carbon management (Table 2.1).

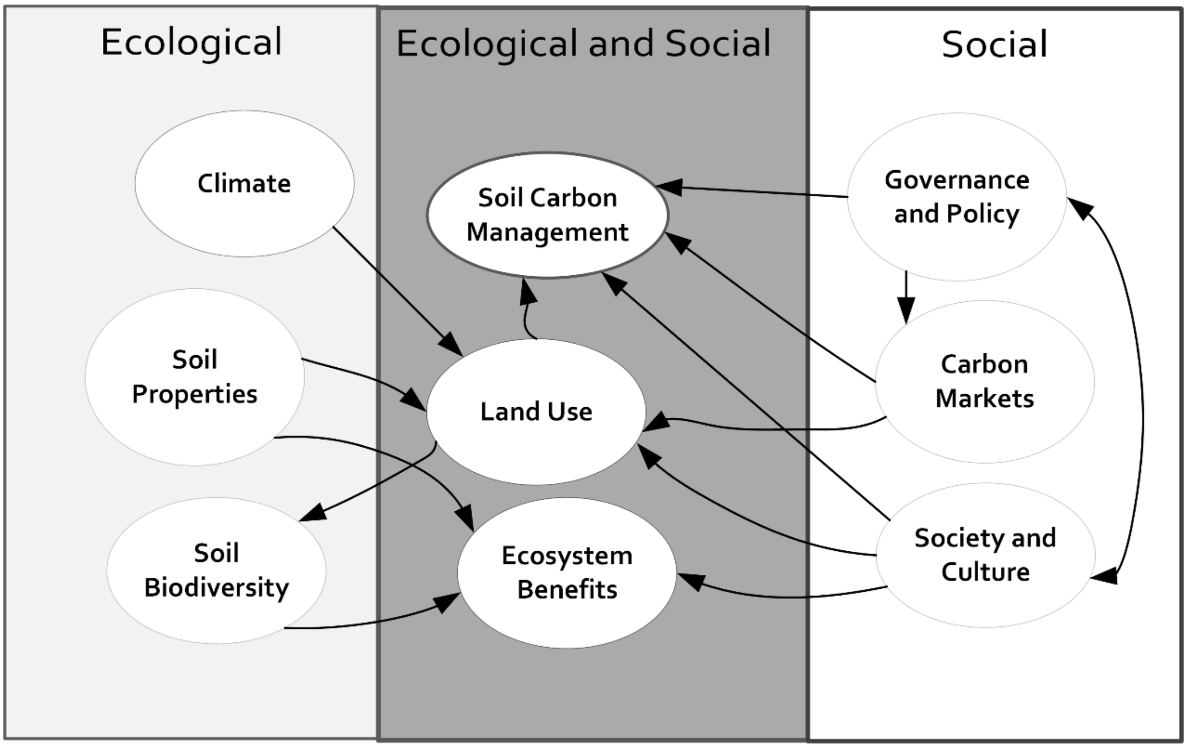

Fig. 2.5. Social-ecological system key components (ecological, social, ecological and social), with corresponding key variables (e.g. climate, land use and society and culture) and proposed interaction of key variables for soil carbon management in Australian agriculture (n=97). Direction of arrows indicates a potential interaction between key variables and could be a positive or negative relationship.

The SES framework portrays the likely direction of interactions between key variables within and between components, and was identified through authors' discussion and supported by the literature (Fig. 2.5). A number of key variables, such as land use (e.g. cropping, mixed cropping, pasture and agroforestry), interact with soil carbon management. For example, sites under continuous cropping have less carbon stock than perennial pasture (Cotching et al., 2013), while woodland and improved pasture have high carbon stocks (Rabbi et al., 2015). Land use interacts with other key variables under ecological components such as climate, soil properties and soil biodiversity (Fig. 2.5). A possible interaction between land use and soil biodiversity is, for example, native tree planting in agricultural lands supporting greater soil biodiversity (Bradshaw et al., 2013). Soil properties, which is a key variable under the ecological component, can influence ecosystem benefits (e.g. co-benefits of soil carbon management), while degradation of soil properties can result in loss of ecosystem benefits (Forouzangohar et al., 2014) (Fig. 2.5). Key variables under the social component include governance and policy settings, carbon markets and society and culture. Carbon markets and governmental policy will, over time, influence the land use variable. Potentially, government policy on soil carbon management and carbon markets along with socio-cultural beliefs will affect soil carbon management in Australia (Fig. 2.5). High levels of policy awareness and an active stance on climate change will diminish uncertainty over potential soil carbon management practices.

The proposed SES framework does not consider the spatial and temporal scales over which the system components would operate. Besides this limitation, this SES framework and its components can be used to explore the key variables under the social, ecological and social-ecological components that will guide the design of an operational SES framework for Australian agriculture. However, a prerequisite will be to explore the interactions between the social, ecological and social-ecological components by examining a range of available data on soil carbon management across multiple levels and contexts.

2.6 Future implications and conclusion

The increasing exponential rate of scientific studies is expanding our knowledge on soil carbon management research. However, there are a number of areas that need to be addressed in future research. In summary, they include the economic benefits of carbon management and the short- and long-term social and ecological benefits of soil carbon management. In particular, we need to improve knowledge on the way carbon management practices influence soil carbon storage and reduce the difficulties (e.g. duration of pasture establishment, forest plants plantation time) in estimating the carbon storage potential. Future research on soil carbon management needs to integrate social variables from the social components of an SES, such as individuals' attitudes to climate change or demographic characteristics, which could influence the adoption of soil carbon sequestration measures by farmers. The engagement of stakeholders in experimental examination would improve soil carbon management in Australia given the low farmer involvement. In tandem with finding ways to engage stakeholders, principally farmers, in soil carbon management research, a more concerted research effort is needed to overcome the challenges of a new technology or methodology of agricultural practices being socially acceptable to farmers. In reality, agricultural soil carbon management adoption and long-term use of those practices that build soil carbon relies on landholder interest and understanding of the implications from data collected at local or farm level.

The review has also revealed that the research has predominately focused on the ecological component of soil carbon management in agricultural land use types, and has been conducted from a scientists' perspective. The sustainability of carbon-building soil management practice will require integration of social components into future research, particularly from a farmer perspective, with site-specific and context-specific information. We made a first attempt at proposing a conceptual SES framework, which may provide guidance as to how the components can be established through their specific social, ecological and social-ecological indicators (see Table 2.1). This simple representation of the complex social-ecological components of soil carbon management in Australia might facilitate a change in the current approach to soil carbon management. Future research may include the extension and operationalisation of the SES conceptual framework and could examine the dynamics (e.g. interactions and feedbacks) of the complex system. The SES framework, once operational, may help to assess the interdependencies of both social and ecological components of soil carbon management, and hence ensure the sustainability of an SES, which may enhance the process of achieving SDGs such as offsetting carbon emissions.

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Type of Work	Page number/s
Text	27- 48
Fig. 2.1	33
Fig. 2.2	35
Fig. 2.3	39
Fig. 2.4	39
Fig. 2.5	46
Appendix A, Fig. 2.1	156
Appendix A, Fig. 2.2	156
Appendix A, Fig. 2.3	157

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Chapter 3

Revealing the social-ecological relationships affecting farmers' current soil carbon management in Australian grazing lands

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3.1 Abstract

Soil carbon sequestration is a way of offsetting GHG emissions, however, it requires agricultural landholders to be engaged in the policy initiative for the quantification of the amounts being sequestered, and this engagement is currently low. By understanding experienced farmers' current social-ecological system (SES) of soil carbon management (SCM) in grazing lands, it will identify those areas that affect their potential engagement in such policy initiatives. This study used a novel approach by operationalising Ostrom's SES framework to identify the current SES features of SCM in high-rainfall grazing lands of New South Wales, Australia, using qualitative and quantitative methods. Utilizing Ostrom's SES framework categories of resource system, resource units, governance, interaction-output and actors 51 SES features of SCM were identified by farm-level interviews. In the current SES of SCM the connectivity among the SES features was 30%, which is relatively low compared with an ideal, fully-connected social network. In stakeholder workshops, consensus was reached on the relationships (e.g. interactions, feedback loops) between specific SES features that were considered to influence SCM. The SES had 10 critical feedback loops, with policy settings and instruments not positively affecting SCM practice. The methodological approach demonstrated that the SES framework can define the current SES for SCM. Defining the SES relationships in SCM can identify the gaps, challenges and needs of stakeholders, particularly farmers, which can then be addressed to achieve local, national and international objectives, such as SCM co-benefits, GHG reduction, carbon sequestration targets and SDGs.

Key words: Social-ecological system; Agri-environmental benefits; Soil carbon management, Australian grazing lands

3.2 Introduction

Sequestering carbon in soil is a key response to mitigating climate change (Bossio et al., 2020; Frank et al., 2017) and agricultural soil carbon management (SCM) holds much promise in this regard (Amin et al., 2016; Sykes et al., 2020; Yang et al., 2019). Farmers' ability to sequester soil carbon will depend on various biophysical and socio-economic factors in their management environment (Bossio et al., 2020). In addition to emissions reduction goals, SCM can provide a range of co-benefits, such as improved water-holding capacity, soil fertility (Frank et al., 2017; Zomer et al., 2017) and productivity (Branca et al., 2013). Land-based SCM could reduce carbon emissions by 23.8 Gt CO_2–equivalent per year (25% contribution to emissions reduction) (Bossio et al., 2020; Lal, 2004). A number of international and national initiatives highlight the importance of SCM for mitigating climate change, including the COP21 initiative to increase soil organic carbon stocks by 0.4% per year (Minasny et al., 2017; Rumpel et al., 2018) and the Australian Government's Emission Reduction Fund (ERF) program (Australian Government, 2020; Verschuuren, 2017). Co-benefits from SCM could also address several UN Sustainable Development Goals, including Zero Hunger (SDG 2), Climate Action (SDG 13) and Land Degradation Neutrality (SDG 15.3) (Amin et al., 2020; Kust et al., 2017), and help to build political, financial and technical momentum to address these goals (Vermeulen et al., 2019).

To study the complex relationships and draw lessons for ecosystem resilience, Ostrom (2007, 2009) proposed a social-ecological system (SES) framework that recognises that the social and ecological features of a system are interconnected. This SES framework has been used to understand the complexity of regional sustainability (Hossain et al., 2020b; Hossain et al., 2020a; Willcock et al., 2016) and the impact on ecosystem services (Hossain et al., 2016; Hossain et al., 2017), transformation systems and product accommodation (Marshall, 2015), and fisheries and water management (de Wet and Odume, 2019; Galappaththi et al., 2019). A systematic review of SCM research in Australia found a limited understanding of the type of SES features and how they interact to influence Australian farmers' soil carbon management (Amin et al. 2020). In addition, the review also found that the analysis of SCM using a SES approach had yet to be undertaken internationally (Amin et al., 2020). The majority of scientific studies, in Australia, emphasised soil carbon accumulation processes and ecological triggers or settings for soil carbon improvement, with little consideration of farmers' perspectives or identification of the influential socio-ecological features in SCM (Amin et al., 2020). Due to scant research in this area, understanding the SES features of SCM and their relationships is limited. This research will reveal the SES of SCM, and highlight where farmers' SCM can be supported or where policy settings need to be altered to encourage other farmers to manage soil carbon.

Due to the dominance of cattle and sheep grazing enterprises in Australia (around 336 million hectares or 50% of land area) (Climate Work Australia, 2021) it is important to undertstand the potential for offsetting GHGs through sequestering carbon in grazing lands especially in summer-dominant rainfall zones with high vegetation retention (de Otálora et al., 2021; Reich et al., 2020; Rey et al., 2017). By involving long term practitioners of SCM in grazing lands it will identify those features that influence their current SCM and where soil carbon policy initiatives can affect the potential engagement of other farmers with less experience in SCM. This study examines for the first time the current SES for SCM by applying Ostrom's SES framework to high-rainfall grazing systems in northern New South Wales, Australia. Our study focused on the following questions:

1. What are the current social and ecological features that influence SCM at the farm level?
2. How do these features interact to influence farmers' SCM?
3. What type of feedback loops operate among these features?
4. What are the implications for farmers and policymakers of the current SES of SCM?

Section 3.3 introduces the conceptual framework, the methodological approach for unravelling the interconnectivities and interrelationships of the SES features, and the study area. Section 3.4 discusses the context of the connectivity between the SES features of SCM (Section 3.4.1), stakeholders' perspectives of social-ecological relationships (Section 3.4.2) and the interaction and feedback in the SES for SCM (Section 3.4.3).

3.3 Methodology

3.3.1 Study area

The farms are located in the Northern Tablelands and Upper Hunter regions of New South Wales (NSW), Australia (Fig. 3.1). Farms are predominately perennial native pastures or a mix of native and introduced perennial pastures with high ground cover throughout the year (Alford et al., 2003). In this area, 68% of land is occupied by agriculture (2.11 million ha), with an estimated agricultural commodity value of $217.8 million. Sheep and cattle grazing are the dominant agri-enterprises, contributing 86% of the total value. Wool and meat (beef and lamb) are the dominant products at 41.7% and 44.5%, respectively (Alford et al., 2003). Farms are located across a broad plateau that ranges in altitude from 750 to 1200 metres above sea level and is in a temperate climate zone where more than 60% of the annual rain falls over summer, which is the peak plant-growing season. Maximum temperatures usually remain below 30° C and annual mean minimum temperatures are around 7° C (Lodge and Whalley, 1989). Average annual rainfall is 750–800 mm with frequent seasonal droughts (1:3.5 years) and less frequent serious droughts (1:10 years) (Alford et al., 2003; Wilson and Lonergan, 2014). Farms are either located on low-fertility soils (granite and sedimentary geology; Chromosol), or comparatively fertile soil (basalt geology; Ferrosol and Dermosol) (Office of Environment and Heritages, 2018).

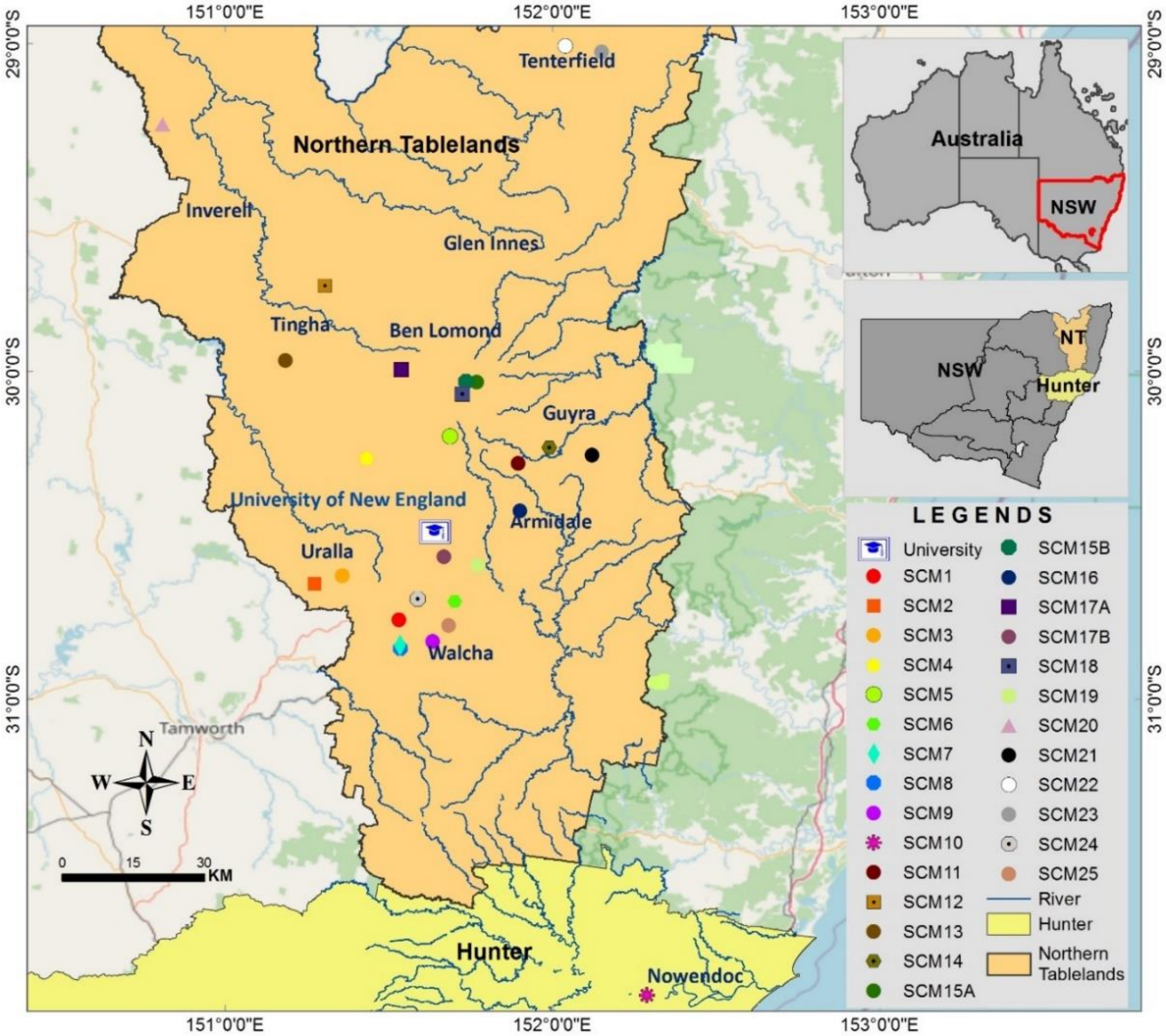

Fig. 3.1. Farm locations in the study area. The abbreviation SCM followed by a number denotes anonymous farm identities, and a letter after a number indicates that those farms are owned by the same farmer (e.g. SCM17A, SCM17B).

Given the favourable climatic conditions, lower land clearance and dominance of grazing agricultural practices, we regard the study area as having medium to high potential for achieving the benefits of SCM, namely offsetting GHG emissions and restoring soil health (Waters et al., 2020; Wilson and Lonergan, 2014). Australia-wide, the high-rainfall zone where there is grazing of modified pastures occupies 71 million ha, and the findings of this research will also have broader relevance to those areas (Australian Government, 2016).

3.3.2. Overview

We used quantitative and qualitative research methods (Appendix B, Fig. 3.1) were employed in four consecutive steps to reveal the SES of SCM for grazing farmers in the study area: (i) Semi-structured farmer interviews for identifying the SES features of farmers' SCM with higher level categories defined by Ostrom's social-ecological system (SES) framework (ii) The farm interview data was used to analyse the interconnectedness and importance of the SES features of farmers' current SCM using Network Analysis (NA); (iii) The features identified from the farmer interview and NA were presented in a number of separate farmer and service-provider (Box 3.1) workshops where the participants developed a SES of SCM; and (iv) finally a consolidated SES for SCM that integrated the farmer and service-provider workshop outcomes was developed. The human research ethics component of the research was approved by the University of New England, Australia (Approval No. HE19-149).

3.3.3 Data collection and analysis

3.3.3.1 Ostrom's social-ecological system (SES) framework

Ostrom argued that social-ecological relationships are complex and can only be understood by examining the whole system as an interconnected set of features (Rocha et al., 2020). This study used Ostrom's SES framework, network analysis and a participatory approach to illuminate the SES relationships in SCM in the case study region. The system boundary for the SCM SES is the agro-ecological region of the Northern Tablelands and into the Upper Hunter Valley, NSW, Australia (Fig. 3.1). We utilised Ostrom's (2007, 2009) five higher-level categories (Appendix B, Fig 3.6) i.e. resource system, resource unit, governance, actors, and interaction-output to organise the features of farmers' SES for SCM. In this study, the resource system features focus on the size, productivity, location and predictability of the system dynamics, and the resource unit features define the growth rate, economic value and spatial and temporal distribution of the resources. The governance and actor categories are about government and non-government organisations, monitoring rules, policy and operational rules, relevant actors, the trust and attitudes of the actors and the social networks. Interaction-output organise the features according to the product of the social or ecological interactions in the resource units (e.g. efficiency, sustainability). Exploring the SES using Ostrom's framework is an approach to understanding the complex characteristics of a system and the relationships (e.g. interactions and feedbacks) between the SES features. Using this approach, this study unpacked the complex interrelationships of the SES for SCM in the grazing lands of Australia.

3.3.3.2 Farm-level interviews

Applying this approach to the semi-structured interview schedule design enabled a structure that would allow sub-themes to emerge but framed around accepted SES higher-level categories. Semi-structured interviews with case study farmers (n=25) were conducted between November 2019 and February 2020. The interview schedule was pre-tested with several long-term practitioners of rotational grazing from the study region, and with an agricultural consultant verify the list of SCM practices. Similar SCM practices were identified by Dumbrell et al. (2016) although the practices were for mixed crop-livestock and cropping-only farmers in low rainfall, dryland environments. Interviewees were purposively selected with the assistance of two intermediaries (Local Land Services, a government natural resource management agency, and Southern New England Landcare, a local non-government 'Landcare' group). Inclusion criteria were farmers who had at least five years' experience implementing at least two types of SCM practices as identified by Dumbrell et al. (2016) (Appendix B, Box 3.1). The identified SES features of SCM in this study were from farmers in the district who were chosen because they were highly experienced in grazing management at farm-level and were operating under similar environmental conditions.

The interview questions were open-ended and designed to draw out the SES features of SCM under each of Ostrom's higher-level categories (resource system, resource units, actors, governance systems and interaction-output) (Appendix B, Fig. 3.6) (McGinnis and Ostrom, 2014; Ostrom, 2007, 2009). The questions canvassed three aspects of the farming operations: (1) demographics (age, gender, education, farming experience, farm debt status, soil types, farm type and proprietorship); (2) farm features and their interrelationships; and (3) directional soil responses (soil pH, soil moisture, soil structure and nutrients) to SCM practices (increase, decrease). The interviews lasted up to 90 minutes and were recorded and transcribed. The features were thematically coded from any part of the interview using NVivo 12 Plus under the five higher-level categories (resource system, resource units, actors, governance systems and interaction-output) into sub-categories based on Ostrom's definitions (McGinnis and Ostrom, 2014; Ostrom, 2007, 2009). This process of thematically coding was over multiple readings of the interview transcript. The structure and organisation of the interview schedule was based on Ostrom (2009), and responses of the farmers to the interview questions were used for the identification and placement of SES features of SCM. Final lists of SES features for SCM were drawn from the detailed farmers' interviews and discussion at the farmer and service provider workshops (section 3.3.3.4).

Table 3.1. Soil carbon management (SCM) features based on stakeholders' interviews

System component of SES	Features
Resource System (RS)	Geographical location
	Size of the farm
	Number of farms under farming
	Farm type (e.g. grazing)
	Proprietorship (e.g. family farm)
	Loan status
	Soil type (e.g. fertile/non-fertile)
	Soil health
Resource Units (RU)	Production potential
	SCM practices
	Climate
	Change of income
	Agri-environmental benefits
	SCM cost
Governance (G)	Support of government organisations
	Support of non-governmental organisations
	Own farm research grant
	Scientific support (e.g. soil test support)
	Government investments
	Private investments
	Carbon pricing and monitoring
	Certainty of payment
	Training and education support

Governance (G)	Expert information (e.g. reliable scientific information on management)
	Soil carbon policy
	Social network (e.g. horizontal/vertical)
	Trusted expert network
Actors (A)	Government officer
	Independent advisors
	Farmers
	Scientists
	Education institute
	Soil stewardship ethics
	SCM attitude
	Technologies available
	Trust
Interaction-output	pH level
	Soil moisture
	Soil structure
	Soil biodiversity
	Landscape aesthetics
	Soil water-holding capacity
	Soil erosion
	Soil nutrients
	Soil carbon content
	Mental health
	Shelter for livestock

3.3.3.3 Network analysis

The features that influence the connectivity were based on the farmer interviews coded from the previous step (Appendix B, Table 3.1). We performed network analysis to determine the current connectedness and influence of the 51 SES features of SCM, and generated a causal loop relationship diagram. One-mode networks (defined in Box 3.1) were used to visualise the connections among features for all farms. This process identified the SES features of SCM; namely, the co-benefits of SCM, SCM cost, SCM practices and positive outcomes (e.g. farm production) (Dumbrell et al., 2016; Kragt et al., 2016). Two-mode networks (see Box 3.1) visualise how the SCM features are connected to each other in the network and how farms are connected to each other on the basis of these SCM features. In other words, two-mode networks depict the closeness of the features in relation to the farms in the network.

In this study, a one-mode network was used to visualise the connections among Ostrom's five higher-level categories of socio-ecological features of SCM, and a numeric distribution network was produced based on farmers' reflections on the features that influence SCM in the study area. We studied specific responses from farmers on each feature they identified and translated these to a specific code to assign a weighted number ('1' or '0'). Positive responses were assigned as '1' and negative response were assigned as '0' to determine the influence of the 'interaction-output' features on other higher-level category SES features within the network. For example, when a farmer responded that an SCM practice has increased because of its positive effect, that outcome was coded as 'positively reinforced' and assigned a value of '1'. Also, the farmers' positive responses to the question of production optimisation from using an SCM were coded as 'yes' and assigned a value of '1' (Appendix B, Table 3.2). Features with multiple response options (e.g. size of the farm, number of farms under farming, farming type, proprietorship, loan status) were used to examine the numeric relationship of the response with the outcome and resource unit features in the network (e.g. number of small farms that agree improvements in nutrient cycling were due to SCM practices and/or improvement in soil health) (Appendix B, Table 3.2).

In the final network diagram for this study, each of the SES features of SCM are represented as nodes (e.g. soil health, production potential). The lines that connect one feature to another feature are referred to as 'edges' (Box 3.1). A one-mode network was constructed on the basis of a positive connectivity having a thicker line (e.g. SCM practices induced soil erosion control, which increased the adoption of SCM practices) and a negative connectivity having a lighter line (e.g. less understanding of soil biodiversity change leads to less adoption of SCM practices) (Appendix B, Tables 3.2 and 3.3). The width of the edges indicates the weight of the responses (e.g. number of farm responses on each connection). For both of the networks, the number of connections for each node represents the likely connectivity of that feature in the network. We analysed the density of the network to reveal the strength of the connectivity of the SES features of SCM in the study area. We used the package 'igraph' in RStudio version 1.1.456 to analyse network properties and visualise the network diagrams, broadly following Ognyanova (2016), Rocha et al. (2020) and Rocha et al. (2015).

