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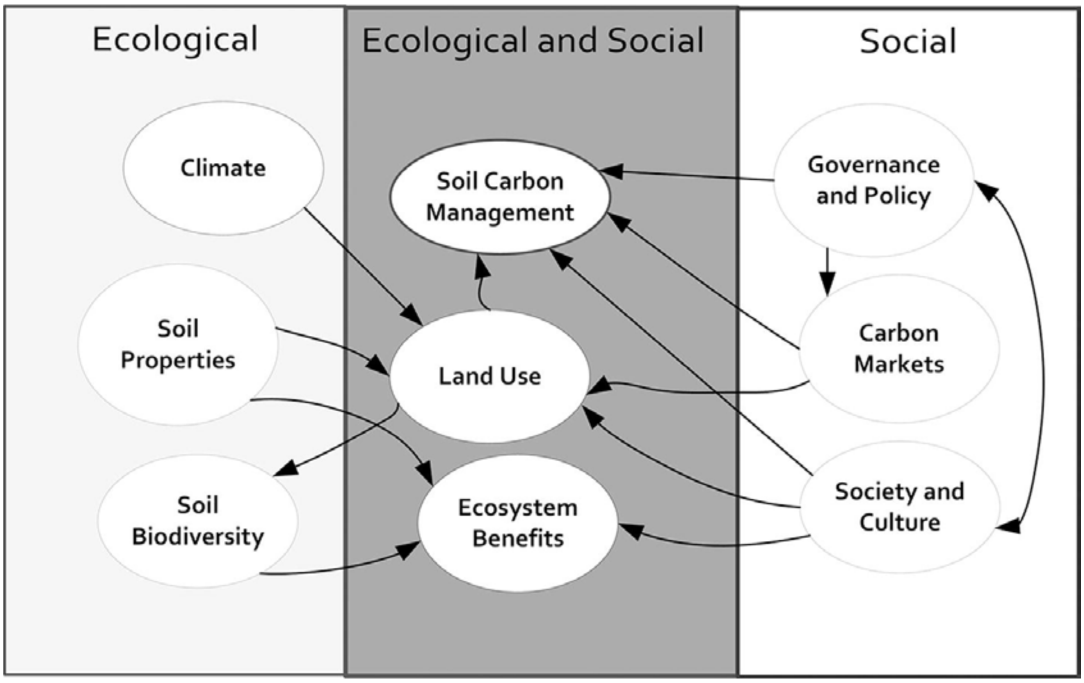
A systematic review of soil carbon management research in Australia and the need for a social-ecological systems framework

Highlights

- Systematic review to identify progress and challenges in soil carbon management (SCM) research.
- A state-of-the-art of the use of social-ecological systems in SCM both in the global and Australian context.
- SCM research predominately focused on ecological components and regional level.
- Carbon management co-benefits were dominated by scientists' perspective.
- Proposed SES framework may help to ensure sustainability of carbon-building management practice.

Graphical abstract



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, 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 synthesized the use of social-ecological systems (SES) 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

1. 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^{o} 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 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 of (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). 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, 2009aMorán-Ordóñez et al., 2017). Following the 4th 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 purchasing 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, 6 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 policy makers 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 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 in 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 are 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 consists 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. Wilson et al. 2010; Wang et al. 2013; Rabbi et al. 2014; Badgery et al. 2014; Bajgai et al. 2014; Preece et al. 2015; Rabbi et al. 2015; Chappell and Baldock 2016; Luo et al. 2016) with poor integration of social and ecological variables that could influence soil carbon management. To include all variables (social and ecological) the concept of social-ecological systems (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).

A 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 inter-related 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 a SES, there is greater potential to manage soil carbon with a consideration of all these variables. In a 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 a SES the use of a 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 for regional sustainability (Hossain et al 2017a; Hossain et al., 2019), determining the impact of ecosystem services (Hossain et al., 2017b) and climate change adaptation, fisheries and water management (de Wet and Odume, 2019; Galappaththi et al., 2019, Aguirre et al., 2019). However, the use of a 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 details the methodology of the study in terms of searching for and reviewing articles