The determination of these relationships was based on NA at the farm level of information drawn from the interviewed farmers. The higher the connectivity, the stronger the relationships and vice versa. The ecological and topographic conditions of the farm such as geographical location, climatic condition and soil type were predetermined features as they are contextual. The nature of relationships (weak, strong and predetermined) between features using the NA were visualised in a causal loop map using the system dynamic (SD) modelling platform STELLA version 1.8.2 (Fig. 3.3).

3.3.3.4 Stakeholders' workshop

Once the features of the SCM SES were identified from the farmers' interviews, the relationships (interactions and feedback loops) between them were examined through participatory workshops with farmers and service providers, without revealing the previous network analysis (Ford and Ford, 1999) (Ford and Ford, 1999) (Appendix B, Fig. 3.1).

Workshops (n=4) were organised between October and December 2020 in locations that were convenient for participants. Each workshop had four to six participants and lasted about 180 minutes. Participants were of mixed age (26–79 years). The workshops were repeated for both the service providers (n=2) and farmers (n=2) to ensure saturation of information and to minimise redundancy and disagreements. Separate workshops for farmers ensured that the perspectives of the service providers did not dominate the farmers' deliberations. The participants in the service provider workshops were all science-trained to tertiary level and were currently working in a role as agronomist and/or scientist for government (e.g. Department of Primary industry, Local Land Services) and non-government organisations (e.g. SNLC, Precision Pasture Armidale), and agricultural system's educator. Participants were allocated sufficient time to discuss their opinions on the features, interactions and feedback loops. To facilitate comparison between workshops, we used the same facilitator, structure, timing and list of SCM features derived from farmer interviews.

At the workshops, we presented the list of SCM features that were the product of the farmer interviews, to participants, who reviewed the list individually. Participants were asked to retain features that, in their experience, help or hinder their current ability to manage soil carbon at farm level and to discard features that neither helped nor hindered. A working list of the features retained was assembled on the basis of overall group discussion and consensus. Participants then collectively mapped the interactions among the agreed features. The direction of the interaction was indicated by arrows and participants conferred amongst each other as the nature of the interaction was positive or negative. At the end of the workshop, feedback loops were identified as either reinforcing or balancing (Box 3.1, Table 3.2).

We compared the resulting SES for SCM from each workshop for similarities, differences and redundancies. Finally, the SCM interactions were consolidated and visualised using the system dynamic (SD) modelling platform STELLA version 1.8.2.

3.4 Results

The interviewed farmers were all undertaking two to three SCM practices, with the average length of experience at 26 years. More than 50% of the total studied farms were dominated by perennial native pastures. Most farms (55%) are located on low-fertility soils and the remainder (45%) are comparatively fertile soil. The farmers interviewed were of mixed age (40–79 years), managing predominantly grazing enterprises, with 70% of farms being more than 500 ha and commercially operating (Appendix B, Table 3.8). This process of qualitatively coding the farmer interviews identified 51 SCM features of SCM in the studied grazing regime (Table 3.1).

3.4.1 Social-ecological networks

The network diagrams (Fig. 3.2) present features as nodes (n=51) (Table 3.1) and interactions as lines between nodes (n=483). High frequency occurs where many lines emanate from one node to many other nodes, and high density occurs where there are many connections between two specific nodes. The one-mode network analysis is shown in Fig. 3.2A. The size of the node indicates the strength or importance of the features to the network. The most important features in each of the five higher-level categories were optimised production potential, SCM practice (resource unit), soil health (resource system), independent advisors, trust, farmers (actors), training and education support, social network, scientific support, non-government organisation (governance), soil moisture and soil structure (interaction-output). Overall, the strongest set of features were within the interaction-output category (soil moisture and soil structure) and the resource units category (SCM practices and cost and agri-environmental benefits). SCM practices was a prominently connected feature in the network (n=23), and was highly influenced by positive SCM outcomes (e.g. improved soil health and soil moisture). The network importance of other resource system features such as proprietorship (e.g. family or company farm), debt status (in-debt or debt-free farm), soil type (high or low fertility) and farm type (e.g. grazing) could not be determined. Geographical location (resource system) had a weak connection to a farmer’s SCM and a predetermined relationship (Fig. 3.2A and Fig. 3.3). Climate was a less densely connected node (n=15); however, connectivity (number of connections) and importance (node size) of climate in the network were high (Fig. 3.2A).

Farmers were intrinsically motivated to undertake SCM irrespective of climate conditions; however, they recognised the importance of climate for soil carbon storage.

The two-mode network shown in Fig. 3.2B visualises the closeness of features (76 vertices/nodes and 828 edges/connections) to the case study farms. In this network, the most densely connected features were SCM practices, SCM cost, climate, training and education support, and other farmers who were in close proximity to the farms. Climate had a predetermined relationship to SCM. Other closely connected features in the network were soil moisture, soil structure, soil health and farm production potential. The features with fewest connections to farms were government organisations, government support and technology availability. Governance features of soil carbon policy, carbon pricing and monitoring, government organisations, investment and support were distantly connected to the farms. Overall, in the two-mode network, the density of relationships between all features was low (30%), which suggests a currently underdeveloped SCM network in the study area and the potential for improvement.

The network analysis suggests the level of connection between features and depicts three types of relationship (strong, weak and pre-determined) between the features in the relationship map in Fig. 3.3. The map shows weak SES relationships between government officers and support, government policy (e.g. soil carbon policy) and SCM. A number of features, including soil type, climate and geographical location, were pre-determined relationships, as farmers considered they were inherent in the system, and had little control over them.

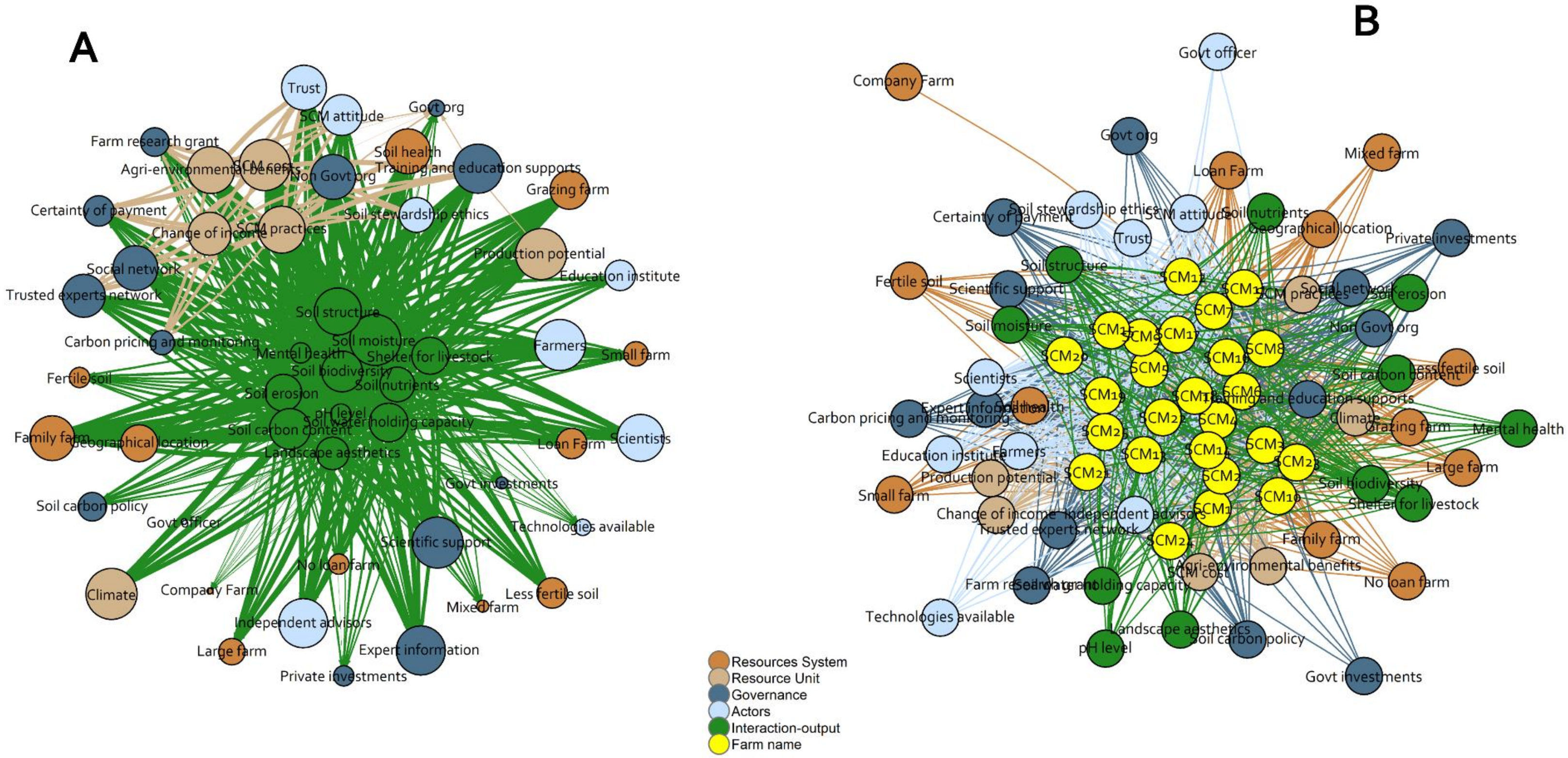

Fig. 3.2. SCM features connectivity network: (A) One-mode network of SCM features demonstrating the connectivity and importance of features in the SES system. (B) Two-mode closeness proximity network of SCM features demonstrating closeness of features to the cluster of farms. Frequency of lines represents connectivity between features.

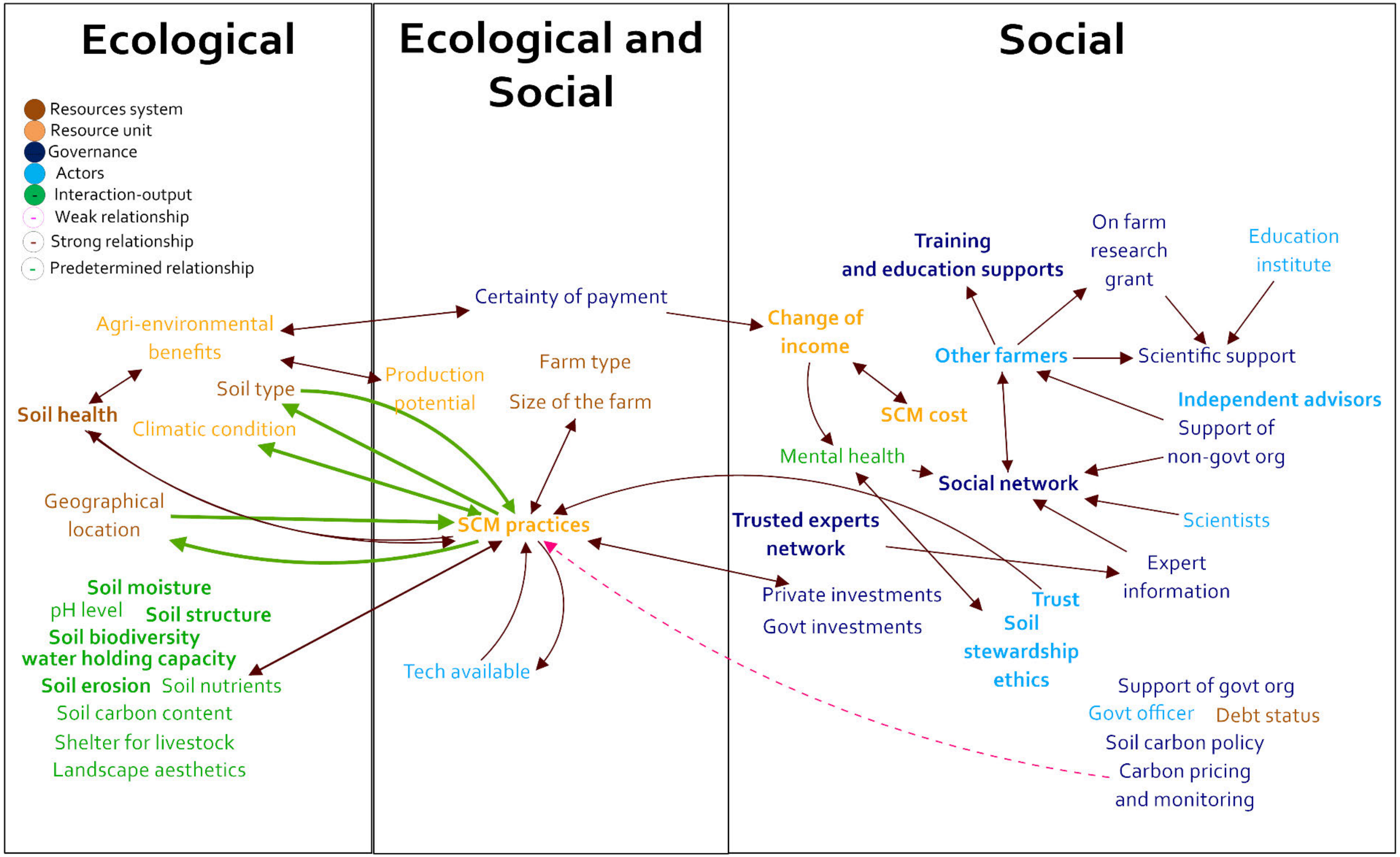

Fig. 3.3. Social-ecological system (SES) for soil carbon management in Australia using network analysis. Brown medium-weighted lines show strong connections, pink dashed lines show weak connections and green heavier-weighted lines show predetermined connections.

In contrast, the majority of features had strong relationships to each other. Certain features, however, were characterised as highly important (shown in bold in Fig. 3.3) and strongly influenced the interactions between other features. Training and education support, participation in the social network, other farmers, SCM attitudes, trust in the SCM practices, non-government organisations, SCM cost and trusted expert network were all identified as important features in the social part of the SES. Soil health and most of the interaction-output features or co-benefits were emphasised in the ecological part.

3.4.2. Farmer and service provider perspectives of SES relationships for SCM

Appendix B, Tables 3.4–3.7 summarise the interactions between features of the SES for SCM that participants in the farmer and service-provider workshops identified as positive, negative or mixed (see also Appendix B, Figs 3.2 and 3.3 for farmers and Figs 3.4 and 3.5 for service providers). Notably for farmers, the most positively influential features of the SES were the co-benefits of SCM, trust, a soil stewardship ethic, training and educational opportunities and their social networks.

Co-benefits encompassed a wide range of features from agronomic factors to mental health and landscape aesthetics. Both farmer workshops highlighted that the accrual of co-benefits from SCM practices positively influenced other features such as production potential, soil health and support of other farmers for SCM (Appendix B, Figs 3.2 and 3.3). Appendix B, Figs 3.2 and 3.3 show that farmers believe that the agri-environmental benefits of SCM practices positively influence the production potential of the farm and improve soil health. Co-benefits of SCM practices (e.g. improved soil moisture, nutrients, water-holding capacity and soil structure) positively influence interest in training and educational support. The farmers' social network was considered to have mixed influence (negative or positive) on the existing SCM practices (Appendix B, Fig. 3.2). While social networks were considered mostly positive, they could also have negative effects where peer pressure undermined innovation in management. Appendix B, Fig. 3.3 shows that a high level of soil stewardship positively influences SCM practices and thereby enhances the co-benefits of SCM. Where there is trust between actors and strong soil stewardship of farmers, then there is interest and adoption of SCM, which they believed could, in turn, improve income to further invest in SCM practices (Appendix B, Fig. 3.3).

Soil carbon policy was either positively or negatively influenced by carbon pricing and monitoring. The farmer workshops tended to elicit negative views of current soil carbon policy, pricing and monitoring mechanisms, and a lack of technology for taking advantage of policies and soil carbon pricing was noted. Service providers also emphasised the positive effects of a soil stewardship ethic but tended to give more weight than farmers to features such as external investment (public and private), carbon policy and the role of extension specialists. Service providers were also circumspect about carbon pricing and monitoring mechanisms but gave qualified support for their potential impact on farmers' income streams. In the absence of clear pricing arrangements, service providers were generally not convinced that SCM practices would result in a change of income. In addition, government and private investment and grants for on-farm research positively influence the availability of the required technology and its adoption, which ultimately influence SCM (Appendix B, Fig. 3.5).

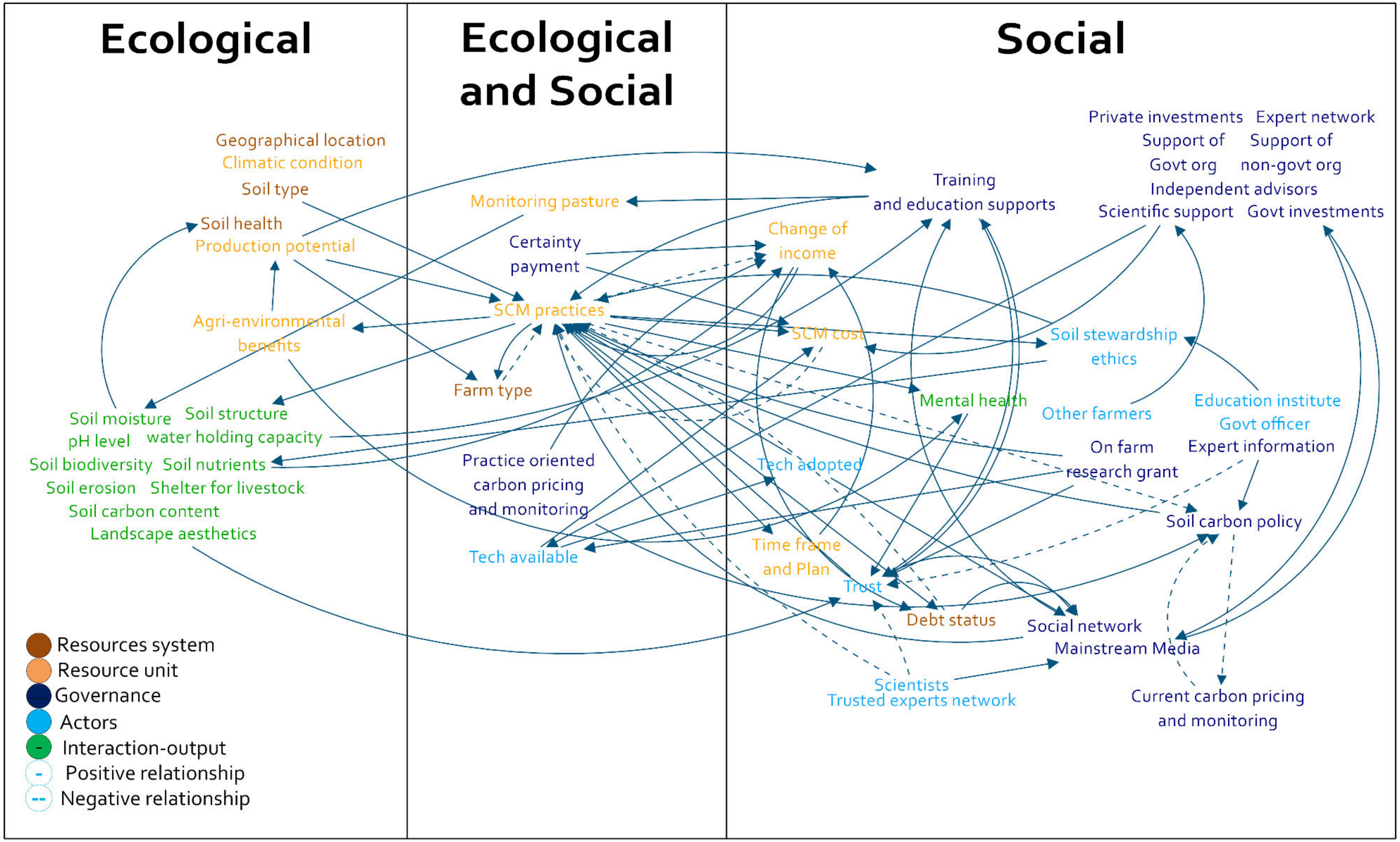

Fig. 3.4. Consolidated social-ecological system (SES) for soil carbon management (SCM) in Australia. Interactions were positive and negative between the identified SCM features, and features were categorised under Ostrom's high-level categories.

3.4.3 Feedback loops in SES for SCM

The workshops identified six reinforcing and four balancing feedback loops. Service providers identified a balancing feedback loop involving debt status (loop 1, Table 3.2 and Fig. 3.4); that is, higher farm debt negatively affects the uptake of SCM. However, outcomes of management such as perennial cover, improved soil health and agri-environmental benefits led to positive mental health and attitudes towards SCM. In contrast, farmers were more likely to continue with SCM despite increasing farm debt, which produced a balancing feedback loop. Even for farmers with insignificant farm debt, it was a reinforcing feedback loop (loop 1, Table 3.2, Fig. 3.4). A positive reinforcing feedback loop was found between SCM co-benefits, soil health and production potential (loops 2 and 7, Table 3.2 and Fig. 3.4). SCM co-benefits were considered to lead to wider soil health improvement and increased production potential of the farm, and were therefore likely to increase farm production (e.g. livestock and productivity gains) which, in turn, reinforces farmers' SCM and other co-benefits.

The implementation of SCM may increase costs but was considered to be balanced by the positive effect of the co-benefits. These could improve farm production even during adverse climatic conditions by ensuring ground cover, soil moisture, nutrients and soil biodiversity (balancing feedback loops 3 and 10, Table 3.2, Fig. 3.4). In the case of feedback loop 4, appropriate time frames and planning for SCM increase income over the long term and increase the co-benefits, which in turn maintain SCM. Farmers' participation in existing social networks (e.g. Landcare groups, and farmers' Facebook groups) increases interest in training and education, possibly leading to more SCM, improved farm production, reduced farm debt and increased farmers' interest in participating in farmers' social networks to seek out further information for SCM (reinforcing feedback loops 5 and 9, Table 3.2 and Fig. 3.4).

Table 3.2. Identified feedback loops of the social-ecological system for SCM in grazing lands

Loop No.	Feedback loops	Connected SES features	Sources
1	Balancing/reinforcing (-/+)/(+/+)	Debt status - SCM practices - agri-environmental benefits - mental health - trust - SCM practices	Service providers/farmers
2	Reinforcing (+/+)	SCM co-benefits - soil health, production potential - SCM practices - SCM co-benefits	Both
3	Balancing (-/+)	SCM cost - SCM practices - SCM co-benefits - change of income - SCM practices	Both
4	Reinforcing (+/+)	SCM practices - timeframe and plan - change of income - SCM practices	Farmers
5	Reinforcing (+/+)	Social network - training and education support - SCM practices - debt status - social network	Farmers
6	Reinforcing (+/+)	Training and education support - SCM practices - SCM co-benefits - training and education support	Farmers
7	Reinforcing (+/+)	SCM practices - SCM co-benefits - production potential and soil health - SCM practices	Both
8	Balancing (-/+)	Production potential and soil health - farming type - SCM practices - SCM co-benefits - production potential and soil health - SCM practices	Service providers
9	Reinforcing (+/+)	Social network - SCM practices - SCM co-benefits - production potential and soil health - SCM practices - social network	Farmers
10	Balancing (-/+)	SCM cost - SCM practices - SCM co-benefits - production potential and soil health - SCM practices	Both

The training and education reinforcing feedback loop (loop 6, Table 3.2 and Fig. 3.4) confirms farmers' interest in improved support for training and education from government and other potential sources. From their perspective, such support leads to greater use of SCM practices, which in turn results in increased co-benefits. SCM had a potentially balancing effect in the production potential and soil health feedback loop (loop 8, Table 3.2 and Fig. 3.4). Farms with lower production potential and less fertile soils may have less capacity for soil carbon storage, which could lead to a negative interest in SCM. However, SCM co-benefits and enhanced production potential along with good soil health could lead to greater adoption of SCM practices

3.5 Discussion – SES dynamics and policy implications for SCM

The novel approach we took helped to identify the features that farmers consider influence SCM and the relationships, interactions and feedback loops between these features. The SES for SCM, built upon long-term practitioners' practice, would be helpful for developing a governance system and policy instruments that supports farmers' capacity to manage soil carbon for co-benefits while also potentially meeting carbon neutrality by 2050. The discussion is focused on the critical SES features and causality (interactions and feedback loops) of the current SES of SCM in the grazing regimes found in this study. The implications of the SES for SCM will be reflected on in the context of local (farm production), national carbon policy (ERF), and international (SDGs) goals related to soil carbon sequestration.

Despite the existence of government carbon farming policies and incentives, highly experienced farmers are hesitant to make use of these incentives due to their opaqueness, with the result that the policies have had limited influence as a feature of the current SES of SCM. On the other hand, the features of farm production potential, SCM practices, training and education support, farmers' social networks (e.g. Facebook groups, Landcare groups and other farmers), scientific support (e.g. soil testing), non-government organisation support (e.g. organising seminars and field days on SCM) and expert SCM information (Fig. 3 and 4) were important for farmers current SCM. Farmers were motivated to manage soil carbon irrespective of resource unit features (e.g. farm type, proprietorship, geographical location, farm size) because of the likely co-benefits of SCM, such as improved soil health and farm production (grass and livestock). The network analysis revealed that the SCM network is underdeveloped in this region (network density 30%), and has the potential to develop stronger information flows, improved connectivity to features and connections to government policies.

This study identified five broad findings that are relevant to soil carbon policy for a more inclusive agenda with improved information flows and greater incentives for other landholders to undertake SCM. These findings were: multiple co-benefits of SCM, inclusion of pluralistic values, valuing and funding training and education schemes, supporting farmers' social networks, and understanding the importance of the SES feedback loops and their interactions for SCM. These broad findings highlights some of the strengths, weaknesses, opportunities and threats of the current SES of SCM in the grazing regimes of Australia, which are not necessarily mutually exclusive.

The SES highlights the critical role of co-benefits in SCM as an opportunity to reframe the narrative of soil carbon policy around this feature of farmers' SCM. This was emphasised in two feedback loops from both the farmers' and service providers' perspective: (i) SCM enhances SCM co-benefits and leads to greater adoption of SCM (reinforcing feedback loop 7, Table 3.2); (ii) the additional cost of SCM (e.g. water infrastructure, fencing for grazing management) was compensated by the SCM co-benefits – improved soil health and production potential – which led to adoption of SCM (balancing feedback loop 3, Table 3.2). These feedback loops demonstrate the dynamism of the SES relationships and provide guidance for policymakers when considering the level and types of public and private investment. Moreover, it could provide opportunities for government to design its communication and incentive strategies for mitigating climate change to align better with farmers' aspirations for SCM.

The SES relationships and feedback loops (Table 3.2, Fig 3.4) also identify the potential weakness of the existing soil carbon projects under ERF. The projects supported by ERF are governed by a centralised authority, using protocols designed to measure and monitor improvements in soil carbon (Australian Government, 2020). The results of this study support the need for pluralism in climate change policymaking in terms of the range of stakeholders whose views contribute to policy, the suite of collateral benefits that may be needed to persuade targeted stakeholders beyond the direct objective of GHG sequestration (Cohen et al., 2021) and the array of motivations that drive farmer behaviours beyond economic advancement. Such co-production of policy is an opportunity that may positively influence farmers' motivation to manage soil carbon at the farm level. Currently, a soil carbon project is designed to focus on a single feature (i.e. improving soil carbon), but does not consider the wider trade-offs and benefits for the whole soil carbon cycle. The farmers' SES of SCM shows that income and lack of debt were not motivating factors for SCM under current policy settings and were weakly connected to many important features in the SES (Fig. 3.4). The dominant neoliberal paradigm has distanced government policy from farmers on the assumption that market forces will be sufficient to lead to change and adoption of SCM. Such an approach is a missed opportunity that may neither take into account nor harness the power of a range of farmer motivations to manage soil carbon.

A valued feature of farmers' SES of SCM was training and education support, which was positively connected to SCM practices, production potential, co-benefits, soil health and trust (Table 3.2). Training and education support is not part of the existing soil carbon project scheme under ERF (Australian Government, 2020). Nevertheless, the value of increased training and education support coupled with grants for on-farm SCM research in the SES for SCM would be to build trust in SCM information and soil carbon policies (Lobry de Bruyn et al., 2017). In addition through farmers knowledge sharing with other farmers there could be an improvement in information flows, with sources they find credible and trustworthy (Rust et al., 2021). As the farmers interviewed in this study were long-term practitioners of SCM the SES was well established and could provide a pathway of SCM for other practitioners, especially those with less experience. The latest funding for soil extension and soil testing under NSS in Australia (Australian Government, 2021), with training as Registered Soil Practitioner recognises the need for reinvigoration of training support and upskilling of farmers for measuring soil carbon. Another valuable resource is that of long-term practitioners of SCM and how to incorporate their experiences in future training programmes.

The strength of the current SES for SCM was farmers' social networks, but they are also under threat as there is a lack of support for, and recognition of farmers' informal and formal social networks by government. The SES relationships anticipate the potential benefits of closer interaction amongst farmers' social networks, training and education and the governance features of soil carbon policy. Training, education and information on practice-oriented carbon pricing (e.g. schemes for long term practitioners who have established SCM) and monitoring mechanisms flowing through social networks (Kragt et al., 2017) could build farmers' trust in soil carbon policy and ensure greater engagement with it. Many of the existing social networks, largely supported by Landcare, are less active than they once were as a social network and require reinvigoration. As social networks are an important feature of SCM, government needs to reinvigorate the social networks (Jones et al., 2019), especially those that are aging or inactive (Lobry de Bruyn and Andrews, 2016), by providing incentives and connecting to those extension agents or independent advisors who already have strong relationships with practitioners as part of their current level of practice.

The identified feedback loops and SES relationships (Table 3.2 and Fig 3.4) showed the strength of the SCM in the grazing regimes by considering the whole SES of SCM. SCM reinforces the positive change of income within a reasonable time frame and planning (loop 4, Table 3.2), and communicating those achievements through farmers' social networks reinforces the positive outcomes of SCM (loops 5 and 9, Table 3.2). However, the change of income due to increased farm production created a trade-off between farm production and GHG emissions (methane and carbon dioxide) from the managed grazing lands as the increased number of livestock in the managed grazing lands switch the sink to a source (Chang et al., 2021). Essentially, SCM cost and farm debt were compensated by the outcomes of SCM such as co-benefits (loops 1 and 10, Table 3.2) but at the cost of additional agricultural GHG emissions. Such increases in GHG emissions from SCM call for improved management practices to retain carbon in soil (Whitehead, 2020), consideration of rotational grazing (Liu et al., 2021) and reduced stocking rates (Bork et al., 2020; Chang et al., 2021) to achieve the government net zero emissions target from this sector. Overall, for a successful soil carbon policy, the interrelationships between the feedback loops shows the importance of focusing on the whole SES for SCM rather than particular relationships.

The consolidated SES for SCM (Fig. 3.4) suggests that soil carbon projects under current government policy need to be more deeply connected with other influential SES features of SCM including: co-benefits, social network and training and education support. The policy design also needs to consider a whole system approach and inclusive participation (i.e. current ERF schemes excludes long term practitioners) to achieve improvements in soil carbon.

The research undertook cross-sectional analysis in a qualitative manner due to unavailability of time series data and confidentiality of the existing farm-level data (e.g. socio-economic, soil test data). The SES relationships were constructed from the lived experience of farmers who have managed their land for decades and may well reflect the SES features of other grazing systems elsewhere in Australia and possibly internationally with similar demographics and environments. 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. It is their SES of current SCM and even though it may not reflect the wider community of graziers not presently engaged in SCM it could assist them as it provides a perspective on what contributes to SCM and what does not help them in their current system. For the service providers it represents what they think is the SES for graziers more generally, but again those SES features originate from the interviewed farmers. The SES features and interrelationships could guide others to explore the gaps, challenges and current needs of stakeholders who are engaged in rotational grazing or are seeking to be to achieve important local, national and international objectives, such as SCM co-benefits, GHG reduction, carbon sequestration targets and SDGs, respectively. In general, the methodology of the study could be useful for operationalising the SES framework to other SCM SESs.

5. Conclusion

We used a novel approach of operationalising Ostrom's SES framework by combining qualitative and quantitative methods to unpack the SES relationships in SCM in a grazing region of Australia. Our SES for SCM shows the relative importance of each SCM feature in the system from the farmers' perspectives, and revealed that farmers place high importance on the features of training and education support, social networks, and co-benefits, which are currently inadequately addressed in existing Australian policy mechanisms such as the ERF. This study revealed the weak connectivity of the current SCM features in the studied system and indicated multiple foci for building a more highly connected SCM network that could be carbon neutral by 2050. The potential feedback loops identified in this study could provide guidance to policymakers to improve the SCM system in Australia so that it can meet not only the farmers' requirements to achieve the identified co-benefits of SCM but also the government's goal of improved soil carbon sequestration that can offset GHG emissions. Our approach to studying the SES for SCM would be useful in similar data-poor regions of the world.

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Fig. 3.1	64
Fig. 3.2	73
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Fig. 3.4	77
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Appendix B, Fig. 3.2	201
Appendix B, Fig. 3.3	201
Appendix B, Fig. 3.4	202
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Chapter 4

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

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4.1 Abstract

Graziers with land of low to moderate fertility soils were interviewed about their soil carbon management (SCM) and how they have maintained their grazing regime despite obstacles such as drought. The science states that soil carbon sequestration and improvement is difficult in low-fertility soils with low clay content. The resilience of these grazing systems (n=25) and the impact of their grazing regime on the SES of SCM provides lessons for others (policy development and farmers) on how to manage soil carbon. Two 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 from the two farming cohorts experienced different levels of confidence in achieving their goals when undertaking the SCM practices, with low-fertility farmers less confident of the outcomes. Farmers lack awareness of government initiatives for SCM under the Emissions Reduction Fund, meant these government endorsed soil carbon projects held little appeal. They were focused on the agri-environmental benefits of SCM practices in a holistic manner, rather than a single goal of increasing soil carbon under a government endorsed programme. These farmers reported a number of benefits that accrue from their grazing regimes, including improvements in production, soil moisture retention and soil health. 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.

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

4.2 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). Agricultural soil carbon management (SCM) has the potential to sequester 0.4 to 0.8 Pg carbon yr^{-1} in agricultural soil (Lu et al., 2011). Agricultural SCM is possible through a number of agricultural 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, permanent pasture, rotational grazing (Liu et al., 2021) sparsely grazed land (Chang et al., 2021) and stock management (Bork et al., 2020) have the potential to increase soil carbon (Lu et al., 2011; Luo et al., 2010). Minasny et al. (2017) suggested that regionally specific SCM efforts had the potential to sequester up to 10 per mille in the first 20 years of those specified practices, where initial stocks of soil organic carbon (SOC) were very low. Research has particularly 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) 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 different SCM practices, a considerable number of studies have also showed 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). The positive effect of soil carbon sequestration through SCM practices (i.e. conservation tillage in cropping and conversion to pasture from cropping) is constrained by climate and soil properties (Rabbi et al., 2015). 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.

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 carbon in 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, 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 involved (Baumber et al., 2020; Kragt et al., 2016), such as payment of carbon credits for different types of farming (Amin et al., 2021). 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).

SCM by grazing management has the potential to cover the widest area of land, since livestock grazing is the largest agricultural enterprise by area in the Australian state of New South Wales (NSW). Case study research has shown that farm business income can 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). 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 to achieve the UN Sustainable Development Goals (SDGs) (Amin et al., 2020).

Ostrom's (2007, 2009) social-ecological system (SES) framework has been widely used for analysing sustainability by examining the interactions and relationships between components of the system (Partelow, 2018). 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), to unpack the complexity of ecosystem services and human wellbeing at regional levels (Hossain et al., 2020b; Hossain et al., 2020a) and to examine the sustainable management of fisheries and water resources (de Wet and Odume, 2019; Galappaththi et al., 2019). SCM involves both social and ecological features of management, and it is helpful to include farmers' perspectives when considering farm-level SCM. Kroebel et al. (2021) suggested that sustainability of farming could be ensured by allowing farmers to participate directly in scientific research and policy to gain a deeper understanding of agri-environmental problems and to obtain the best management solution at the farm level. Grazing regimes cover more than half of Australia's land area 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 storage of soil carbon to contribute towards 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) and were set under the 2015 Paris Agreement.

The SES used to examine the factors that influence SCM in the grazing systems reported here has been described in Amin et al. (2021), where the features of the SES for SCM were fully described. What is of interest in this paper is that despite the land being subject to permanently limiting variables such as low clay content soil types and low land capabilities, these long-term practitioners of rotational grazing have continued to maintain this form of grazing regime.

Recent research has suggested that these practices have been adopted in grazing regimes due to a strongly held soil stewardship ethic (Gosnell, 2021). In contrast, other researchers (Li Liu et al., 2016; Orgill et al., 2018) have found graziers' soil carbon stock to have declined after undertaking SCM. Considering these variable explanations for sustained SCM, our study explored the distribution and pattern of farmers' SCM practices based on identified SES features in grazing regimes in NSW, Australia. This study focused on the following research questions:

- What is the distribution of farmers' SCM practices under particular grazing regimes?
- Is there a pattern to farmers' SCM practices based on SES features?
- What are the implications of farmers' experience for customising interventions in SCM?

4.3 Methodology

4.3.1 Selection of study area

The farms studied were mostly 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. 4.1). Grazing enterprises contribute 86% of the total value of Australia's agricultural production, with wool (41.7%) and meat (44.5%) being the dominant products. 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 rainfall falling over summer. Seasonal drought is common and occurs every 3.5 years, and severe drought is predicted to take place every 10 years. 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.

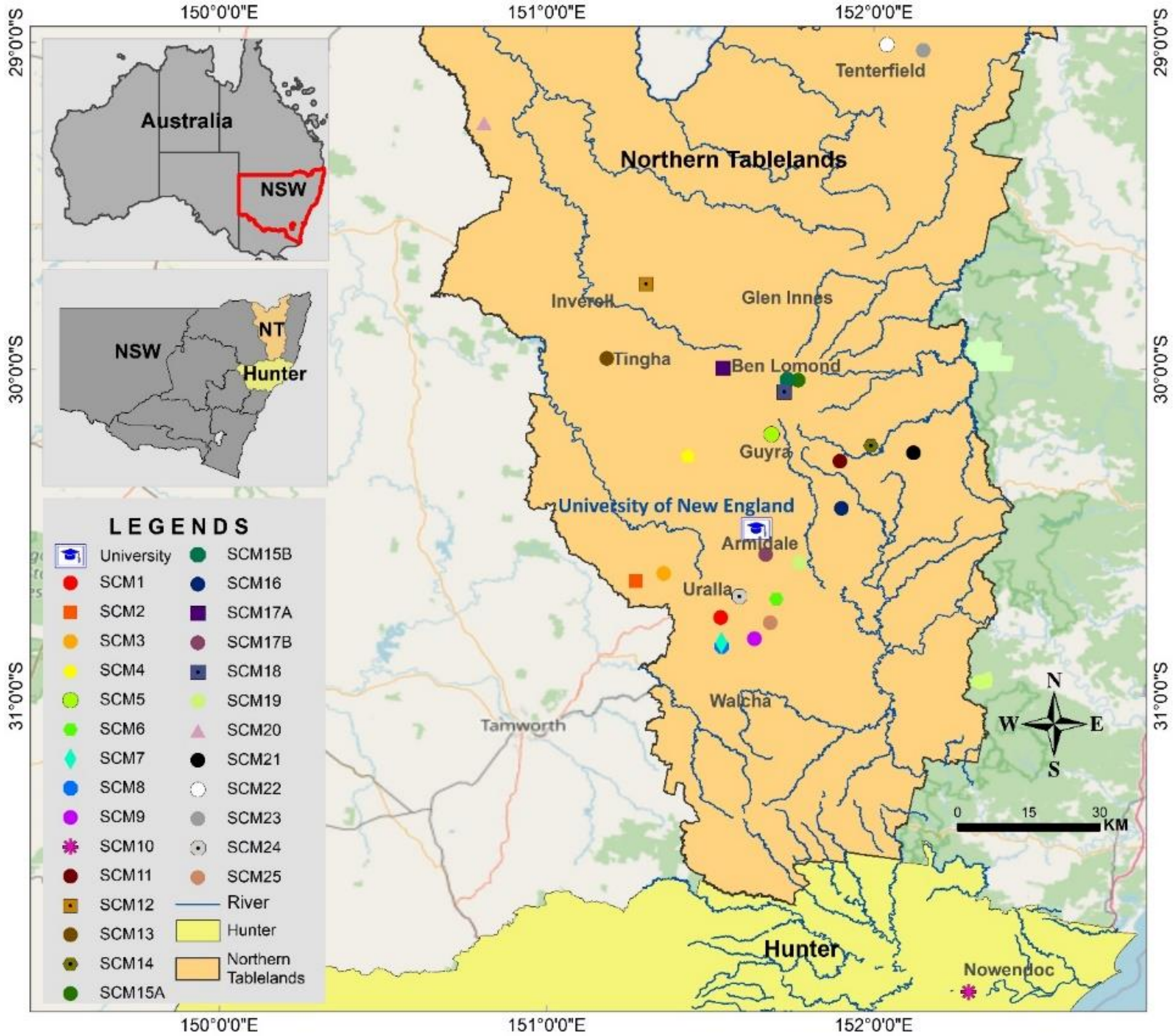

Fig. 4.1. Farm location in Northern Tablelands and Upper Hunter regions of New South Wales. Here, the identification numbers represent different farms (e.g. SCM1, SCM2) and a letter after the numbers represent farms owned by the same farmers (e.g. SCM17A, SCM17B).

4.3.2 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 of SCM practices in grazing regimes and the implications for public policy. 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 iterated Ostrom's first-tier features of resource system, resource units, governance, actors and interaction-output to analyse the sustainability of SCM in the grazing systems of Australia. When iterating 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. Under this iteration, 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 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).

4.3.3 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 chosen purposively in terms of their higher performance with current SCM practices. The majority of the study participants were known leading graziers who are highly motivated by their stewardship ethics. Their landholdings are often subject to periods of recurring drought, exacerbated in some instances by inherent low fertility and limited 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 4.1). 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 (Appendix C, Table 4.1). 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 questions comprised three aspects: first, questions on age, gender, education, farming experience, debts status, soil types, farm types and proprietorship; second, questions on farm features (e.g. types of SCM, economic aspects, governance systems, relevant actors) and their relationships in the current SCM system; and third, the co-benefits (e.g. soil moisture, mental health) of SCM practices.

The transcribed interviews were coded using NVivo12 to themes under Ostrom's first-tier SES features. The information coded in NVivo12 was then analyzed using a range of queries such as word frequency query and crosstab query to examine the difference in terms of farm context (e.g. moderate-fertility farms and low-fertility farms). The discussion about each SCM feature was coded from the interviews under each SES higher-level category. For example, discussion about the support of government or non-government organizations was coded under the 'governance system' category. In addition, SCM features (Appendix C, Table 4.1) were analyzed to explore the distribution and patterns relevant to the SES categories 'moderate-fertility farms' and 'low-fertility farms'. Given the importance of soil fertility and land capabilities for SCM, we confirmed the soil type and land capabilities of the interviewed farms through the NSW Government's online land capability mapping service eSPADE version 2 (Office of the Environment and Heritage, 2018), and confined the next steps in our analysis to farm soil types. To finalize the category of 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), locations of the farms were used. The farmers who were interviewed comprised two cohorts, one with moderate-fertility farms and the other with low-fertility farms. We summarized the information on the distribution of SCM practices and analyzed the differences and context. The differences in the pattern 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.

4.3.4 Network map

A one-mode network represents the connectivity (Box 4.1) of one set of features with another set. A one-mode network was employed to visualize for the fertile and less fertile soil type farms the influence on the other features of SCM of the outcomes of the SCM and the resources unit features of SCM practices, SCM cost, change of income and agri-environmental benefits . 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. 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 (Appendix C, Table 3.3). In the network diagram, each feature is represented as circle and is termed a 'node' (e.g. SCM cost, trust) and connections from one feature to another are 'lines'. The width of the line indicate the number of positive responses for each connection.

Box 4.1. Glossary of terms

Connectivity: The interaction of the one feature (e.g. SCM practices) with another feature in a network.

Soil stewardship ethics: is considered to be instilling a sense of soil conservation responsibility from the currently practicing farmers to other farmers in the community through SCM.

Practice-oriented schemes: Practice-oriented carbon pricing and monitoring mechanisms for particular SCM approach (e.g. rotational grazing on low-fertility farms).

Holistic livestock grazing management: Grazing management that matches the natural process by using less artificial inputs and human actions and managing lands, animal and water holistically to receive sustainable economic benefits.

Regenerative agricultural practices: Grazing practices with a functional ecosystem process (using less artificial inputs and human actions) that produce ecosystem services (e.g. water and nutrient cycling) and ensure water cycling throughout the year.

4.4 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 soil organic carbon processes 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.

4.4.1. 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 fertility (Table 4.1). The majority of farms were grazing enterprises with livestock for meat (n=21, Appendix C, Table 4.2), and a few also had cattle and sheep breeding. A few of the farms (n=4) were mixed 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 as identified by the farmer was found to be aligned to the information in eSPADE on land capability (Table 4.1). 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 4.1). 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 (58%) (Table 4.1). Similarly, human capital in terms of farmers' age and farming experiences was also similar for both cohorts (Table 4.1). A large proportion of farmers (80%) manage only one property and a smaller proportion (20%) manage between two to four properties (Table 4.2).

Table 4.1. Distribution of the current SCM resource system in the studied farms (n=25)

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

Table 4.2. Distribution of the current SCM practices (percentages) in the studied farms (n=25)

SCM practices	Types of responses	Moderate-fertility farm (n=12)	Low-fertility farm (n=13)
No of practices	Up to 4 practices	50	77
	More than 4 practices	50	23
Soil testing	Yes	75	77
	No	25	23
Tillage practices: no till	Yes	100	100
	No	0	0
Rotational grazing management	Yes	100	100
	No	0	0
Mulching	Yes	17	31
	No	83	69
Native vegetation establishment, exc. trees	Yes	17	8
	No	83	92
Increasing pasture area	Yes	17	15
	No	83	85
Intercropping with perennial pasture	Yes	8	23
	No	92	77
Legume in pasture	Yes	77	46
	No	33	54
Tree planting	Yes	50	85
	No	50	15
Bio-char	Yes	8	0
	No	92	100
Bio-nutrient addition	None	67	55
	Compost	17	15
	Biodynamics	16	15
	Manure	0	15

All of the interviewed farmers (100%) were undertaking rotational grazing, although farmers referred to it differently, using the terms time control grazing, holistic grazing, cell grazing, rotational grazing and strategic grazing (Appendix C, Table 4.2). Other than rotational grazing practices, no till for sowing of introduced pastures, 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. SCM19, SCM24).

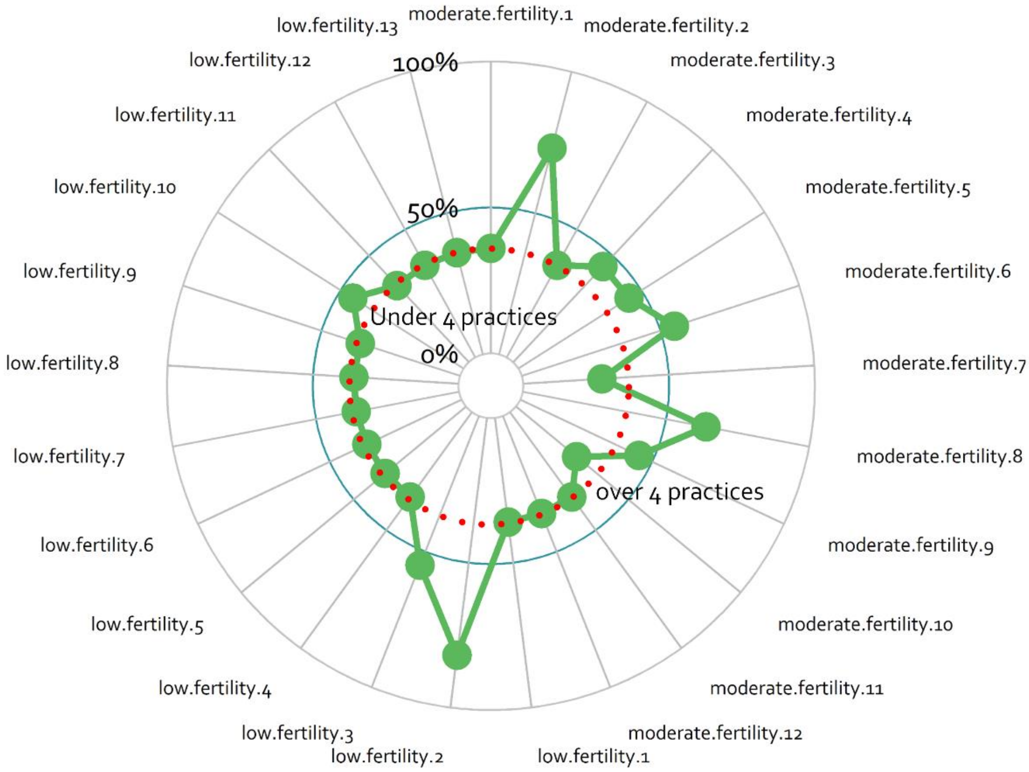

Fig. 4.2. Distribution of SCM practices (n=11) between the low-fertility and moderate-fertility farms in the grazing regimes of the Northern Tablelands and Upper Hunter (n=25).

Up to four different types of SCM practices were used by 77% of the low-fertility farms and 50% of the moderate fertility farms (Fig. 4.2). Conversely, more than four SCM practices were used on 50% of the moderate-fertility farms and 23% of the low-fertility farms (Table 4.2). However, one low-fertility farm (SCM4) practiced the highest variety of SCM practices (n=9) (Fig. 4.2). The distribution of SCM practices was similar between the farms regardless of soil fertility or land capability (Table 4.2). The points of difference in distribution of SCM practices were found for tree planting, which was higher (85%) for the low-fertility farms compared to the moderate-fertility farms (50%) (Table 4.2). 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 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 (Table 4.2). Usually, the addition of nutrients to the soils was in the form of manure, compost and biodynamics (i.e. holistic, ethical and ecological approach of nutrient addition) but this practice was undertaken by less than 30% of those interviewed (Table 4.2). More than half of the moderate-fertility (67%) and low-fertility farms (55%) did not apply additional nutrients, although a few were using balanced chemical fertilizers after soil testing (Table 4.2). Three-quarters of the farms (~75%) that had been soil tested were tested either before or after starting the SCM practices (Table 4.2). 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. 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; however, they stated that they had no control over climatic conditions. Thus, the farmers' main focus was on adapting to the current climatic situation by applying holistic livestock grazing management and regenerative agricultural practices (Box 4.1).

4.4.2. Impacts of SCM practices of farming cohort

We studied the common and different impacts of SCM practices on the moderate-fertility and low-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 impost 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 farmers experienced fairly similar agri-environmental benefits after adopting these SCM practices, such as more extensive ground cover throughout the year, even during severe drought periods, and reduced erosion and increased soil moisture retention in grazing lands.

The perceptions of soil carbon change after the introduction of the SCM were very similar for both types of farms (Fig. 4.3). Farmers from both cohorts believed that farm production had increased regardless of underlying fertility (Fig. 4.3). Tree planting was higher in the low-fertility farms (Table 4.2), with a corresponding increase in shelter for livestock in the low-fertility farms (77%) compared with the moderate-fertility farms (42%) (Fig. 4.3). Moderate-fertility farms (58%) experienced a decrease in the use of additional nutrients after introducing SCM practices. More than 50% of the low-fertility farms and 42% of the moderate-fertility farms experienced an increase in pH (i.e. became more alkaline) after introducing SCM, which indicated an improvement in soil condition where soils were normally acidic. Improvements in soil moisture and structure were higher in the low-fertility farms (92%) compared to the moderate-fertility farms (Fig. 4.3). For the moderate-fertility farms, 58% of farmers experienced an increase in soil moisture, and 83% of farmers experienced an improvement in soil structure. Similar to soil moisture retention, perceived soil biodiversity change (i.e. observed density of soil microorganisms) was also higher 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 positive changes in soil moisture, pH and biodiversity after introducing SCM reflect the multiple benefits farmers consider when undertaking SCM practices.

Both farming cohorts experienced an increase in production potential after the introduction of the SCM (Fig. 4.3). According to all of these experienced farmers, rotational grazing is the best management practice for improving soil health. While undertaking the current SCM practices, farmers in both cohorts observed improvements in soil health (e.g. pH, soil organic carbon, soil structure) (Fig. 4.3). Despite not precisely measuring changes in soil condition, farmers experienced positive changes in soil nutrients and overall soil health after introducing SCM practices (Fig. 4.3), as reflected in this quote from SCM8: "*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*".

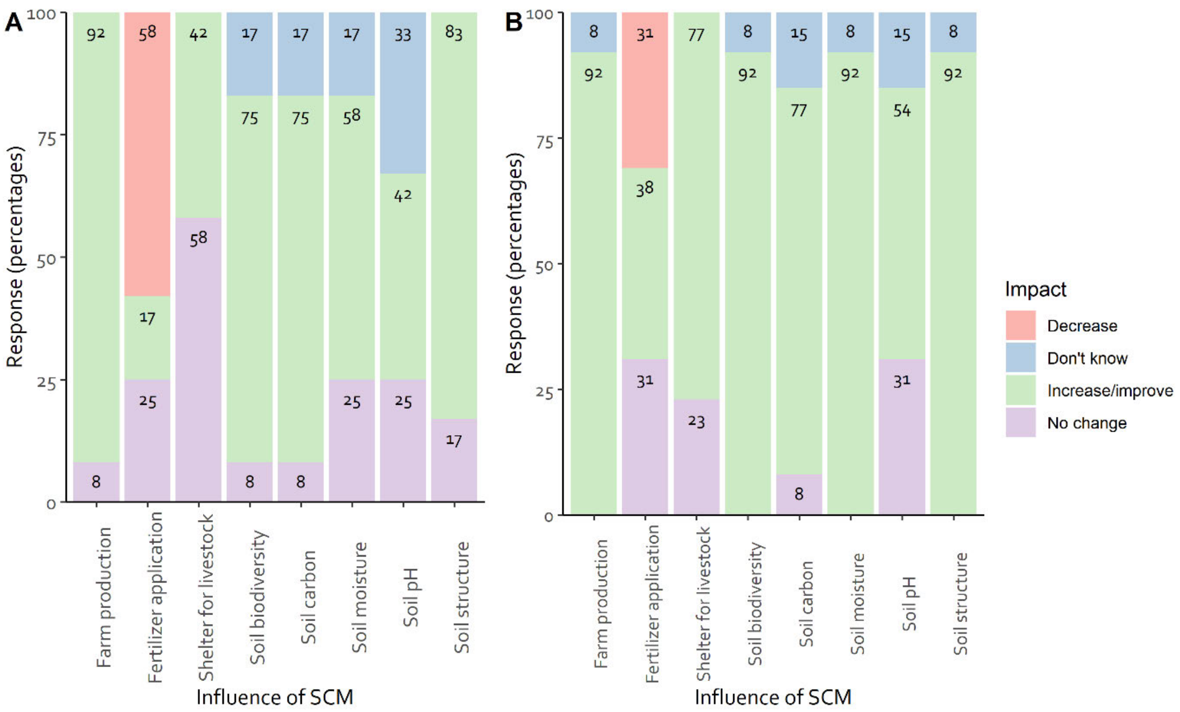

Fig. 4.3. Pattern of impact of SCM practices in the (A) Moderate-fertility farms and (B) Low-fertility farm as experienced by farmers in grazing regimes of the Northern Tablelands and Upper Hunter.

4.4.3 Network of SCM outcomes and farmers' SES of SCM

Using network maps (Fig. 4.4), we describe 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 maps show the common and different points of connectivity (Box 4.1) between the SES features (Fig. 4.4). The connectivity between the SES features and sizes of the nodes for the features was largely similar for both farming cohorts (Fig. 4.4). For example, the nodes of soil health, independent advisor, social network and SCM attitudes were similar in size (i.e. similar in importance in the network) for both farming cohorts. However, a small number of features differed in importance between the moderate-fertility and low-fertility farms, and these are discussed in the following section.

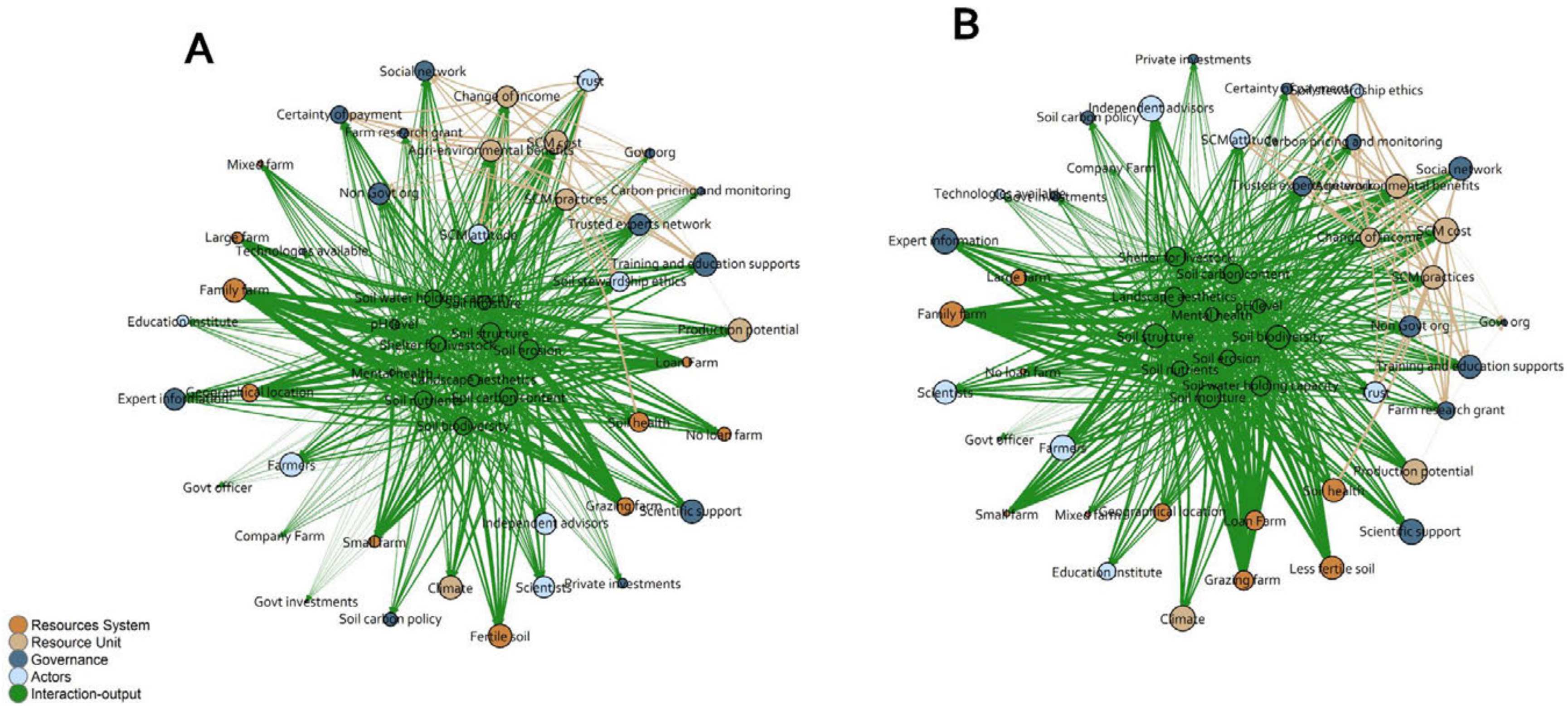

Fig. 4.4. SCM features connectivity network based on the influence of SCM outcomes (in centre) and resource unit features (SCM practices, SCM cost, change of income, agri-environmental benefits) for (A) Moderate-fertility farms and (B) Low-fertility farms. The circle size relates to the importance of the feature for SCM. The lines represent connectivity between features.

4.4.3.1 Relationships between interaction-output, resource units and resource system features in the network

The resource unit features that have influenced SCM equally for both farming cohorts were SCM practices, agri-environmental benefits, SCM cost and production potential. However, change of income was found to be slightly more important in the moderate-fertility farms than the low-fertility farms in relation to SCM resource unit features, but in both cohorts, farmers experienced higher costs when initiating SCM practices that lessened over time, and income improved as SCM practices became more established (Fig. 4.4). The network map also revealed that changes in interaction-output features were similar in both farming cohorts for soil water-holding capacity and soil carbon content (Fig. 4.4). 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 than the moderate-fertility farms, whereas soil erosion control was considered to be a more important outcome of SCM for the moderate-fertility farms (Fig. 4.4). 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 are reflected in this quote from SCM 1: "*[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"*.

4.4.3.2 Relationships between SCM governance and actor features in network

The features in the SCM governance and actor categories exhibited a similar pattern of importance to both farming cohorts. The most to least important features in these 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 nodes) for both cohorts, with moderate-fertility farmers not seeking government investment on their farms after introducing SCM practices (Fig. 4.4). 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 institutes 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. 4.3) 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 than moderate-fertility farms.

The network map showed that moderate-fertility farms would be more certain than the low-fertility farms about payments for the SCM from the government (Fig. 4.4), 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 after having a good outcome (i.e. improved soil moisture, improved soil biodiversity) from SCM. This is because certainty of payment for SCM is singularly focused on soil carbon content, and farmers from both farming cohorts experienced similar changes in carbon content (Fig. 4.4) in their farm soil but with different levels of effort. 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 (Fig. 4.3). 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 SCM2 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 (Box 4.1) on SCM was more pronounced for the moderate-fertility farms than the low-fertility farms (Fig. 4.4). In this study, In this study, soil stewardship ethics is considered to be 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 SCM2: *"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".*

4.5 Discussion

4.5.1 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. Moderate-fertility farms have adopted diversified practices for improving soil health and production at the farm level (Fig. 4.3). There were generally more SCM practices used in moderate-fertility farms than low-fertility farms. Low-fertility farms chose fewer interventions (e.g. two to four SCM in most of the farms), possibly due to the constraints of low land capability (Table 4.1). The presence of tree planting was higher (85%) in the low-fertility farms than the moderate-fertility farms (Table 4.2). The higher prevalence of this practice might be because the low-fertility farms 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. Farms with hills and ridges with shallow stony soils might be better off planting trees in order to prevent soil erosion, improve amenity value and provide shade and shelter for stock. If grants were available for the tree planting, it may make it cost effective and attractive to implement, with in-kind labor contributions. The 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 and land capability of those farms (Table 4.1). Low-fertility farms were less likely to reduce fertilizer applications (Fig. 4.3), and the land had inherently low capability. 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 (Table 4.2), while low-fertility farms do not, allowing the former to explore better SCM options for their 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.

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 linked to the SCM practices of the low-fertility farms than 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 to receive and deliver information on SCM. High reliance on individual advisors was common among the farmers from both cohorts when choosing SCM management practices (Fig. 4.4). The interviews revealed that these individual advisors were one of the most substantial influences on farmers' decisions and behaviours in relation to SCM practices for both types of farms. Government organizations had less influence as an actor, 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 4.1) in the existing practices of land management, but there was little physical evidence collected of soil change, such as soil testing, with implementation of an SCM practice. 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. 4.4). 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. 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.

4.5.2 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. 4.5). A Sankey diagram is used to visually highlight the commonalities and/or differences in the SES features on the basis of the 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. 4.5). 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 getting a return in time with improved farm production. Thus, farmers suggested that flexible financing and funding could address this challenge before the benefits had become evident. The motivation for other famers to adopt a new practice depends on proof of concept; however, it is highly challenging to showcase substantial outcomes 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. 4.5).

Farmers in both farming cohorts (n=6) nominated water and fencing infrastructure development and drought as major challenges for SCM through rotational grazing (Fig. 4.5). 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. 4.5). However, 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 considered it more difficult to participate in carbon trading and access a price on carbon compared to the low-fertility farms (Fig. 4.5). This difference might be related to the moderate-fertility farms after several decades of rotational grazing have reached a new 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 ERF 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 (Box 4.1) and different settings of carbon pricing (Fig. 4.5). 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. The current ERF scheme is not considering the SCM currently being practiced and its effect on soil carbon level while registered; therefore, for these farmers to participate in the scheme they need to acquire new land. In addition, the potential opportunity proposed to overcome the obstacles for farmers 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.

Lack of knowledge on best management practices, conversion of cultivable lands to pasture land or no agriculture and the need for training on grazing-based land management such as rotational grazing (e.g. cell grazing, time control grazing, holistic grazing) were the other challenges experienced only in the low-fertility farms (Fig. 4.5). The farmers of the moderate-fertility farms were more flexible because the inherently better land capability of their farms allowed them greater choice of land management techniques. Thus, they could experiment more without challenging their farm production. Securing finance for additional labor was the key challenge in moderate-fertility farms, whereas costs related to nutrient amendments were the most important challenges in the low-fertility farms (Fig. 4.5). The potential solutions proposed by the farmers were arranging training and education funds and the provision of flexible financing and funding by banks and other financial organizations. This could be achieved through a participatory discussion with the farmers' networks to introduce a new initiative into the ERF of funding loans based on improvements to natural capital resulting from their current management practices (Fig. 4.5).

Although the farmers have experienced low connectivity (Box 4.1) 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 (Figs 4.3 and 4.4), farm production and ground cover during the recent drought period of 2019–2020. Farmers in both farming cohorts have relied more on individual advisors and organizations such as Landcare than government, and yet have retained a sense of optimism that they can overcome the impact of drought through their SCM practices and flexible financing and funding (Fig. 4.5). Farmers from both farming cohorts believed that other farmers' negative attitudes towards a changing in grazing management could be resolved by sharing their SCM successes through the farmers' social networks.

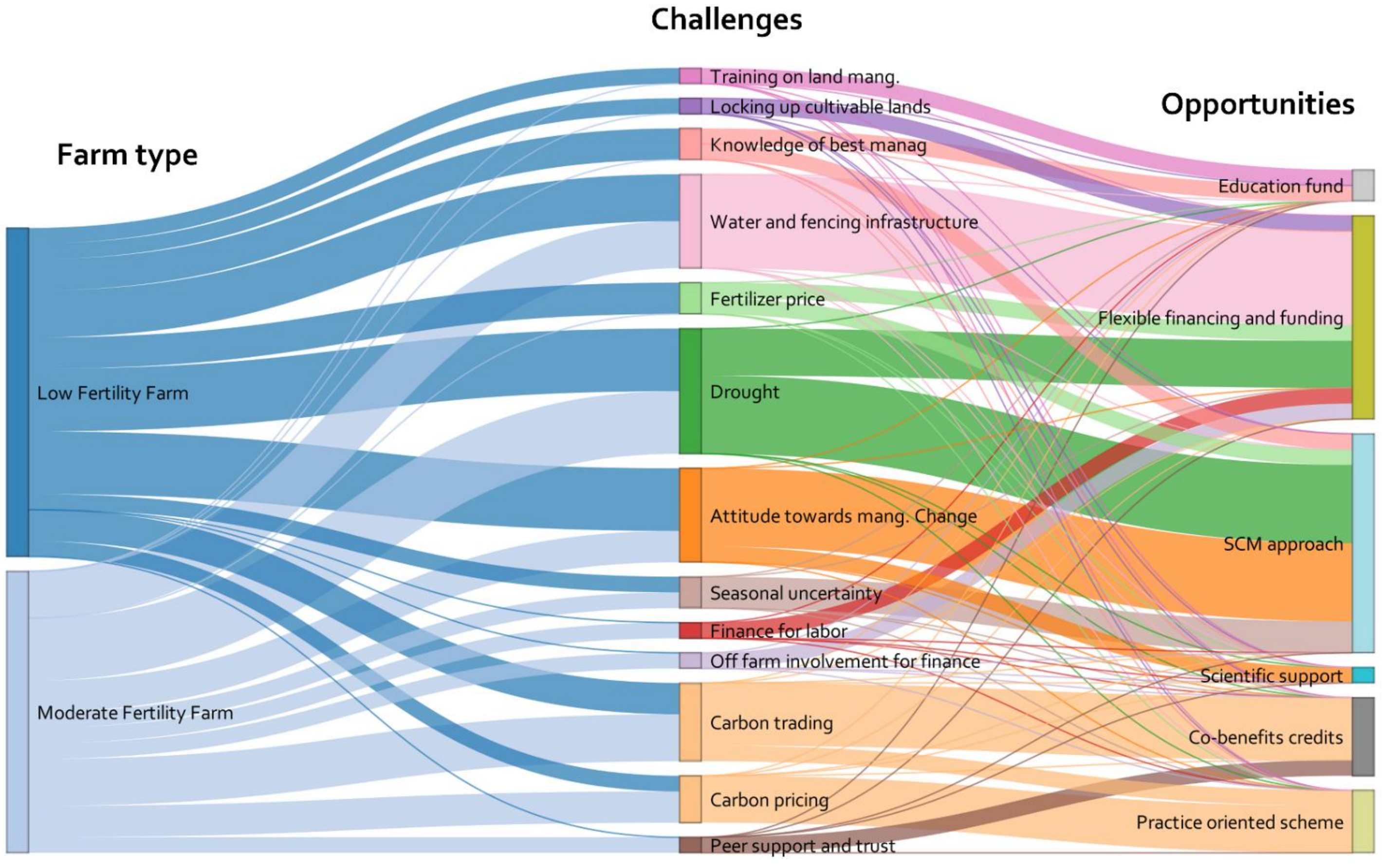

Fig. 4.5. Challenges experienced by farmers and proposed potential opportunities under the existing SCM practices in grazing regimes categorized according to farm type. Here the weight or thickness of a line indicates the level of connection to other aspects, with greater line thickness indicating stronger connections between related challenges and opportunities for each SES feature.

This study found that grazing farmers with low-fertility soils and low land capability have been observing improvements in soil and have persisted with their grazing management despite the obstacles. 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 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 observed 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 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. It is their SES of current SCM and even though it may not reflect the wider community of graziers not presently engaged in SCM it could assist other farmers as it provides a 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).

4.6 Conclusion

This study found that grazing farmers from both farming cohorts have observed improvements in soil and 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. Thus, the 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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STATEMENT OF AUTHORS' CONTRIBUTION

(To appear at the end of each thesis chapter submitted as an article/paper)

We, the PhD candidate and the candidate's Principal Supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the candidate's contribution as indicated in the *Statement of Originality*.

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Fig. 4.2	105
Fig. 4.3	108
Fig. 4.4	109
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Chapter 5

General discussion and synthesis

5.1 Overview

This chapter is the synthesis of the three main research chapters (Chapters 2, 3 and 4) that addressed research questions RQ1 to RQ5 of this study, and provides implications for policy and practice of the studied social-ecological system (SES) of soil carbon management (SCM) in grazing regimes for farmers' sustained SCM (RQ6). Fig. 5.1 presents the flow diagram of the thesis to understand the role of the SES framework for examining Australian farmers' capacity to manage soil carbon. Overall, this thesis aimed to: 1) examine current trends of SCM research in Australia and the role of an SES framework for examining farmers' capacity to manage soil carbon (Chapter 2) using a systematic literature review, 2) understand the connectivity and relationships (interactions and feedback loops) of SES features of SCM in the grazing regimes of Australia (Chapter 3) using farmers' interviews and stakeholder workshops (farmers and service providers), and 3) explore the distribution and pattern of SCM practices based on long-term practitioners' SES for SCM in the grazing regimes using farmer interviews (Chapter 4). The purpose of Chapter 4 was to understand the lessons from grazing farmers' SES for customising interventions in SCM at public policy level (Fig. 5.1). In Chapter 5, the implications for policy and practice of the studied SES for SCM in grazing regimes for farmers' sustained SCM are discussed.

The systematic review revealed that SCM research in Australia is predominantly focused on ecological components and has been undertaken from scientists' perspectives (Fig. 5.1). The interaction between the social and ecological variables of SCM is absent from the SCM research. In addition, farmers' perspectives of SCM are largely absent from the existing SCM research in Australia. Given the considerable research gap, the next steps of this research focused on determining the social and ecological features of SCM in grazing land. After examining the connectivity through the network analysis and causal loop maps, this study explored the current SES relationships that help or hinder SCM, and identified the weak connections of current SCM to the existing governance and natural resource management (NRM) policy in Australia. The exploration of the SES relationships in SCM also revealed the 10 critical feedback loops in the existing SCM system and highlighted the areas where farmer support is needed to sustain the existing system of SCM. For example, co-production of policy may positively influence farmers' motivation to participate in SCM and beyond the direct soil carbon project under the ERF, which is focused on a single feature (i.e. improving soil carbon), but the scale is often not considering the wider trade-offs of the whole carbon cycle. This thesis showed that understanding the relationships across feedback loops and focusing on the all-inclusive SES for SCM could resolve this problem and contribute to the government SDG targets, including zero hunger (SDG 2), good health and wellbeing (SDG 3), sustainable management of water (SDG 6), climate action (SDG 13), responsible production and consumption (SGD 12) and land degradation neutrality (15.3).

Once the relationships and critical feedback loops of the current SES for SCM were established, the next level of research focused on the farm-level distribution and pattern of SCM practices based on long-term practitioners' SES for SCM in the studied grazing regimes. Chapter 4 explored how farmers from the low-fertility and moderate-fertility farming cohorts have shown resolve to continue their grazing regime because the benefits are diverse and affect whole-farm sustainability. However, farmers lack awareness of the government initiatives for SCM under the ERF, and they are also not engaged in soil carbon projects as they focus on the wider agri-environmental benefits of SCM practices in a holistic manner rather than a singular goal of increasing soil carbon. These long-term practitioners are also currently ineligible for funding as the soil carbon projects need to be undertaken on lands not currently managed for soil carbon by approved methods, and they are unlikely to move to new locations. This study identified the major impediments that the policy instruments (i.e. soil carbon projects under ERF) need to address to secure the involvement of long-term practitioners in current ERF, and also identified that farmer participation requires a more targeted, customised and nuanced government policy (i.e. mentoring the less experienced farmers under ERF, knowledge co-production) to achieve government SDG targets.

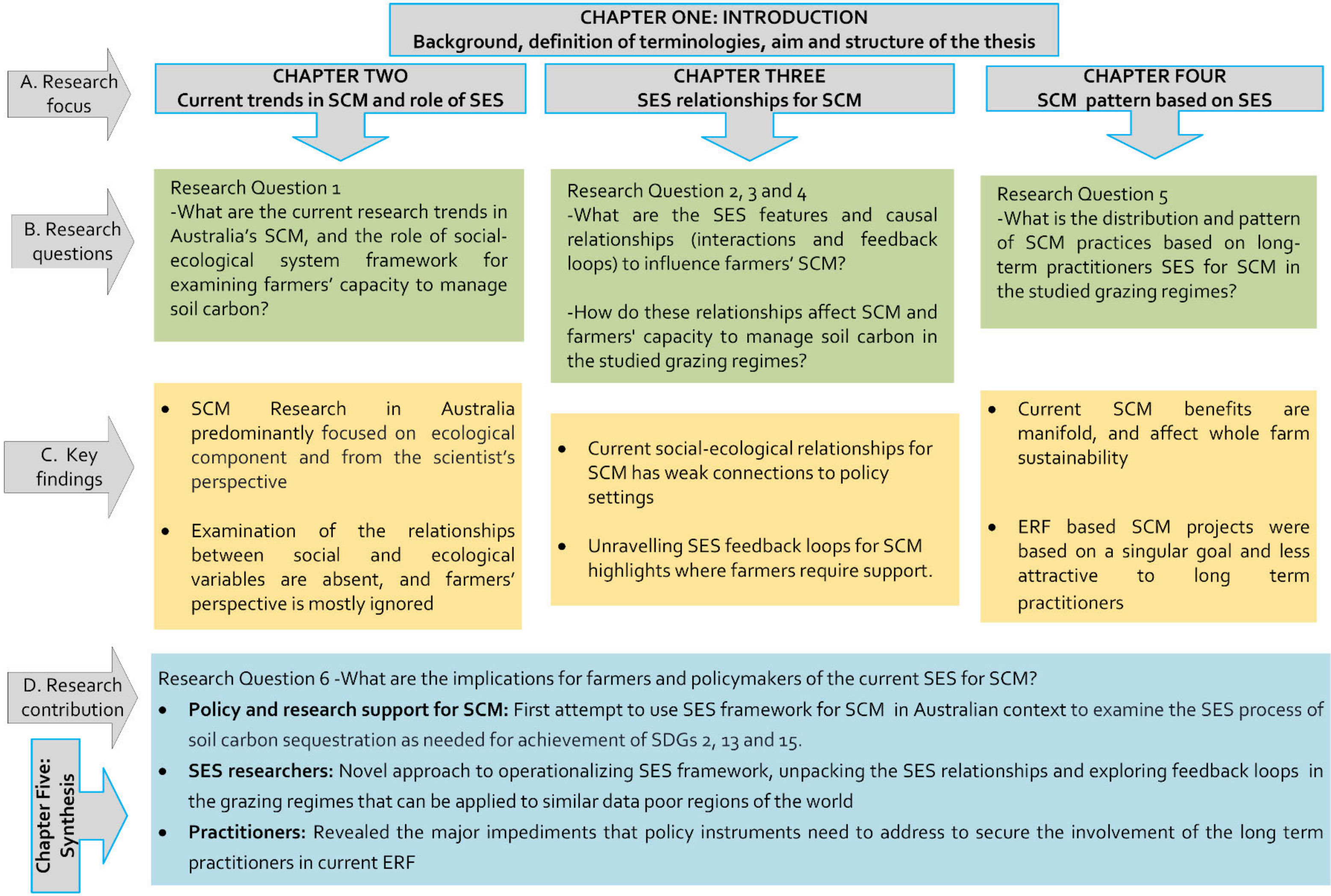

Fig. 5.1. Flow diagram to understand the role of the SES framework for examining Australian farmers' capacity to manage soil carbon

5.2 Current trends in SCM and role of SES (Chapter 2)

The trends in SCM research in Australia and the role of SES were reviewed in this study to understand the critical role of SCM features for farmers' capacity to manage soil carbon. The first stage of the systematic review examined the progress made in SCM research in Australia, and the second stage of the systematic review focused on the use of the SES framework in SCM. During the initial screening of articles, it became clear that the SES framework has not been used in Australian SCM research, and therefore the second stage of the review focused on the use of SES framework in SCM research elsewhere in the world. Chapter 2 used NVivo12 plus to undertake quantitative and qualitative analysis of the selected articles on the basis of dominant component (i.e. social, ecological) and spatial scale (i.e. regional, local and farm level) and to synthesise the coded themes (i.e. future research gaps, trends in soil carbon management research, key research focus, policy implications and potential co-benefits of SCM) from different parts of the articles.

The study revealed that SCM research in Australia has been predominately focused on regional soil carbon level changes, which remains the current focus (Wang et al., 2022), and little research has examined the farm level (i.e. local level) of change in soil carbon. As a result, farm-level data on soil carbon that could guide farmers and policymakers in Australia are lacking. This study found that SCM research trends related to carbon level change through different practices (e.g. organic amendments, converting the cropping to pasture) increased after 2011, coinciding with the introduction of the carbon farming initiatives (CFI). From 2015, the research plateaued with the incorporation of CFI into the ERF. This levelling out of research was due to changes in government policy and a cessation of government research funding for soil carbon studies. The examination of the trends in SCM research in Australian agriculture revealed that the focus has been mainly on particular land use types and the effect of land use activities (e.g. grazing and cropping) (Orgill et al., 2014; Orgill et al., 2018), and to a lesser extent the influence of socio-economic conditions on soil carbon (Rochecouste et al., 2015). According to the existing data and knowledge acquired from the SCM research, the leading influential factor in soil carbon sequestration in Australia is climate, followed by soil type (i.e. parent materials), land use and land management (Fig. 5.2) (Chappell and Baldock, 2016; Rabbi et al., 2015). Again, in Australia, the prevalent data and knowledge management unit is the national level, followed by regional level then farm and paddock level (Fig. 5.2). Farm and paddock-level data on soil carbon is limited, and this information is a prerequisite for understanding the change in carbon levels for SCM.

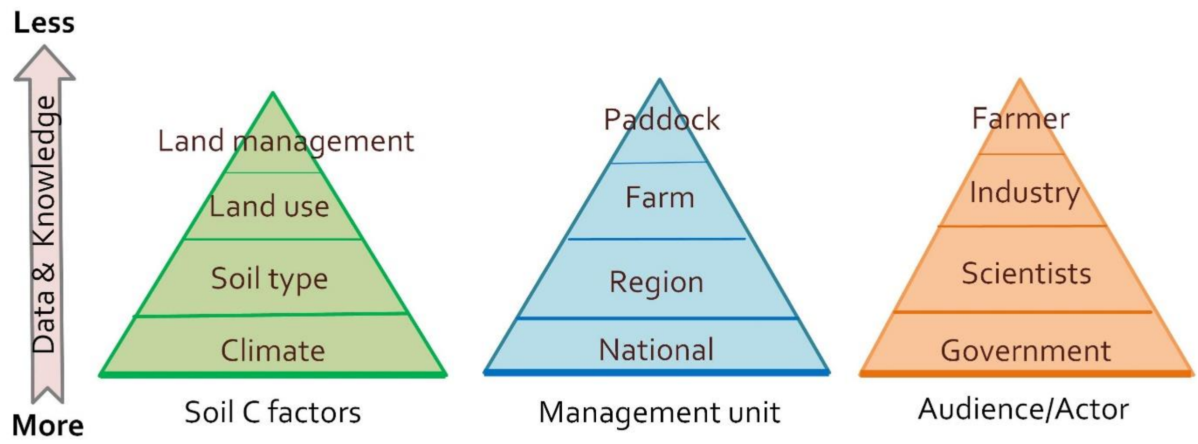

Fig. 5.2. Prevalent features of soil carbon factors, management unit and audience in SCM research in Australia

This study showed that in Australia, soil carbon data are available to the government, followed by scientists, industry and then farmers, but it is collected from a particular time period with no follow-up data currently being collected (Fig. 5.2). Farmers are the most data-poor actors who need to know about the soil carbon level to understand its influence on soil health and production. Modelling and auditing of soil organic carbon predominantly on a larger spatial scale was the most researched topic (O'Leary et al., 2016). Less research has assessed potential soil carbon storage through different agricultural land uses following reforestation in agricultural lands (Paul et al., 2016), the co-benefits of carbon farming, and community values on climate change mitigation through soil carbon sequestration in agricultural soils. Other understudied areas of SCM research are the effect of combined management practices on soil carbon stock, changes in tillage practices and their effect on soil carbon levels, the effects of the cropping system or effects of biochar on soil carbon (Luo et al., 2016; Macdonald et al., 2013). The opaque nature of knowledge and the consequences of land management change on soil carbon result in farmers continuing their mainstream practices rather than modifying SCM techniques to improve carbon storage at the farm level. Farm-scale SCM research in Australia has focused on the ecological aspects of emissions reduction through revegetation (Longmire et al., 2015) and the importance of management practices, cover crops and pasture for storing carbon (Bajgai et al., 2014). The socio-economic and policy aspects of SCM have largely focused on regional-scale impacts.

SCM research in Australia has predominantly focused on the role of the ecological component with the majority of articles studying the features of this component (i.e. soil texture, climate and topography, water availability, vegetation types and land use practices). The features under the social component (i.e. policy instruments, farmer's attitudes towards climate change, preference for land use change and farm characteristics) and their interactions with the ecological features have not been examined in detail. The study found that co-benefits of SCM are the main consideration in farmers' adoption of SCM in Australia; however, these co-benefits have largely been identified from scientists' perspectives rather than the farmers' perspectives. Around 70% of the SCM research did not consider the farmers' capacity when examining SCM. Similar to the previous trends with regard to spatial scale, co-benefit studies at the farm level are uncommon in Australian SCM research. The research revealed that both ecological and social components need to be studied comprehensively, and understanding the SES is useful for identifying and determining the critical relationships involved in managing soil carbon at a landscape scale for an integrated management approach (Van Oosterzee et al., 2014). Following the work of Ostrom (2007, 2009), this study proposed the key components for an SES for SCM. The SES framework illustrated the likely direction of the interaction between the features of the SCM and between components, and revealed the importance of a comprehensive understanding of the relationships between the SCM features at the farm level. For example, one of the proposed interactions within the SES framework was carbon markets, and governmental policy will influence the land use variable, which, over time, will affect SCM in Australia.

5.3 SES relationships in SCM in the grazing regimes (Chapter 3)

Limited understanding of the SES features of SCM and their interactions influence Australian farmers' management of soil carbon and affect their potential engagement in soil carbon policy initiatives, which is currently low. Cattle and sheep grazing enterprises use over 50% of Australia's land area (around 336 million hectares), and grazing lands in summer-dominant rainfall zones with high vegetation retention have a high potential for offsetting GHGs through sequestering carbon in soil (Australia, 2021; Reich et al., 2020; Rey et al., 2017). Unpacking experienced farmers' current SES for SCM in grazing lands could assist farmers' engagement with soil carbon policy initiatives to achieve the government's target of achieving the UN's Sustainable Development Goals of zero hunger (SDG 2), good health and wellbeing (SDG 3), sustainable management of water (SDG 6), climate action (SDG 13), responsible production and consumption (SGD 12) and land degradation neutrality (15.3) (Lal et al., 2021).

This study applied a novel SES approach. Initially, this study used semi-structured interviews (n=25) with graziers and separate stakeholder workshops (i.e. farmers and service providers) in the high-rainfall grazing regimes of the Northern Tablelands and Upper Hunter to explore the SES features of SCM and the interactions that influence Australian farmers' management of soil carbon. The interviewed farmers had been undertaking two to three SCM practices often for a decade (96%) and in some cases for 40 years, and 70% of farms were more than 500 ha in size (largest 3,350 ha). Workshops were repeated for service providers (n=2) and farmers (n=2) to ensure saturation of information and to minimise redundancy and disagreements. Separate workshops for farmers ensured the perspectives of service providers did not dominate the farmers' deliberations. The semi-structured interview was based on Ostrom's high-level categories (i.e. resource system, resource units, actors, governance and interaction-output. This study identified 51 SCM features from the interviewed farmers. Network analysis was performed to determine the current connectedness and influence of the 51 SES features of SCM that either helped or hindered, and a causal loop relationship diagram was also generated. The workshop participants (n=4 workshops) collectively mapped the interactions among the agreed features. The arrows indicate the direction of the interaction, and participants discussed whether the nature of the relationship was positive or negative. At the end of the workshop, feedback loops were identified as either reinforcing or balancing. Reinforcing feedback loops reinforce, accentuate or magnify the initial change in the systems; for example, increased farm productivity is reinforced by sustainable land management (SLM) practices, management practices are supported by flexible financing and then adoption of SLM ensures more production. Balancing feedback loops balance, moderate or oppose the initial change in the system; for example, drought reduces soil moisture and grass production, but incorporating mulch on the bare soil retains moisture, which can balance the effect of low rainfall and ensure farm production. The SCM interactions were consolidated and visualised using the system dynamic (SD) modelling platform STELLA.

The network analysis proposed the causality between features, and it depicted three types of relationship (strong, weak and predetermined) between the features in the causal loop map. The map shows weak SES relationships between government officers and support, government policy (e.g., soil carbon policy) and SCM. SCM co-benefits encompass a wide range of features from agronomic factors to mental health and landscape aesthetics. Training and education support, participation in the social network, other farmers, SCM attitudes, trust in the SCM practices, non-government organisations, SCM cost and trusted expert network were all identified as important features in the social part of the SES. Soil health and most of the interaction-output features or co-benefits were emphasised in the ecological part. Both farmer workshops highlighted that the accrual of co-benefits from SCM practices positively influence other features such as production potential, soil health and support of other farmers in SCM. Farmers believed the agri-environmental benefits of SCM practices positively influence the production potential of the farm and improve soil health. The co-benefits of SCM practices (e.g. improved soil moisture, nutrient, water-holding capacity and soil structure) positively influence interest in training and educational support. Social networks were considered mostly positive for SCM, although they could have negative effects where peer pressure undermines innovation in management.

This study identified six reinforcing and four balancing feedback loops. The feedback loops identified in this study revealed the substantial SES interactions that influence Australian farmers' capacity to manage soil carbon at the farm level and could affect their potential engagement in soil carbon policy initiatives such as the ERF. Balancing feedback loops imply potential solutions for recovering the financial liability and investment cost of SCM of the farms through adoption of SCM. The reinforcing feedback loops indicate the critical features (i.e. social network, SCM co-benefits, training and education support) of SES for SCM to increase adoption of SCM practices and how these features could reinforce the SES for SCM at the farm level to ensure soil carbon sequestration when incorporated in policy. For example, farmers' participation in social networks for SCM increases their interest in training and education on SCM and adoption of SCM practices. Again, training and education support on SCM practices ensure improved SCM co-benefits and good soil health, and the success of the practising farmers encourages other farmers to adopt SCM practices and participate in farmers' social networks for knowledge sharing and improvement of the practices. The feedback loops identified in this study focused largely on the co-benefits of improved farm production and good soil health from current SCM practices, which reinforce or balance on-farm management processes. These feedback loops identified that the co-benefits from SCM have kept farmers motivated to continue their practice, and knowledge of these co-benefits has also filtered out through the existing social networks. To maintain farmers' interest and engage less experienced farmers in SCM practices, continued and improved support from training and education from government and other potential sources were emphasised. Overall, unpacking the SES feedback loops for SCM was important for identifying where the currently practising farmers need support. The feedback loops revealed how resilient the SES for SCM could be to future shocks and perturbations through these balancing and reinforcing feedback loops.

5.4 Farm-level distribution and pattern of SCM based on long-term practitioners' SES (Chapter 4)

Despite the land being subject to permanently limiting variables such as low clay content soil types and low land capabilities, long-term practitioners of rotational grazing have continued to maintain their form of grazing regimes. Research suggested that this perseverance is due to a strongly held soil stewardship ethic (Gosnell, 2021), and some (Orgill et al., 2018) have summarised that while undertaking SCM, graziers have achieved a decline in soil carbon sequestration. Considering these variable explanations for sustained SCM, this study focused on exploring the distribution and pattern of farmers' experiences in SCM practices based on identified SES features in the grazing regimes of NSW Australia in order to identify the potential for soil carbon sequestration through sustained use of practices on grazing lands. The study used an SES approach and developed a questionnaire based on Ostrom's high-level categories of resource system, resource units, governance, actors and interaction-output to analyse the distribution and pattern of the SCM in the grazing regime of Australia. The interviewed farmers (n=25) were practising SCM most often for decades in the Northern Tablelands and Upper Hunter of NSW, Australia. The majority of the study participants were considered to be leading graziers who are highly motivated by their stewardship ethics. The farms have often been subject to periods of recurring drought, exacerbated in some instances by inherent low fertility and limited land capability. To understand the importance of soil fertility and land capabilities for SCM, the study confirmed the soil type and land capabilities of the interviewed farms through eSPADE version 2 of the NSW Office of Environment and Heritages and confined the analysis based on the farm soil types (moderate-fertility and low-fertility farming cohorts). The differences in the pattern of SCM practices of the farmers based on SES categories were visualised and explored in a network map for both the low-fertility and moderate-fertility farming cohorts.

The study explored that moderate-fertility farms have adopted diversified practices to get the best option for improving soil health and production at the farm level. Low-fertility farms choose fewer interventions (e.g. 2–4 SCM in most of the farms), possibly due to the constraints of limited land capability. The number of SCM practices used in moderate-fertility farms was generally more than in the low-fertility farms. Moderate-fertility farms have experienced less use of additional nutrients after introducing the SCM practices, which might be because of the inherently higher soil fertility and land capability of those farms. Low-fertility farms were less likely to have reduced fertiliser applications, as the land is inherently affected by low land capability. The influence of soil stewardship ethics on SCM was more pronounced for the moderate-fertility farms compared to the low-fertility farms, which we hypothesise as being because 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 more SCM practices than the low fertility farms, which allows the farmer to explore better SCM options for their soil health improvement with a minimum risk of farm production loss.

Regardless of resource endowment, all farmers considered their social networks as a platform for sharing the experience of challenges and opportunities of certain SCM practices to the wider community. Both farming cohorts have continued their grazing regime because the experienced benefits are diverse and affect whole-farm sustainability (Fig. 5.3). It was confirmed that soil carbon projects under the ERF are less attractive to farmers, as the farmers are more focused on the results of SCM than the actual amount of soil carbon change. The long-term practitioners are ineligible to participate in SCM of the ERF as soil carbon sequestration is accounted for once joining the scheme and the long-term practices have created uncertainty about soil carbon saturation (Fig. 5.3). Farmers were focused on a number of benefits that accrue from their grazing regimes, including improvements in production, soil moisture retention and soil health. Farmers in more "stressed" environments also emphasised mental health and landscape aesthetics as outcomes of SCM. These features of the farmers' SCM present tangible benefits that are not easily quantified and visibly included in the ERF, but were important for farmers in managing their soil (Fig. 5.3).

5.5 Research challenges, contribution and implications

The main aim of this PhD research was to explore the relationships of the SES features that required time series or detailed qualitative data. Due to a lack of time series data, a qualitative approach was chosen to collect data. The data collection process was disrupted by the mega-drought of 2019, the bushfires in 2019–2020 and Covid-19 travel restrictions. The qualitative approach to determining the SES relationships for SCM required travel to the farmers' locality and spending time building sufficient rapport to have a successful interview. The data collection plan had to be modified several times to continue the research process because of the disruptions to data collection.

This thesis has contributed to our understanding of SCM in grazing regimes and revealed the relationships (interactions and feedback loops) between the SES features of SCM in a framework. To secure the involvement of farmers in the current ERF SCM policy, it is necessary to address the major impediments that were identified in this study, as expanded on below. The research contributions of this thesis for particular audiences are discussed below.

5.5.1 SES researchers

The study is the first attempt to research the role of SES for SCM. It revealed the first ever key component-based SES framework for unravelling interdependencies of both social and ecological components of SCM and analysing sustainability of the system. The approach of a two-stage systematic review and use of NVivo12 plus to analyse the reviewed articles is novel and repeatable for future SES research. This thesis used a novel approach to operationalising an SES framework for SCM in the grazing regimes of Australia. This study used Ostrom's high-level categories of the general SES framework to unpack the SES relationships in SCM. Use of various software (e.g. igraph and Network 3D of RStudio and STELLA used for SD modelling) was demonstrated in this study and is repeatable in future studies for comprehensive quantitative modelling studies such as SES relationships using time series data at the farm level. This study used a unique SES approach: firstly, SES relationships from farmer interviews (n=25) were examined in a quantitative manner using social network analysis; secondly, revealed relationships were verified qualitatively using participatory stakeholder workshops; and, finally, consolidated SES relationships were visualised in a causal loop map. The feedback loops for SCM were also explored with regard to the consolidated SES relationships. This approach improved Ostrom's SES framework for SCM and provided a simplistic understanding of the complex interrelationships of the SES features for SCM. Our approach and findings are novel and will be useful for operationalising the SES framework for similar data-poor regions of the world.

Moreover, this study used a novel SES approach to examine not only the sustainability of the current SCM practices for both low-fertility and moderate-fertility soils types, but also the existing policy, to ensure that the farmers are represented. The investigation identified how farmers have continued to manage soil carbon and what features have helped or hindered their management. This approach is replicable for similar data-poor regions of the world. The SES for SCM of this study is that of experienced farmers; however, time depth and how the SES changes over time were not considered in this research. This research characterised variables as "features" to make complex SES terminology more accessible to a wider audience, and introduced a new SES approach (network analysis) for translating the qualitative response to a quantitative response in order to understand the strength of the connectivity between features.

Another important contribution of this study is the co-production of knowledge on policy implications for sustainable SCM from the experienced graziers (Fig. 5.3). Our approach with in-depth interviews and workshops meets knowledge co-production principles for sustainability research (Norström et al., 2020). The knowledge co-production that was achieved through the interviews and workshops of this study was context-based (i.e. SES relations for SCM in the grazing regimes), pluralistic (i.e. recognises multiple ways of knowing and doing), goals oriented (i.e. clearly defined meaningful goal related to challenges of unravelling the SES relationships for participatory SCM policy) and interactive. The methods used in this thesis are a way forward to ensuring policy and programs make a difference to the lives of landholders and those that rely on farmers for food and clothing. The approach used in this thesis is a way to incorporate farmers' local experience of SCM for the future and the preservation of local knowledge. In the business world, it would be corporate knowledge, or a more old-fashioned term – wisdom.

5.5.2 Policy and research support for SCM

This thesis identified that important social aspects (farmers' attitudes toward management change, connections of the government policy with farm-level practices) are often discounted in SCM research in Australia. This study showed that SES features are interlinked in SCM, and both ecological and social components need to be considered comprehensively. This study results suggested an SES for managing slow variables, such as soil carbon at a landscape spatial scale, for an integrated management approach, and proposed a novel key component-based SES framework in the Australian context. The SES framework, once operational, may help to assess the interdependencies of both the social and ecological components of SCM at the farm level and hence ensure the farm-level sustainability of the SES, which may enhance the process of achieving the SDGs, especially those related to soil (2, 3, 6, 13, 15 and 17) (Lal et al., 2021).

The next steps of the study unpacked the SES relationships in SCM to determine the importance and potential contribution of grazing enterprises in Australia to offsetting GHGs through sequestering carbon in soil. In the studied system (mainly rotational grazing), carbon market, SCM pricing and monitoring, and financing were negatively related to SCM (Fig. 5.3). SCM practices provide co-benefits to the practising farmers and build trust with other farmers. They also enhance soil stewardship ethics, which, in turn, positively contributes to the SCM economy (Fig. 5.3). However, this SES relationship was overlooked in the framing of the ERF, which has a minor emphasis on soil stewardship and focuses on farmers taking up practices for SCM not previously practised at the location.

While unpacking the SES relationships in SCM, this thesis revealed five broad themes (i.e. co-benefits, training and education, farmers' social networks, inclusion of pluralistic values and interconnected feedback loops of SCM) that are relevant to soil carbon policy for a more inclusive agenda with improved information flows and greater incentives for landholders to undertake SCM in Australia. The study highlighted the role of co-benefits in the farmers' decision-making process. Both the service providers and farmers experienced that SCM enhances co-benefits and the co-benefits compensate for the additional costs of SCM, which essentially leads to greater adoption of SCM and sustained use. Again, according to the SES for SCM, training and education support were positively connected to trust, production potential and soil health (Lobry de Bruyn et al., 2017). Moreover, our SES relationships showed that training and information on SCM pricing and monitoring need to flow through farmers' social networks to build trust and ensure greater engagement (Kragt et al., 2017).

The thesis revealed that the most prevalent governance feature for the long-term grazing practitioners was training and education support, followed by farmers' social networks, pluralistic views of the climate policy, and carbon pricing and monitoring (Fig. 5.5). Current SCM projects under the ERF are mainly focused on carbon pricing and monitoring, whereas consideration of the important farmers' perspective (Fig. 5.5) for successful SCM, support for education and training and social networks, is absent. The existing social networks of the practitioners of SCM (i.e. rotational grazing) generally involve networking with like-minded graziers (e.g. biodynamic farming, cell or plan grazing, holistic agriculture, regenerative agriculture), which could be geographically dispersed or local neighbours who do not necessarily practise the same grazing management but are long-standing friends, and online platforms through social media (i.e. Facebook, Twitter). Many of the existing social networks, largely supported by Landcare, are less active than they once were as a social network and require reinvigoration. As a prevalent feature of SCM, government needs to reinvigorate the social networks (Jones et al., 2019), especially those that are aging or inactive, by providing incentives and using extension agents or independent advisors who motivate these practitioners as part of their current level of practice.

The feedback loops emphasised co-benefits in a particular SES and provided guidelines for the level and types of public and private investment in SCM. The study results support the pluralistic values in climate change policymaking in terms of considering the range of stakeholders' views to encourage other stakeholders' participation in current SCM systems. Such co-production of policy may positively influence farmers' motivation to participate in SCM and beyond the direct soil carbon project under the ERF, which focuses on a single feature (i.e. improving soil carbon), but the scale does not often consider the wider trade-offs of the whole carbon cycle. This thesis showed that understanding the relationships across feedback loops and focusing on the all-inclusive SES for SCM could resolve this problem. For example, SCM reinforces the positive change of income in a reasonable time frame and with planning, but this could lead to increased numbers of livestock in the managed grazing lands, which will convert the sink to a source. However, with a detailed understanding provided by all-inclusive SES for SCM, reducing stocking rates (Bork et al., 2020) and introducing rotational grazing (Liu et al., 2021) could resolve this problem. The emergent features and interrelationships could guide the policy and research to explore gaps (e.g. prevalent governance features and social network ignored in current ERF), challenges (e.g. farmers' experienced important co-benefits were harder to measure) and the requirements of the stakeholders (e.g. farmers' SCM agenda focused more on the results of SCM than the actual value of soil carbon change) to achieve local, national and international goals such as SCM co-benefits, GHG reduction targets and SDGs (Lal et al., 2021) (Fig. 5.1). The SES for SCM suggests a more suitable governance arrangement such as nested or polycentric governance (Marshall, 2008; Ostrom, 2007). This type of governance places resources, people and funding where it is needed and is the most useful.

Increasing soil carbon in grazing systems accounts for 5% of ERF projects (Baumber et al. 2019) but any of these practices needs to be *new* to the ERF approved project area to ensure 'additionality'. The current focus of the policy is converting cropland to permanent pasture, rejuvenating pastures, or changing grazing patterns. Participation in the ERF is difficult for the farmers interviewed. They are long-term practitioners of their SCM practices and there is a high degree of uncertainty about the extent to which extra carbon will be sequestered. It is possible that they have achieved as much (or nearly as much) soil carbon sequestration as is possible in their grazing systems. Since soil carbon storage is only rewarded by the ERF upon joining the scheme, it is possible that our interviewed farmers have little room to secure increases in soil carbon and thus the rewards are minimal. These obstacles are a considerable disincentive for long-term practitioners of rotational grazing as their system has probably reached an equilibrium in soil carbon, and future improvements in soil carbon are unlikely. The most likely candidates for the ERF scheme are farmers who have either acquired farms in poor condition and want to improve them, as they would be eligible to claim their management is *new* to the ERF project area, or farmers who are inexperienced in rotational grazing management and newly adopt rotational grazing techniques to sequester more soil carbon on their farm. Farmers such as those interviewed have limited ability to re-locate or acquire *new* lands in order to achieve attractive enough soil carbon gains to make undertaking an ERF-accredited soil carbon project worthwhile. Limitations include attachment to place and the capital costs of re-location or acquisition of more land. Equally, supporting farmers *new* to rotational grazing requires significant training and educational support.

Currently, participation in the ERF is voluntary but studies show the process of the accounting and incentives present many obstacles to farmers' participation (Evans 2018; Kragt et al. 2016). According to our study, farmers are disconnected from the SCM governance system (e.g. ERF); therefore, increasing engagement in the current government policy is imperative for greater uptake, notwithstanding that many would be ineligible due to their long-term practitioner status. Lack of connection of government with grazing farmers could seriously hamper progress towards the goal of net zero emissions by 2050, especially given grazing lands account for 50% of Australia's agricultural land area (Climate Work Australia, 2021) and could be a substantial contributor to the achievement of carbon neutrality. Data on the areas of pasture, perennial pasture and improved pasture are collected by the Australian Bureau of Statistics (ABS 2021), but data are not collected on the area of grazing land managed by farmers committed to SCM and undertaking rotational grazing as part of a grazing regime.

Another critical step in the policy settings is documenting soil carbon sequestration. The Australian Government is currently reviewing the ERF's soil carbon protocol (Australian Government 2021b), which may result in wider eligibility criteria. The National Soil Strategy (NSS) of Australia, which was instigated in 2014, has prioritized for the next 20 years a set of new actions funded under this strategy (ABS 2021). Actions include establishing a farm-level soil database that is developed with farmers' participation via soil testing incentives, with the aim of enabling farmers to enhance stewardship of their land and earn revenue from carbon trading and improvements in natural capital (Australian Government 2021a). The NSS also seeks to help farmers use soil testing to identify areas where practices can be changed and use can be made of relevant technologies. Badgery et al. (2020) showed that the carbon sequestration method developed under the ERF that is related to land use and management changes include converting cropping land to grazing lands, incorporating organic amendment and reducing tillage. In addition, the science is uncertain about the extent of farm-level carbon sequestration with various changes in land use and how quickly carbon can be built up in the soil profile under specific SCM practices (Badgery et al. 2020). The ERF guide to grazing systems methods states, "*A review of soil carbon sequestration potential (Sanderman et al. 2009)concluded that there is potential to build soil carbon in grazing systems by improving pasture production and managing grazing pressure to increase inputs of plant biomass into the soil"*, but does not offer greater detail on the amounts expected and under what types of environmental settings (CER 2015).

Most of the farmers have been measuring the co-benefits of SCM management through informal observation, and farmers considered they were *paid* for storing soil carbon as agri-environmental benefits without necessarily being part of an authorised scheme. While farmers have proven they have an appetite for soil carbon sequestration by undertaking particular land management activities (e.g. rotational grazing) (Smith et al. 2020), farmers reported that further support through education and scientific advice on techniques would be helpful, which is something that is already reflected in the objectives of the NSS. SCM practices and farmers' attitudes towards practices are largely unaffected by the land's capability. Policy needs to consider the current SCM as an SES rather than a singular entity. Incentives, initiatives and introduction of support at the farm level should be informed by farmers' participation and dialogue within social networks. The ERF needs to consider the introduction of low-cost alternatives to current soil carbon auditing, perhaps through farmers' trusted networks and independent advisors with whom they already have established relationships. 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. 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).

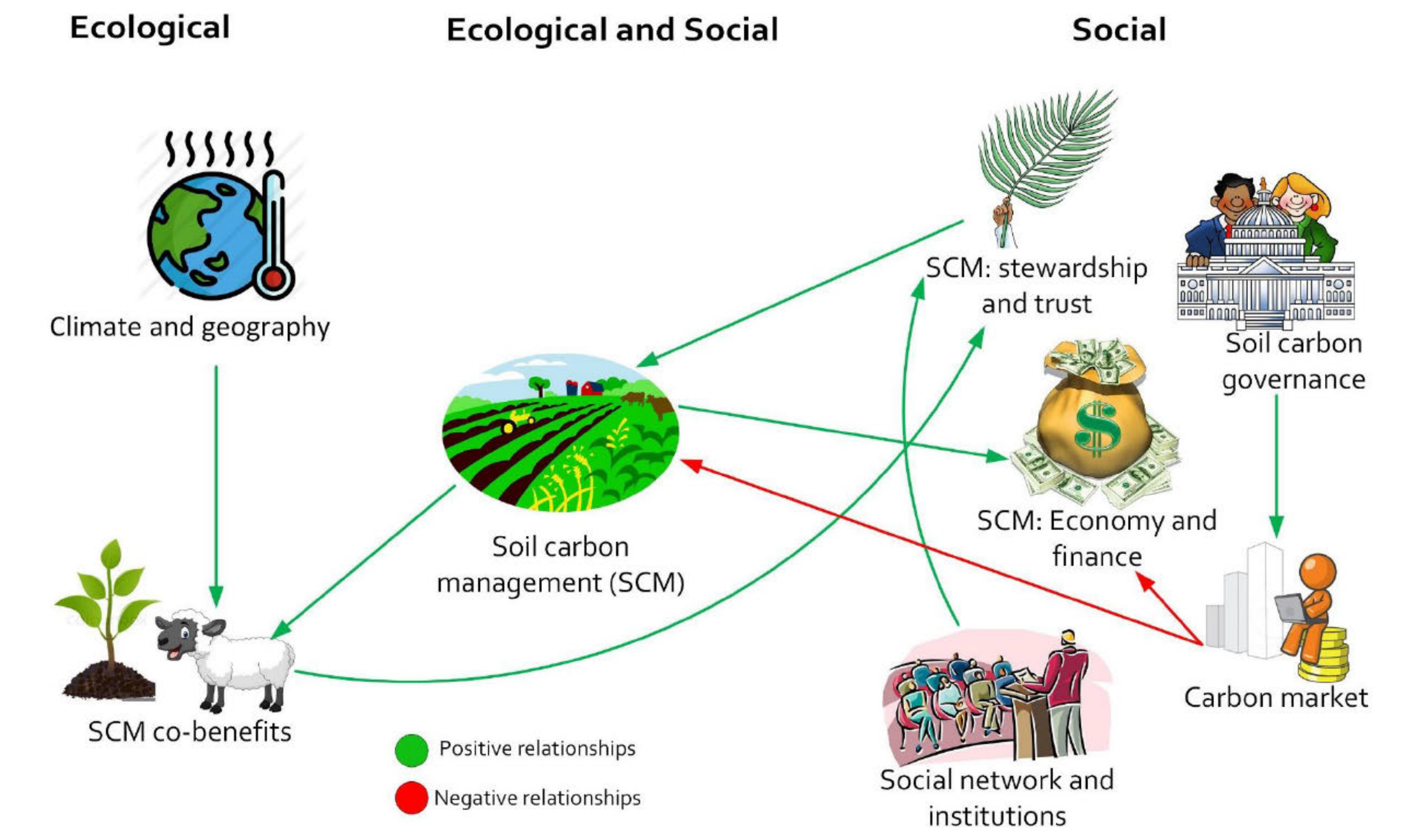

Fig. 5.3. Overview of the current SES relationships in SCM in the grazing regimes of Australia

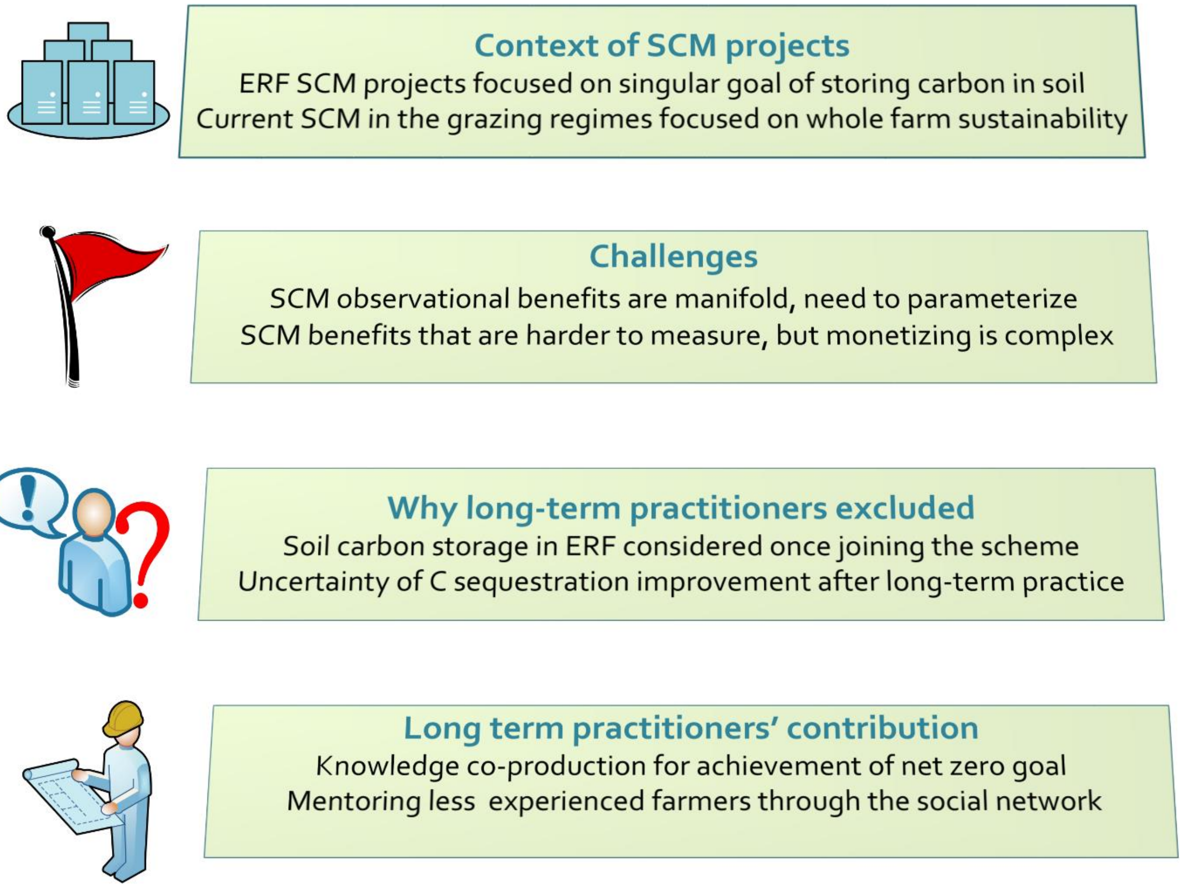

Fig. 5.4. Context of the soil carbon projects under emissions reduction funds and potential contribution of long-term practitioners

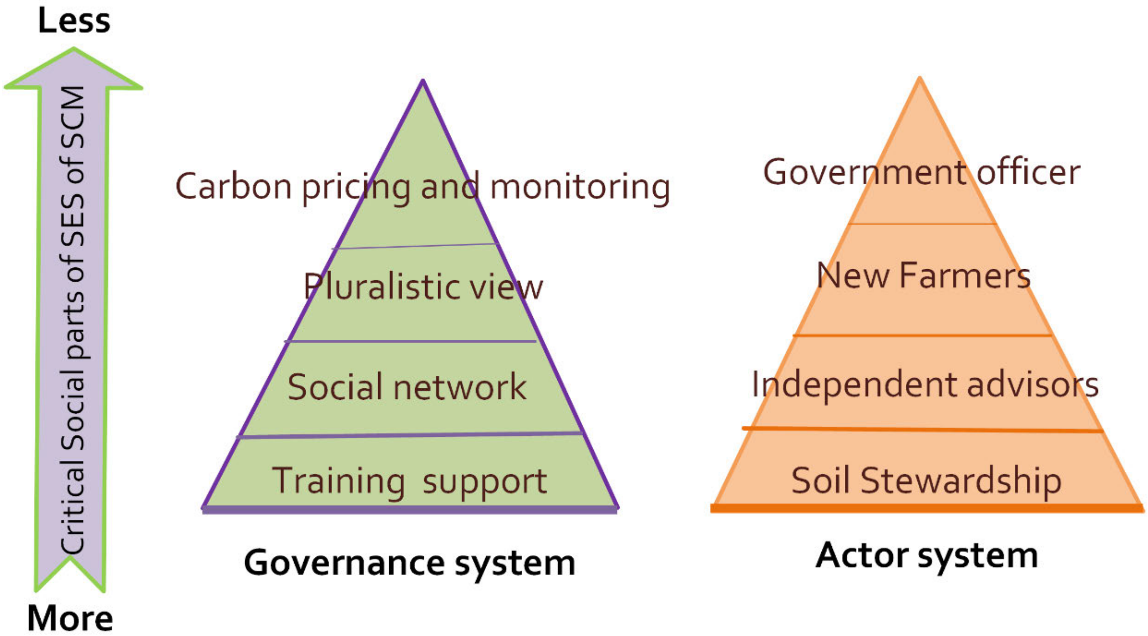

Fig. 5.5. Prevalent SES features of SCM under governance and actor systems of the current SES for SCM in the grazing regimes

5.5.3 Practitioners

The type of grazing management needs to be new to the ERF-approved project area, thus for long-term practitioners, their involvement with the ERF will be difficult for two reasons: (i) the high degree of uncertainty of the carbon sequestration in soil, as their system probably reached an equilibrium for long-term practices (e.g. rotational grazing management) and (ii) soil carbon sequestration is accounted for once joining the scheme. Farmers from both the moderate-fertility and low-fertility farming cohorts focus on a number of benefits they accrue from their SCM and on whole-farm sustainability. They are not just focused on soil carbon (Fig. 5.4). In fact, most farmers have poor records of their soil carbon, and there is a lack of longitudinal records of soil carbon change through soil testing (Lobry de Bruyn and Andrews, 2016). Farmers from both farming cohorts experienced other tangible benefits from their SCM practices such as improvements in mental health (Brown et al., 2021) and landscape aesthetics, but these features are not usually factored into policies or programs.

Thus, soil carbon policy needs to consider the SCM as a complete package to ensure long-term practitioners' participation in the current ERF. Our study findings suggested that the younger and less experienced farmers may be more willing and able to engage in the ERF schemes, and they could be more engaged with the process when mentored by long-term practitioners who are using existing or reinvigorated social networks (Fig. 5.4). This thesis found that the farming community is an aging workforce, with weak succession plans to inform the next generation of landholders and managers. The role of land ownership influences the choice of SCM; for example, industry have their own interests in land management. This thesis revealed that the start-up costs of SCM and changing to rotational grazing initially results in the land manager compromising or risking farm income. Our SES for SCM showed that SCM in Australia needs to consider these perspectives of the practitioners for the success of future SCM, especially for soil carbon sequestration outcomes.

The Australian ERF is a federally funded program but all natural resources, including soil, are governed by state governments. However, improving social networks and soil governance are interrelated, as governance affects the level of government support and funding of social networks like Landcare or education and extension services delivered by state-operated organisations such as Local Land Services or the Department of Planning, Industry and Environment in NSW. This research revealed that the most critical actor system feature in the current SES for SCM is soil stewardship ethics, followed by independent advisors, other farmers and government officers (Fig. 5.5). Government officers are the most prevalent actors in terms of the level of SCM data and knowledge (Fig. 5.2), and demonstrate substantial importance in the ERF for carbon pricing and monitoring along with the registration process. However, according to the graziers who are practising SCM, individual advisors are the most important actor, as they largely influence the adoption of their SCM practices. This thesis showed that this important group of people (i.e. individual advisors) could be an intermediary or change agent for linking farmers to government policy. The SES for SCM of this study also revealed that funding for on-farm research with farmers to obtain more localised data on their SCM practice could help to achieve government targets for soil carbon sequestration.

5.6 Future research directions

Scientific studies are expanding our knowledge of SCM research, and our study findings suggest that there are a number of areas that need to be addressed in future research for the success of the SCM and achieving the net zero goal and improving knowledge of the short- and long-term social and ecological benefits of SCM and the practices that influence soil carbon storage and reduce the difficulties (e.g. duration of pasture establishment, forest plant plantation time) in estimating the carbon storage potential. Given the low farmer involvement in the research process, future research on soil carbon management needs to integrate social variables and engage practitioners in experimental examination to improve SCM practices in Australia. Agricultural SCM adoption and long-term use of those practices depends on practitioners' interest in and understanding of SCM technology at the farm level. Future research may include the extension and operationalisation of the SES conceptual framework, and could examine the dynamics (e.g. interactions and feedbacks) of the complex system and longitudinal changes over time. The next level of research needs to quantitatively examine the interaction and feedback loops of SES for SCM using farm-level time series data (socio-economic, soil test data) for comprehensive understanding of the influence of features on each other. Also, to understand and ensure the long-term practitioners SCM influence, future research should examine the longitudinal impact of the rotation grazing management on soil carbon. The evidence from these parameter values would then be able to verify the fact of the long-term practitioners' observational records of SCM co-benefits (e.g. soil moisture, nutrient, pasture production and financial records) so that they can be included in the ERF process. The big gap identified in this research is around farmers who have not yet adopted SCM practices. What might influence them to take it up? What would be their SES look like using Ostrom's model? How does their engagement with the ERF differ from the farmers cohorts interviewed in this study?

5.7 Conclusion

SCM research in Australia is dominated by the ecological features, predominately from scientists' perspectives, with farmers' perspectives being largely ignored. Current SCM initiatives of the Australian Government are less attractive to the long-time practitioners who have been practising rotational grazing for decades in the grazing regimes of Australia. Although grazing management has been included in the current policy initiatives it is generally only attractive to a practitioner who acquires new land to register for a soil carbon project and earn soil carbon credits. However, disregarding possible carbon saturation status under long-term SCM practices, the uncertainty of the policy for practice-orientated carbon pricing (e.g. carbon credits for particular grazing management considering the state of the edaphic and climatic factors) and a low participatory government decision-making process has led to low participation of the currently practising farmers in government-led soil carbon project initiatives. Some of the landholders have started soil carbon projects on existing land and introduced at least one new practice with some baselining of SOC levels. The issue is for farmers who have been practicing improved SCM for many years is that they have possibly reached a new equilibrium of soil carbon, thus in most instances they have little to gain from ACCUs. However, landholders who are yet to start or only partway along adjusting their SCM have greater potential on their existing land.

The thesis revealed that SCM needs to consider comprehensive social and ecological interactions and feedback loops for successful decision making that can ensure soil carbon sequestration. This study operationalised Ostrom's SES framework and unpacked the interactions among the SES features of SCM in the grazing premises. As the studied farmers are focused on the broad agri-environmental benefits of SCM practices in a holistic manner, the current structure and eligibility criteria for soil carbon projects are unlikely to engage these long-term practitioners. Hence, future government policy needs to consider the type of structures and rewards that will broaden the scope of eligible farmers for soil carbon projects. Thus, government soil carbon policy should focus on a broader agenda that aligns to farmers' practice and soil stewardship ethics. This broader agenda should be equally focused on the results of SCM and the actual value of soil carbon change. This shift in policy from a single-issue focus is recognising that farmers' SES for SCM is focused on a number of SCM outcomes that include biophysical soil characteristics (i.e. soil moisture, soil structure and nutrients) and other benefits (i.e. improved mental health, landscape aesthetic), which are harder to measure and more valued in the stressed environments of lower soil fertility. The current SES relationships in SCM have weak connections to the existing policy settings, and by recognising current SES dynamics and their relationship to policy, there is a chance to change this dynamic. The SES relationships determined in this study provide a guide to research and policy for achieving the goal of net zero emissions by 2050, given that grazing lands account for 50% of Australia's agricultural land area. Moreover, the SES relationships provide an understanding of a simpler metric of soil organic carbon, such as 100% ground cover that a large percentage of farmers understand and relate to. This could be a way of calculating biomass and soil carbon accounting inputs and losses (erosion, microbial decomposition, residue removal) to see if the system is accruing or deficient in soil carbon. The SES approach used in this thesis is novel and applicable to other data-poor regions of the world. Also, the experience of farmers who are focused on whole-farm sustainability and who have managed to sustain their SCM through challenging times needs to be connected to younger and less experienced farmers' SCM. This experience encompasses the broader system dynamics that sustain farming and can potentially improve soil carbon sequestration. The results of this PhD thesis reflect the knowledge of experienced long-time practitioners and are useful for achieving a more targeted, customised and nuanced government policy for achieving the global SDG targets.

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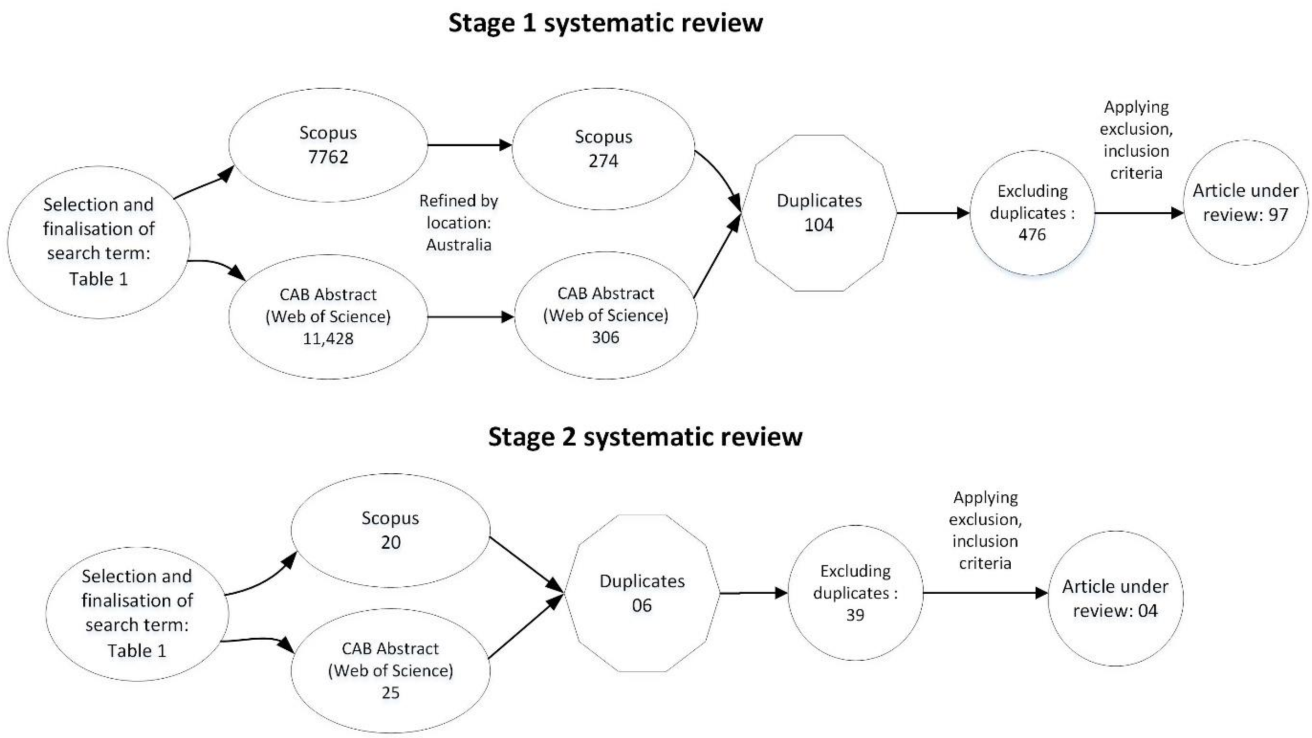
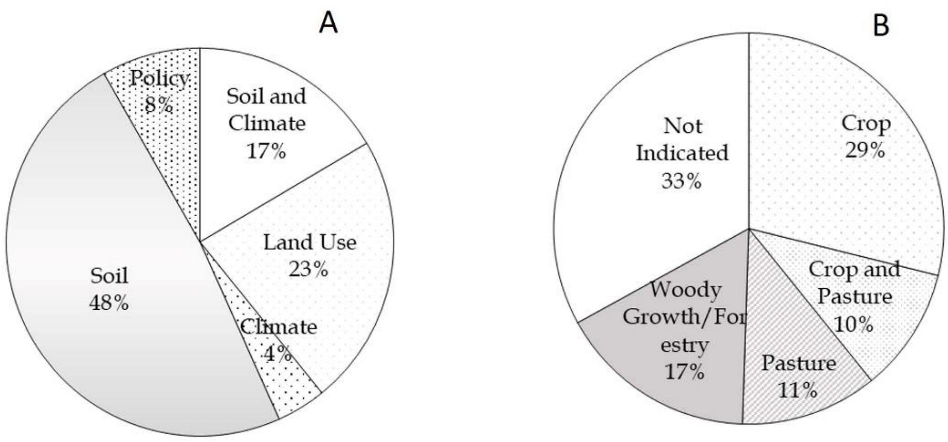
Appendix A

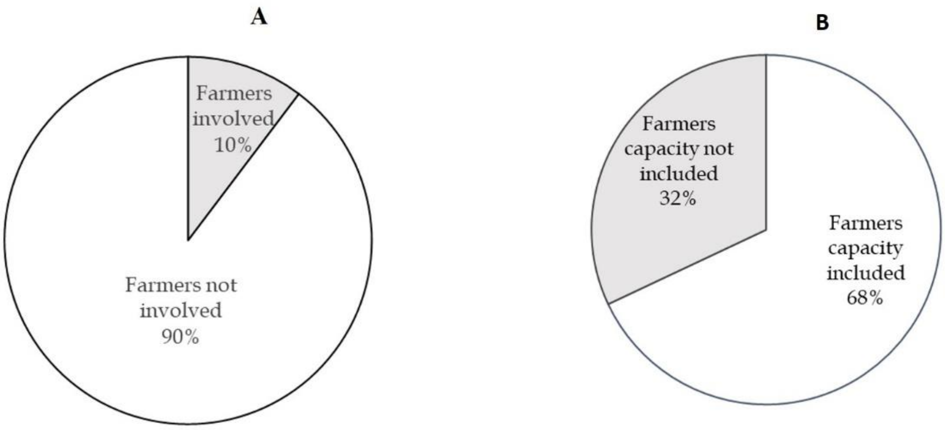
Supplementary Information: Chapter 2



Appendix A, Fig. 2.1. Flow chart of the two stages of the systematic reviews of this study. Stage 1 was to review the scientific works on soil carbon management in Australia and Stage 2 was to review the scientific works on the extent of SES use in soil carbon management.



Appendix A, Fig. 2.2. Ecological and social component of soil carbon management in Australia from Stage 1 of the systematic review. A. The types of ecological and social variables (e.g. soil, climate) examined in the scientific articles n= 97. B. The types of land use (crop, pasture) where the research was conducted in the articles n=97



Appendix A, Fig 2.3. Soil carbon management research in Australian agriculture. A. Proportion of articles with farmers' involvement in research (n=97) and B. Proportion of articles that included discussion of farmers' capacity for soil carbon management (n=97).

Appendix A, Table 2.1. Search terminology used for systematic review

Stage of the search	Search term used
Stage 1 search terms	"soil carbon" OR "carbon sequestration" OR "soil organic carbon" OR SOC OR "soil management" AND (farmer* OR agriculture) AND Australia
Stage 2 search terms	"soil carbon" OR "carbon sequestration" OR "soil organic carbon" OR SOC OR "soil management" AND (farmer* OR agriculture) AND "socio-ecological" OR "social and ecological" OR "social-ecological" OR SES OR "human-nature*" OR "human-environment"

Appendix A, Table 2.2. Status of soil carbon management research in Australian agriculture up to 2018 (n=97 articles)

Soil carbon research	Level of spatial scale	Component of SES	Focus of research	Published articles on topic
Land use studies				
Long-term agriculture effect on soil type and carbon stock	National, **Regional*,** Local or farm	Social-ecological, **Ecological*,** Social	• Soil organic carbon dynamics, APSIM, RothC, Agro-C model ability to simulate the SOC from long term experiments • Measuring the soil organic carbon (SOC) stock in pasture and cropping • Effect of improved SOC levels on farm productivity, soil-water use efficiency, biodiversity and tillage • Potential impact of soil properties and climate on soil carbon stock	Chan, 2001; Schneider, 2007; Maraseni et al., 2008; Baldock et al., 2012; Davy and Koen, 2013; Hoyle et al., 2013; Roper et al., 2013; Wang et al., 2013; Bryan, 2014; Sanderman et al.,2013a; Sanderman et al.,2013b Orgill et al., 2014; Ahmad et al., 2015; Rabbi et al., 2015; Zhao et al., 2015; Grundy et al., 2016; Robertson et al., 2016; Wocheslander et al., 2016; Doran-Browne et al., 2018; Orgill et al., 2018; Chappell and Baldock, 2016.

Soil carbon research	Level of spatial scale	Component of SES	Focus of research	Published articles on topic
Land use effects	National, **Regional*,** Local or farm	Social-ecological, **Ecological*,** Social	• Trade-offs and synergies of carbon farming, agricultural production and biodiversity conservation • Land use change effect on biodiversity and carbon sequestration • Context of greenhouse gas emission from land-based sectors	Wilson et al., 2010; Kragt et al., 2012; Bradshaw et al., 2013; Rabbi et al., 2015; Morán-Ordóñez et al., 2017 Harper et al., 2007; Forouzangohar et al., 2014; Hobley et al., 2017; Chan et al., 2010; Chan, 2001; Cowie et al., 2012; Maraseni, 2016; Minasny et al., 2017; Race 2013.
Agroforestry	National, **Regional***	**Ecological***, Social	• The approach to develop forestry practices in the agricultural lands • The factors that limit biodiversity and carbon sequestration potential • The dynamics of tree-pasture growth, forest product yield, the potentials of carbon stock change in soil	Donaghy et al., 2010; George et al., 2012; Mitchell et al., 2012; Renwick et al., 2014; Longmire et al., 2015; Preece et al., 2015; Hobbs et al., 2016; Paul, 2016; Harper et al., 2017; Dwyer et al., 2010.
Social, economic and policy context of soil carbon	National, Regional	Social-ecological, **Social***	• Soil carbon sequestration benefits in terms of socio-economic and political context • Socio-economic factors that influence tillage practices	Dwyer et al., 2009; Maraseni, 2009; Thamo et al., 2013; Liu et al., 2018; Grace et al., 2010; Gunasekera et al.,

Soil carbon research	Level of spatial scale	Component of SES	Focus of research	Published articles on topic
			• Political trend in carbon stock management	2007; McHenry, 2009b; Van Oosterzee et al.,2014; Sinnett et al., 2016.
Carbon farming initiatives related research	**National***, Regional	Social-ecological, **Social***	• Assessing the co-benefits of carbon farming and community values on climate change mitigation • The cost and benefits of emission reduction funds in Australia • Factors affecting adoption of carbon farming	Bryan et al., 2015; Page and Bellotti, 2015; Dumbrell et al., 2016; Kragt et al., 2016; Verschuuren, 2017; Evans, 2018; Rochecouste et al., 2017.
Economic return of tree planting in agricultural lands	**Regional***	**Social-ecological***, Social	• Monetary return from carbon plantings and agriculture • Model based estimation of the total carbon emission reduction possibilities from environmental plantings	Crossman et al., 2011; Grace et al., 2010; Paterson and Bryan, 2012.
Grazing intensity and climate change effect	National, Regional	**Ecological***	• Influence of grazing on SOC, ground cover and biodiversity • Uncertainties and magnitudes of carbon flux due to intensive grazing and climate change	Dean et al., 2012; Waters et al., 2017
Soil management studies				

Soil carbon research	Level of spatial scale	Component of SES	Focus of research	Published articles on topic
Combined management practices and environmental effect	National, **Regional***	**Ecological*,** Social	• Effect of improved management practices (e.g. no till, stubble retention, stubble burning, and nitrogen fertiliser) to promote macro-aggregates formation and effect of the environmental variables (temperature, rainfall)	Wang et al., 2004; Wang and Dalal, 2006; Dean et al., 2012; Cotching et al., 2013; Liu et al., 2016; O'Leary et al., 2016; White and Davidson, 2016; Sarker et al., 2018; Dumbrell et al., 2017; Page et al., 2013b; Zhao et al., 2013.
No till and trash retention, Crop residue retention	National, **Regional***, Local or farm	Social-ecological, Ecological	• No till and trash retention for total organic carbon stock change measurement • Measurement of soil organic carbon stock change by crop residue retention in the crop field	Page et al., 2013; Rabbi et al., 2014; Conyers et al., 2015; Luo et al., 2016; Bajgai et al., 2014; Chan and Heenan, 2005; Hardie, and Cotching, 2009; Mitchell et al., 2016; Zhou et al., 2016.
Tillage effect and factor of adoption	National, Regional	**Social-ecological***, Social, Ecological	• Changes in tillage-based soil carbon under different tillage practices • Factor of adopting the different tillage practices by farmers	Ugalde et al., 2007; D'Emden et al., 2008; Young et al., 2009; Rochecouste et al., 2015.

Soil carbon research	Level of spatial scale	Component of SES	Focus of research	Published articles on topic
Minimum/zero/ conservation tillage and crop rotations	Regional**,** **Local or farm***	**Social-ecological***, Ecological	• Estimation and comparing the conventional and zero tillage base greenhouse gas emission in crop rotation • Minimum tillage and crop rotation in irrigated vertisols	Blair and Crocker, 2000; Hulugalle, 2008; Maraseni and Cockfield, 2011; Senapati et al., 2014.
Cropping system effect	National, Regional	Ecological	• Analysing the agronomic benefits of soil organic carbon (SOC) in grain cropping system • Estimation of SOC and its uncertainty caused by cropping and environment	Luo et al., 2014; Petersen and Hoyle, 2016; Macdonald et al., 2013.
Bio-char	National, **Regional***	Social-ecological, Ecological	• Bio-char production for renewable energy generation and soil carbon sequestration • Bio-char effect on soil chemistry and plant species response	McHenry, 2009a; Singh et al., 2014; Drake et al., 2015

*Dominant component within the category

Appendix A, Table 2.3. A comprehensive list of variables within the social and ecological components of carbon management research from NVivo12 plus analysis of Stage 1 of the systematic review (n=97)

Component	Variables with ecological or social component
Ecological	Climate (rainfall, temperature and evaporation), soil textural fraction (sand, silt and clay), aridity, topography (slope and elevation), plant diversity, forestry practices (production forestry, plantation forestry) geographic location, water availability, micro-climate, vegetation types, parent material (soil depth, soil type), land uses (pasture type, cropping and mixed, native forest)
Social	Policy instruments (taxes, subsidies and certification for carbon management), access to quality information, access to diverse income streams, farm characteristics (farm size, farm income, local/farm agricultural practices, tillage practices, ground cover maintenances, farm productivity, nutrient management), Carbon governance, information source from trusted peers, social networking system for carbon management, computability with the existing carbon management plans, farmers' attitude and perceptions of climate change, desirability and preference of the land use change, administrative arrangements, social response to land use change, awareness of the carbon farming policy, willingness to adopt carbon farming practices, communication level of co-benefits, Soil management history, opportunity cost of land (property value change due to new management approach), financial cost and benefits (e.g. establishment and management cost, labour requirements), Market of forest products

Appendix A, **2.1 List of Reviewed Articles**

Ahmad, W., Singh, B., Dalal, R. C., and Dijkstra, F. A. (2015) Carbon dynamics from carbonate dissolution in Australian agricultural soils. Soil Research.

Bajgai, Y., Kristiansen, P., Hulugalle, N., and McHenry, M. (2014) Changes in soil carbon fractions due to incorporating corn residues in organic and conventional vegetable farming systems. Soil Research 52, 244-252.

Baldock, J. A., Wheeler, I., McKenzie, N., and McBrateny, A. (2012) Soils and climate change: potential impacts on carbon stocks and greenhouse gas emissions, and future research for Australian agriculture. Crop & Pasture Science 63, 269-283.

Blair, N., and Crocker, G. J. (2000) Crop rotation effects on soil carbon and physical fertility of two Australian soils. Australian Journal of Soil Research 38, 71-84.

Bradshaw, C. J. A., Bowman, D. M. J. S., Bond, N. R., Murphy, B. P., Moore, A. D., Fordham, D. A., Thackway, R., Lawes, M. J., McCallum, H., Gregory, S. D., Dalal, R. C., Boer, M. M., Lynch, A. J. J., Bradstock, R. A., Brook, B. W., Henry, B. K., Hunt, L. P., Fisher, D. O., Hunter, D., Johnson, C. N., Keith, D. A., Lefroy, E. C., Penman, T. D., Meyer, W. S., Thomson, J. R., and Thornton, C. M. (2013) Brave new green world consequences of a carbon economy for the conservation of Australian biodiversity. Biological Conservation 161, 71-90.

Bryan, B. A., Crossman, N. D., Nolan, M., Li, J., Navarro, J., and Connor, J. D. (2015) Land use efficiency: anticipating future demand for land-sector greenhouse gas emissions abatement and managing trade-offs with agriculture, water, and biodiversity. Global Change Biology 21, 4098-4114.

Bryan, B. A., Nolan, M., Harwood, T. D., Connor, J. D., Navarro-Garcia, J., King, D., Summers, D. M., Newth, D., Cai, Y., Grigg, N., Harman, I., Crossman, N. D., Grundy, M. J., Finnigan, J. J., Ferrier, S., Williams, K. J., Wilson, K. A., Law, E. A., and Hatfield-Dodds, S. (2014) Supply of carbon sequestration and biodiversity services from Australia's agricultural land under global change. Global Environmental Change 28, 166-181.

Chan, K. Y. (2001) Soil particulate organic carbon under different land use and management. Soil Use and Management 17, 217-221.

Chan, K.Y., Heenan, D.P. (2005) The effects of stubble burning and tillage on soil carbon sequestration and crop productivity in southeastern Australia. Soil Use and Management 21, 427-431.

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, 7-15.

Chan, K.Y., Conyers, M.K., Li, G.D., Helyar, K.R., Poile, G., Oates, A., Barchia, I.M. (2011) Soil carbon dynamics under different cropping and pasture management in temperate Australia: results of three long-term experiments. Soil Research 49, 320-328.

Chappell, A., and Baldock, J. A. (2016) Wind erosion reduces soil organic carbon sequestration falsely indicating ineffective management practices. Aeolian Research 22, 107-116.

Conyers, M., Liu, D. L., Kirkegaard, J., Orgill, S., Oates, A., Li, G., Poile, G., and Kirkby, C. (2015) A review of organic carbon accumulation in soils within the agricultural context of southern New South Wales, Australia. Field Crops Research 184, 177-182.

Cotching, W. E., Oliver, G., Downie, M., Corkrey, R., and Doyle, R. B. (2013) Land use and management influences on surface soil organic carbon in Tasmania. Soil Research 51.

Cowie, A. E., R.:Eady, S. (2012) Greenhouse gas accounting for inventory, emissions trading and life cycle assessment in the land-based sector: a review. Crop & Pasture Science 63, 284-296.

Crossman, N. D., Bryan, B. A., and Summers, D. M. (2011) Carbon payments and low-cost conservation. Conservation Biology 25, 835-845.

D'Emden, F. H., Llewellyn, R. S., and Burton, M. P. (2008) Factors influencing adoption of conservation tillage in Australian cropping regions. Australian Journal of Agricultural and Resource Economics 52, 169-182.

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Davy, M. C., and Koen, T. B. (2013) Variations in soil organic carbon for two soil types and six land uses in the Murray Catchment, New South Wales, Australia. Soil Research 51, 631-644.

Dean, C., Wardell-Johnson, G. W., and Harper, R. J. (2012) Carbon management of commercial rangelands in Australia: Major pools and fluxes. Agriculture, Ecosystems and Environment 148, 44-64.

Donaghy, P., Bray, S., Gowen, R., Rolfe, J., Stephens, M., Hoffmann, M., and Stunzer, A. (2010) The bioeconomic potential for agroforestry in Australia's northern grazing systems. Small-scale Forestry 9, 463-484.

Doran-Browne, N., Wootton, M., Taylor, C., and Eckard, R. (2018) Offsets required to reduce the carbon balance of sheep and beef farms through carbon sequestration in trees and soils. Animal Production Science 58, 1648-1655.

Drake, J. A., Carrucan, A., Jackson, W. R., Cavagnaro, T. R., and Patti, A. F. (2015) Biochar application during reforestation alters species present and soil chemistry. Science of the Total Environment 514, 359-365.

Dumbrell, N. P., Kragt, M. E., and Gibson, F. L. (2016) What carbon farming activities are farmers likely to adopt? A best–worst scaling survey. Land Use Policy 54, 29-37.

Dumbrell, N.P., Kragt, M.E., Meier, E.A., Biggs, J.S., Thorburn, P.J. (2017) Greenhouse gas abatement costs are heterogeneous between Australian grain farms. Agronomy for Sustainable Development 37, 28.

Dwyer, J. M., Fensham, R. J., and Buckley, Y. M. (2010) Agricultural legacy, climate, and soil influence the restoration and carbon potential of woody regrowth in Australia. Ecological Applications 20, 1838-1850.

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Appendix B

Supplementary Information: Chapter 3

Appendix B, Table 3.1. List of SCM features based on farmers' interviews that influence the connectivity among the features.

Driving features	Dimensions
pH level	Interaction-output
Soil moisture	
Soil structure	
Soil biodiversity	
Landscape aesthetics	
Soil water-holding capacity	
Soil erosion	
Soil nutrients	
Soil carbon content	
Mental health	
Shelter for livestock	
Farm production	Resource units
SCM practices	
Change of income	
Agro-environmental benefit	
SCM cost	

Appendix B, Table 3.2. Interview responses on the features of SCM at farm level (SCM1)

Features	Response	Weight
Geographical location	Considered	1
Size of the farm	Large farm	Large farm
Number of farms under farming		Single
Framing type	Grazing	Mixed
Proprietorship	Family farm	Family farm
Loan status	No loan	Loan Farm
Soil type	Less fertile	Less fertile

Production potential	yes	1
Soil health	yes	1
SCM practices	Intensive	1
Climate	Yes	1
Change of income	yes	1
Agro-environmental benefits	yes	1
SCM cost	yes	1
Government support	no	0
Non-government support	yes	1
Grants for on-farm research	yes	1
Scientific support	yes	1
Government investments	yes	0
Private investments	no	1
Carbon pricing and monitoring	yes	1
Certainty of payment	no	1
Training and education support	yes	1
Expert information	yes	1
Soil carbon policy	no	1
Social network	no	1
Trusted expert network	yes	1
Government officer	no	0
Independent advisors	yes	1
Farmers	yes	1
Scientists	yes	1
Education institute	yes	1
SCM attitude	yes	0
Soil stewardship ethics	no	0

Technologies available	no	1
Trust	no	1
pH level	optimised	1
Soil moisture	increase	1
Soil structure	improved	1
Soil biodiversity	increase	1
Landscape aesthetics	yes	0
Soil water holding capacity	yes	1
Soil erosion	yes	1
Soil nutrients	increase	1
Soil carbon content	increase	1
Mental health	improved	1
Shelter for livestock	increase	1

Appendix B, Table 3.3. Network/relationship of the SCM features at farm level (SCM1) in the grazing lands of Northern Tablelands and Upper Hunter

Outcome variable	SES indicator	Response
pH level	Geographical location	0
Soil moisture	Geographical location	1
Soil structure	Geographical location	1
Soil biodiversity	Geographical location	0
Landscape aesthetics	Geographical location	1
Soil water-holding capacity	Geographical location	1
Soil erosion	Geographical location	1
Soil nutrients	Geographical location	1
Soil carbon content	Geographical location	1
Mental health	Geographical location	1
Shelter for livestock	Geographical location	1
pH level	Small farm	0
Soil moisture	Small farm	1
Soil structure	Small farm	1
Soil biodiversity	Small farm	0
Landscape aesthetics	Small farm	1
Soil water-holding capacity	Small farm	1
Soil erosion	Small farm	1
Soil nutrients	Small farm	1
Soil carbon content	Small farm	1
Mental health	Small farm	1
Shelter for livestock	Small farm	1
pH level	Number of farms under farming	0

Soil moisture	Number of farms under farming	1
Soil structure	Number of farms under farming	1
Soil biodiversity	Number of farms under farming	0
Landscape aesthetics	Number of farms under farming	1
Soil water-holding capacity	Number of farms under farming	1
Soil erosion	Number of farms under farming	1
Soil nutrients	Number of farms under farming	1
Soil carbon content	Number of farms under farming	1
Mental health	Number of farms under farming	1
Shelter for livestock	Number of farms under farming	1
pH level	Grazing	0
Soil moisture	Grazing	1
Soil structure	Grazing	1
Soil biodiversity	Grazing	0
Landscape aesthetics	Grazing	1
Soil water-holding capacity	Grazing	1
Soil erosion	Grazing	1
Soil nutrients	Grazing	1
Soil carbon content	Grazing	1
Mental health	Grazing	1
Shelter for livestock	Grazing	1
pH level	Family farm	0

Soil moisture	Family farm	1
Soil structure	Family farm	1
Soil biodiversity	Family farm	0
Landscape aesthetics	Family farm	1
Soil water-holding capacity	Family farm	1
Soil erosion	Family farm	1
Soil nutrients	Family farm	1
Soil carbon content	Family farm	1
Mental health	Family farm	1
Shelter for livestock	Family farm	1
pH level	No loan	0
Soil moisture	No loan	1
Soil structure	No loan	1
Soil biodiversity	No loan	0
Landscape aesthetics	No loan	1
Soil water-holding capacity	No loan	1
Soil erosion	No loan	1
Soil nutrients	No loan	1
Soil carbon content	No loan	1
Mental health	No loan	1
Shelter for livestock	No loan	1
pH level	Production potential	0
Soil moisture	Production potential	1
Soil structure	Production potential	1
Soil biodiversity	Production potential	0
Landscape aesthetics	Production potential	1
Soil water-holding capacity	Production potential	1

Soil erosion	Production potential	1
Soil nutrients	Production potential	1
Soil carbon content	Production potential	1
Mental health	Production potential	1
Shelter for livestock	Production potential	1
pH level	Soil health	0
Soil moisture	Soil health	1
Soil structure	Soil health	1
Soil biodiversity	Soil health	0
Landscape aesthetics	Soil health	1
Soil water-holding capacity	Soil health	1
Soil erosion	Soil health	1
Soil nutrients	Soil health	1
Soil carbon content	Soil health	1
Mental health	Soil health	1
Shelter for livestock	Soil health	1
pH level	SCM practices	0
Soil moisture	SCM practices	1
Soil structure	SCM practices	1
Soil biodiversity	SCM practices	0
Landscape aesthetics	SCM practices	1
Soil water-holding capacity	SCM practices	1
Soil erosion	SCM practices	1
Soil nutrients	SCM practices	1
Soil carbon content	SCM practices	1
Mental health	SCM practices	1
Shelter for livestock	SCM practices	1

pH level	Climate	0
Soil moisture	Climate	1
Soil structure	Climate	1
Soil biodiversity	Climate	0
Landscape aesthetics	Climate	1
Soil water-holding capacity	Climate	1
Soil erosion	Climate	1
Soil nutrients	Climate	1
Soil carbon content	Climate	1
Mental health	Climate	1
Shelter for livestock	Climate	1
pH level	Change of income	0
Soil moisture	Change of income	1
Soil structure	Change of income	1
Soil biodiversity	Change of income	0
Landscape aesthetics	Change of income	1
Soil water-holding capacity	Change of income	1
Soil erosion	Change of income	1
Soil nutrients	Change of income	1
Soil carbon content	Change of income	1
Mental health	Change of income	1
Shelter for livestock	Change of income	1
pH level	Agri-environmental benefits	0
Soil moisture	Agri-environmental benefits	1
Soil structure	Agri-environmental benefits	1
Soil biodiversity	Agri-environmental benefits	0
Landscape aesthetics	Agri-environmental benefits	1

Soil water-holding capacity	Agri-environmental benefits	1
Soil erosion	Agri-environmental benefits	1
Soil nutrients	Agri-environmental benefits	1
Soil carbon content	Agri-environmental benefits	1
Mental health	Agri-environmental benefits	1
Shelter for livestock	Agri-environmental benefits	1
pH level	SCM cost	0
Soil moisture	SCM cost	1
Soil structure	SCM cost	1
Soil biodiversity	SCM cost	0
Landscape aesthetics	SCM cost	1
Soil water-holding capacity	SCM cost	1
Soil erosion	SCM cost	1
Soil nutrients	SCM cost	1
Soil carbon content	SCM cost	1
Mental health	SCM cost	1
Shelter for livestock	SCM cost	1
pH level	Support of government organisation	0
Soil moisture	Support of government organisation	0
Soil structure	Support of government organisation	0
Soil biodiversity	Support of government organisation	0
Landscape aesthetics	Support of government organisation	0
Soil water-holding capacity	Support of government organisation	0
Soil erosion	Support of government organisation	0

Soil nutrients	Support of government organisation	0
Soil carbon content	Support of government organisation	0
Mental health	Support of government organisation	0
Shelter for livestock	Support of government organisation	0
pH level	Support of non-government organisation	0
Soil moisture	Support of non-government organisation	1
Soil structure	Support of non-government organisation	1
Soil biodiversity	Support of non-government organisation	0
Landscape aesthetics	Support of non-government organisation	1
Soil water-holding capacity	Support of non-government organisation	1
Soil erosion	Support of non-government organisation	1
Soil nutrients	Support of non-government organisation	1
Soil nutrient cycling	Support of non-government organisation	1
Soil carbon content	Support of non-government organisation	1
Mental health	Support of non-government organisation	1
Shelter for livestock	Support of non-government organisation	1
pH level	On farm research grant	0
Soil moisture	On farm research grant	1
Soil structure	On farm research grant	1

Soil biodiversity	On farm research grant	0
Landscape aesthetics	On farm research grant	1
Soil water-holding capacity	On farm research grant	1
Soil erosion	On farm research grant	1
Soil nutrients	On farm research grant	1
Soil carbon content	On farm research grant	1
Mental health	On farm research grant	1
Shelter for livestock	On farm research grant	1
pH level	Scientific support	0
Soil moisture	Scientific support	1
Soil structure	Scientific support	1
Soil biodiversity	Scientific support	0
Landscape aesthetics	Scientific support	1
Soil water-holding capacity	Scientific support	1
Soil erosion	Scientific support	1
Soil nutrients	Scientific support	1
Soil carbon content	Scientific support	1
Mental health	Scientific support	1
Shelter for livestock	Scientific support	1
pH level	Government investments	0
Soil moisture	Government investments	1
Soil structure	Government investments	1
Soil biodiversity	Government investments	0
Landscape aesthetics	Government investments	1
Soil water-holding capacity	Government investments	1
Soil erosion	Government investments	1
Soil nutrients	Government investments	1

Soil carbon content	Government investments	1
Mental health	Government investments	1
Shelter for livestock	Government investments	1
pH level	Private investments	0
Soil moisture	Private investments	1
Soil structure	Private investments	1
Soil biodiversity	Private investments	0
Landscape aesthetics	Private investments	1
Soil water-holding capacity	Private investments	1
Soil erosion	Private investments	1
Soil nutrients	Private investments	1
Soil nutrient cycling	Private investments	1
Soil carbon content	Private investments	1
Mental health	Private investments	1
Shelter for livestock	Private investments	0
pH level	Carbon pricing and monitoring	0
Soil moisture	Carbon pricing and monitoring	1
Soil structure	Carbon pricing and monitoring	1
Soil biodiversity	Carbon pricing and monitoring	0
Landscape aesthetics	Carbon pricing and monitoring	1
Soil water-holding capacity	Carbon pricing and monitoring	1
Soil erosion	Carbon pricing and monitoring	1
Soil nutrients	Carbon pricing and monitoring	1

Soil carbon content	Carbon pricing and monitoring	1
Mental health	Carbon pricing and monitoring	1
Shelter for livestock	Carbon pricing and monitoring	1
pH level	Certainty of payment	0
Soil moisture	Certainty of payment	0
Soil structure	Certainty of payment	0
Soil biodiversity	Certainty of payment	0
Landscape aesthetics	Certainty of payment	0
Soil water-holding capacity	Certainty of payment	0
Soil erosion	Certainty of payment	0
Soil nutrients	Certainty of payment	0
Soil carbon content	Certainty of payment	0
Mental health	Certainty of payment	0
Shelter for livestock	Certainty of payment	0
pH level	Training and education support	0
Soil moisture	Training and education support	1
Soil structure	Training and education support	1
Soil biodiversity	Training and education support	0
Landscape aesthetics	Training and education support	1
Soil water-holding capacity	Training and education support	1
Soil erosion	Training and education support	1
Soil nutrients	Training and education support	1

Soil carbon content	Training and education support	1
Mental health	Training and education support	1
Shelter for livestock	Training and education support	1
pH level	Expert information	0
Soil moisture	Expert information	1
Soil structure	Expert information	1
Soil biodiversity	Expert information	0
Landscape aesthetics	Expert information	1
Soil water-holding capacity	Expert information	1
Soil erosion	Expert information	1
Soil nutrients	Expert information	1
Soil carbon content	Expert information	1
Mental health	Expert information	1
Shelter for livestock	Expert information	1
pH level	Soil carbon policy	0
Soil moisture	Soil carbon policy	0
Soil structure	Soil carbon policy	0
Soil biodiversity	Soil carbon policy	0
Landscape aesthetics	Soil carbon policy	0
Soil water-holding capacity	Soil carbon policy	0
Soil erosion	Soil carbon policy	0
Soil nutrients	Soil carbon policy	0
Soil carbon content	Soil carbon policy	0
Mental health	Soil carbon policy	0
Shelter for livestock	Soil carbon policy	0
pH level	Social network	0

Soil moisture	Social network	0
Soil structure	Social network	0
Soil biodiversity	Social network	0
Landscape aesthetics	Social network	0
Soil water-holding capacity	Social network	0
Soil erosion	Social network	0
Soil nutrients	Social network	0
Soil carbon content	Social network	0
Mental health	Social network	0
Shelter for livestock	Social network	0
pH level	Trusted expert network	0
Soil moisture	Trusted expert network	1
Soil structure	Trusted expert network	1
Soil biodiversity	Trusted expert network	0
Landscape aesthetics	Trusted expert network	1
Soil waterholding capacity	Trusted expert network	1
Soil erosion	Trusted expert network	1
Soil nutrients	Trusted expert network	1
Soil carbon content	Trusted expert network	1
Mental health	Trusted expert network	1
Shelter for livestock	Trusted expert network	1
pH level	Government officer	0
Soil moisture	Government officer	0
Soil structure	Government officer	0
Soil biodiversity	Government officer	0
Landscape aesthetics	Government officer	0
Soil waterholding capacity	Government officer	0

Soil erosion	Government officer	0
Soil nutrients	Government officer	0
Soil nutrient cycling	Government officer	0
Soil carbon content	Government officer	0
Mental health	Government officer	0
Shelter for livestock	Government officer	0
pH level	Independent advisors	0
Soil moisture	Independent advisors	1
Soil structure	Independent advisors	1
Soil biodiversity	Independent advisors	1
Landscape aesthetics	Independent advisors	1
Soil water-holding capacity	Independent advisors	1
Soil erosion	Independent advisors	1
Soil nutrients	Independent advisors	1
Soil nutrient cycling	Independent advisors	1
Soil carbon content	Independent advisors	1
Mental health	Independent advisors	1
Shelter for livestock	Independent advisors	1
pH level	Farmers	0
Soil moisture	Farmers	1
Soil structure	Farmers	1
Soil biodiversity	Farmers	0
Landscape aesthetics	Farmers	1
Soil water-holding capacity	Farmers	1
Soil erosion	Farmers	1
Soil nutrients	Farmers	1
Soil nutrient cycling	Farmers	1

Soil carbon content	Farmers	1
Mental health	Farmers	1
Shelter for livestock	Farmers	1
pH level	Scientists	0
Soil moisture	Scientists	1
Soil structure	Scientists	1
Soil biodiversity	Scientists	0
Landscape aesthetics	Scientists	1
Soil water-holding capacity	Scientists	1
Soil erosion	Scientists	1
Soil nutrients	Scientists	1
Soil nutrient cycling	Scientists	1
Soil carbon content	Scientists	1
Mental health	Scientists	1
Shelter for livestock	Scientists	1
pH level	Education institute	0
Soil moisture	Education institute	1
Soil structure	Education institute	1
Soil biodiversity	Education institute	0
Landscape aesthetics	Education institute	1
Soil water-holding capacity	Education institute	1
Soil erosion	Education institute	1
Soil nutrients	Education institute	1
Soil nutrient cycling	Education institute	1
Soil carbon content	Education institute	1
Mental health	Education institute	1
Shelter for livestock	Education institute	1

pH level	SCM attitude	0
Soil moisture	SCM attitude	1
Soil structure	SCM attitude	1
Soil biodiversity	SCM attitude	0
Landscape aesthetics	SCM attitude	1
Soil water-holding capacity	SCM attitude	1
Soil erosion	SCM attitude	1
Soil nutrients	SCM attitude	1
Soil nutrient cycling	SCM attitude	1
Soil carbon content	SCM attitude	1
Mental health	SCM attitude	1
Shelter for livestock	SCM attitude	1
pH level	Soil stewardship ethics	0
Soil moisture	Soil stewardship ethics	1
Soil structure	Soil stewardship ethics	1
Soil biodiversity	Soil stewardship ethics	0
Landscape aesthetics	Soil stewardship ethics	1
Soil water-holding capacity	Soil stewardship ethics	1
Soil erosion	Soil stewardship ethics	1
Soil nutrients	Soil stewardship ethics	1
Soil nutrient cycling	Soil stewardship ethics	1
Soil carbon content	Soil stewardship ethics	1
Mental health	Soil stewardship ethics	1
Shelter for livestock	Soil stewardship ethics	1
pH level	Technologies available	0
Soil moisture	Technologies available	0
Soil structure	Technologies available	0

Soil biodiversity	Technologies available	0
Landscape aesthetics	Technologies available	0
Soil water-holding capacity	Technologies available	0
Soil erosion	Technologies available	0
Soil nutrients	Technologies available	0
Soil nutrient cycling	Technologies available	0
Soil carbon content	Technologies available	0
Mental health	Technologies available	0
Shelter for livestock	Technologies available	0
pH level	Trust	0
Soil moisture	Trust	0
Soil structure	Trust	0
Soil biodiversity	Trust	0
Landscape aesthetics	Trust	0
Soil water-holding capacity	Trust	0
Soil erosion	Trust	0
Soil nutrients	Trust	0
Soil nutrient cycling	Trust	0
Soil carbon content	Trust	0
Mental health	Trust	0
Shelter for livestock	Trust	0

Appendix B, Table 3.4. Positive interactions identified by farmer workshops

These features *positively* influenced …	These features
Co-benefits of SCM – Improved soil moisture, nutrients, water holding capacity and soil structure)	• Production potential • Soil health • Support of other farmers for SCM • Interest in training & educational

Co-benefits of SCM – Mental health and landscape aesthetics	Interest in SCM practices
Agri-environmental benefits of SCM	• Production potential of the farm • Soil health
Training & education	Other farmers not yet involved in SCM
Soil stewardship ethic	• SCM • Co-benefits from SCM
Trust between actors and strong soil stewardship	Interest in and adoption of SCM, which in turn could improve income, leading to further investment in SCM
Farmers' social network	• SCM • Interest in training and education • Mental health

Appendix B, Table 3.5. Positive interactions identified by service-provider workshops

These features *positively* influenced	These features
SCM practices	Co-benefits of SCM
Soil stewardship ethic	• Participation of other farmers who were not undertaking SCM and seeking grants for on-farm research • Support from government & non-government organizations • Seeking reliable scientific information • Participation in social networks
Certainty of payment	• Cost of SCM • Income
Effective carbon pricing and monitoring	Change of income, which might result a positive effect on the debt status and lead to more adoption of SCM
• Government investment • Private investment • Grants for on-fam research	Availability and adoption of technology, which ultimately influences SCM
• Government officers • Training & education • Education institutes • Scientists	• Trust • Soil stewardship ethic • Farmers' social network • Mainstream media

Appendix B, Table 3.6. Mixed interactions identified by farmer (F) and service-provider (SP) workshops

Group	These features either *positively* or *negatively* influenced	These features
F	SCM practices	Change of income, depending on how quickly a change resulted in benefits
F	• Non-government organisations' support • Scientific support • Independent advisors • Grants for on-farm research	• SCM, depending on whether the interaction between actors either built or eroded farmers' trust and confidence in SCM
SP	Carbon pricing and monitoring	• Soil carbon policy, depending on the extent to which policy was practice-oriented and based on land use and management.

Appendix B, Table 3.7. Negative interactions identified by farmer workshops

These features *negatively* influenced	These features
• Current soil carbon policy • Carbon pricing & monitoring • Lack of available technology	SCM
Farmers' social network	SCM

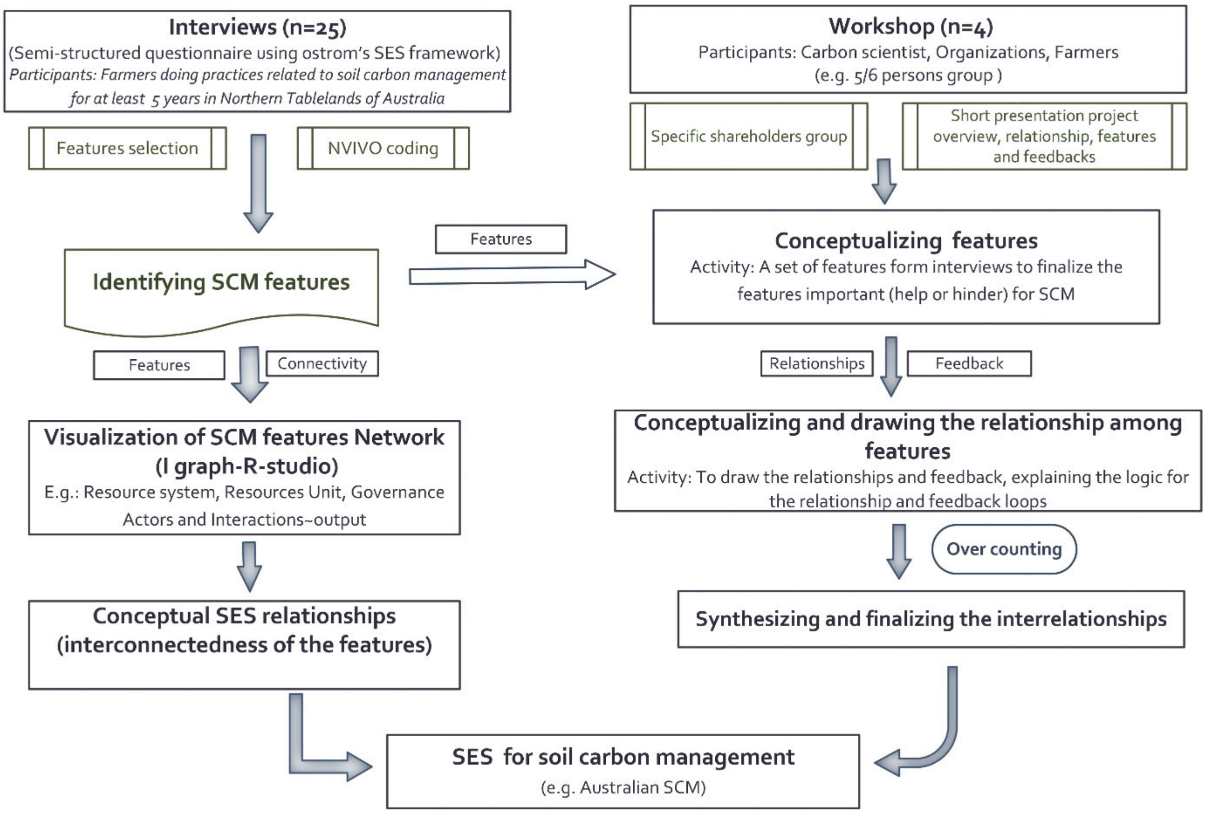
Appendix B, Box 3.1. Soil carbon management practices (Dumbrell et al., 2016)

No-till cropping practices
Bio-char application
Mulching on bare soil
Increase area for pasture by decreasing area for crop
Inter cropping with perennial pasture
Perennial pasture planting
Tree belt planting
Rotational grazing implementation
Stubble retention after crop harvest
Legume in pasture
Others (specified by farmers e.g. grazing management)

Appendix B, Table 3.8. Farming experience, SCM practices of the interviewed farmers and farm soil types.

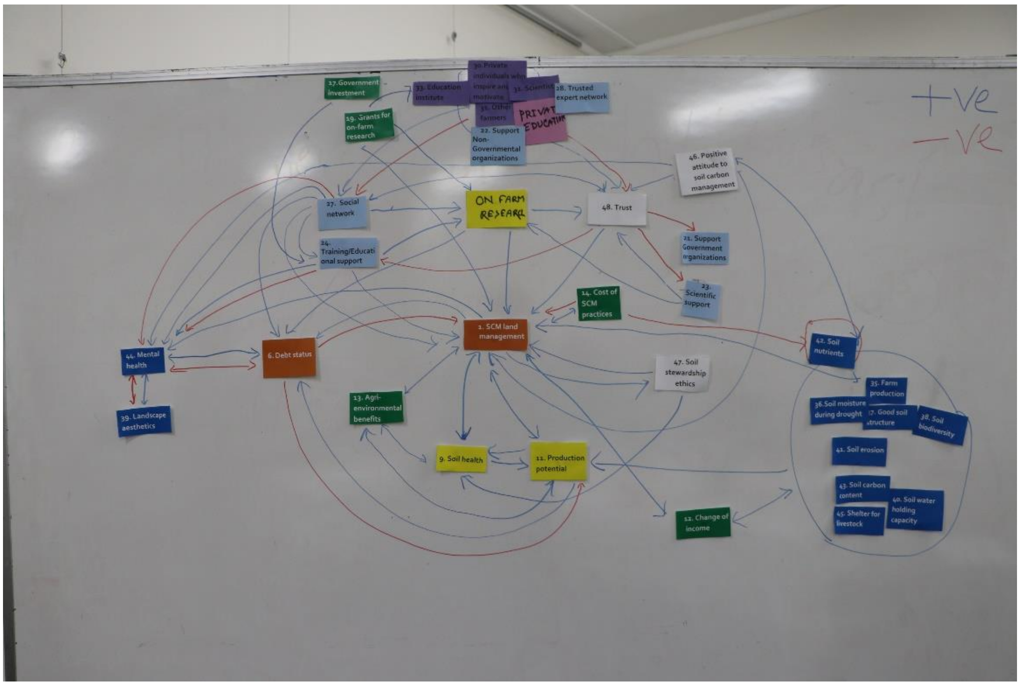
Farm No.	Age	Total farm experience	Farm experience in SCM practice at current location	Farm area (ha)	Soil type	Soil carbon management practices								
						Mulching	Native vegetation establishment	Increasing pasture area	Intercropping with perennial pasture	Stubble retention	Legume in pasture	Tree Planting	Bio-char	Grazing system
SCM1	65	40	29	40	Sedimentary	No	No	No	No	No	No	Yes	No	Strategic
SCM2	66	45	40	3350	Granite	Yes	Yes	Yes	Yes	Yes	Yes	No	No	Rotational
SCM3	56	8	8	1250	Granite	Yes	No	No	No	No	Yes	Yes	No	Rotational
SCM4	69	50	40	3000	Basalt	No	Yes	No	No	No	No	No	No	Rotational
SCM5	59	40	36	120	Basalt	Yes	No	Yes	No	Yes	Yes	Yes	No	Rotational
SCM6	40	25	8	400	Sedimentary	No	No	No	No	No	No	Yes	No	Rotational
SCM7	59	40	40	1450	Sedimentary	No	No	No	No	No	Yes	Yes	No	Rotational
SCM8	61	40	40	999	Sedimentary	No	No	No	No	No	No	Yes	No	Rotational
SCM9	68	48	48	1202	Granite	No	No	No	No	No	Yes	Yes	No	Strategic
SCM10	61	12	10	923	Basalt	No	No	No	No	No	Yes	No	No	Rotational
SCM11	73	60	30	2000	Basalt	Yes	No	No	Yes	No	Yes	Yes	No	Rotational
SCM12	55	36	12	1400	Basalt	No	No	No	No	Yes	Yes	Yes	No	Rotational
SCM13	51	30	15	8	Granite	No	No	No	No	No	No	Yes	No	Rotational
SCM14	45	25	25	1500	Granite	No	No	No	No	No	Yes	Yes	No	Rotational
SCM15	64	40	20	260	Basalt	Yes	No	Yes	No	No	Yes	Yes	No	Rotational

SCM16	64	40	10	1620	Basalt	No	No	No	No	No	No	Yes	No	Rotational
SCM17	71	51	5	220	Basalt	Yes	No	No	No	No	Yes	Yes	Yes	Rotational
SCM18	71	50	16	45	Basalt	Yes	No	No	No	Yes	Yes	No	No	Time control
SCM19	54	25	5	64	Granite	No	No	No	Yes	No	No	Yes	No	Rotational
SCM20	58	10	9	454	Basalt	Yes	No	No	No	No	No	No	No	Rotational
SCM21	42	17	6	527	Basalt	No	Yes	No	No	No	No	No	No	Rotational
SCM22	82	64	64	2134	Granite	Yes	No	No	No	No	Yes	No	No	Rotational
SCM23	55	5	3	43	Granite	Yes	No	No	No	Yes	No	Yes	No	Rotational
SCM24	62	15	15	2626	Granite	No	No	Yes	Yes	No	No	Yes	No	Rotational
SCM25	69	55	55	530	Granite	No	No	No	No	Yes	Yes	No	No	Rotational
Total= 25 farms	Average= 60 years	Average =35 years	Average= 24 years	Average= 1047 ha										

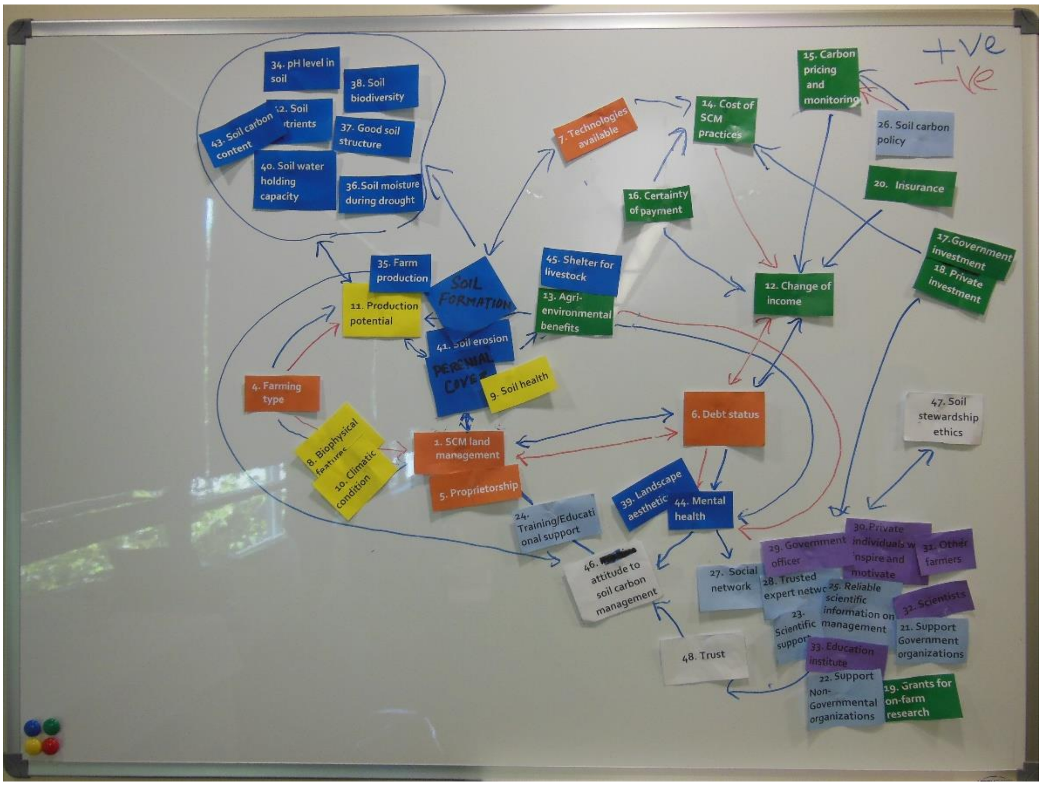


Appendix B, Fig. 3.1. Schematic diagram of the research steps

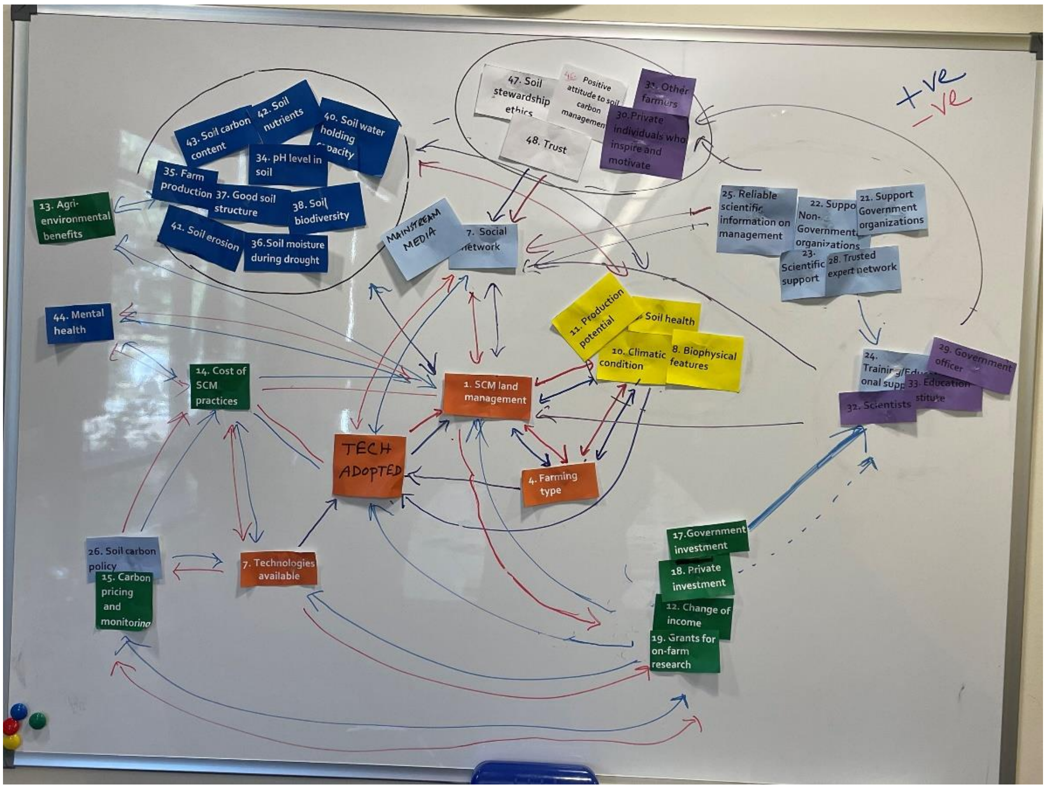
Appendix B, Fig. 3.2. SES framework for SCM of Australian agricultural system conceptualized during workshop1 (first farmer workshop)



Appendix B, Fig. 3.3. SES framework for SCM of Australian agricultural system conceptualised during workshop 2 (second farmer workshop)



Appendix B, Fig. 3.4. SES framework for SCM of Australian agricultural system conceptualised during workshop 3 (first service provider workshop)



Appendix B, Fig. 3.5. SES framework for SCM of Australian agricultural system conceptualised during workshop 4 (second service provider workshop)

[redacted]

Appendix B, Fig. 3.6. Ostrom's social-ecological systems framework (Ostrom, 2009)

References

Dumbrell, N.P., Kragt, M.E., Gibson, F.L. (2016) What carbon farming activities are farmers likely to adopt? A best–worst scaling survey. Land Use Policy 54, 29-37.

Ostrom, E. (2009) A general framework for analyzing sustainability of social-ecological systems. Science 325, 419-422.

Appendix C

Supplementary Information: Chapter 4

Appendix C, Table 4.1. Soil carbon management (SCM) features based on stakeholders' interviews (Amin et al., 2021)

System component of SES	Features
Resource System (RS)	Geographical location Size of the farm Number of farms under farming Farm type (e.g. grazing) Proprietorship (e.g. family farm) Loan status Soil type (e.g. fertile/non-fertile) Soil health
Resources Units (RU)	Production potential SCM practices Climate Change of income Agri-environmental benefits SCM cost
Governance (G)	Support of government organisations Support of non-government organisations Own farm research grant Scientific support (e.g. soil test support) Government investments Private investments Carbon pricing and monitoring Certainty of payment Training and education support Expert information (e.g. reliable scientific information on management) Soil carbon policy Social network (e.g. horizontal/ vertical) Trusted expert network
Actors (A)	Government officer Independent advisors Farmers Scientists

	Education institute
	Soil stewardship ethics
	SCM attitude
	Technologies available
	Trust
Interaction-Output	pH level
	Soil moisture
	Soil structure
	Soil biodiversity
	Landscape aesthetics
	Soil water-holding capacity
	Soil erosion
	Soil nutrients
	Soil carbon content
	Mental health
	Shelter for livestock

Appendix C, Table 4.2. Socio-demographic characteristics of the interviewed farmers and distribution of SCM practices in grazing regimes (n=25).

Farm No.	Gender	Education		Off farm income Yes [redacted] √ [redacted]	Ownership	No of properties	Farming type	Farm area (ha) *Large farm >500 ha Small farm <500 ha*
		Diploma	Specialisation					
SCM1	Male	Bachelor	Agriculture	√	Family	1	Grazing	40
SCM2	Male	Masters	Agriculture: Masters	√	Family	1	Mixed	3350
SCM3	Male	Bachelor	General	√	Family	1	Grazing	1250
SCM4	Male	Bachelor	Agriculture and General	√	Family	1	Grazing	3000
SCM5	Male	Bachelor	Agriculture, Technical and General	√	Family	2	Mixed	120
SCM6	Male	Bachelor Diploma	Agriculture	√	Family	1	Mixed	400
SCM7	Male	High School	Agriculture	√	Family	4	Grazing	1450
SCM8	Male	High School	Agriculture	√	Family	1	Grazing	999
SCM9	Male	High School	Agriculture	√	Family	1	Grazing	1202
SCM10	Female	Masters	Economics Masters	√	Family	2	Grazing	923
SCM11	Male	High School	General	√	Family	1	Grazing	2000
SCM12	Male	Masters	Specialized Masters	X	Family	2	Grazing	1400
SCM13	Female	Masters	Agriculture Masters	√	Family	1	Grazing	8
SCM14	Male	Bachelor Diploma	Agriculture and General	X	Family	1	Grazing	1500
SCM15	Male	High School	Agriculture and General	X	Family	1	Grazing	260
SCM16	Female	High School	General	X	Family	1	Grazing	1620
SCM17	Male	High School	General	√	Family	1	Mixed	220
SCM18	Male	Masters	Agriculture Masters	√	Family	1	Grazing	45
SCM19	Male	High School	General	√	Family	1	Grazing	64
SCM20	Female	PhD	Agriculture PhD	√	Family	1	Grazing	454

SCM21	Male	Bachelor	General	X	Company	1	Grazing	527
SCM22	Male	Bachelor Diploma	Agriculture	√	Family	3	Grazing	2134
SCM23	Female	Masters	Specialized Masters	√	Family	1	Grazing	43
SCM24	Male	High School	General	√	Family	1	Grazing	2626
SCM25	Male	High School	Agriculture and General	X	Family	1	Grazing	530
				[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

Reference

Amin, M.N., Lobry de Bruyn, L., Hossain, M.S., Lawson, A. Wilson, B., (2021) Revealing the social-ecological relationships affecting farmers' current soil carbon management in Australian grazing lands. Environmental Management. Springer (Under review)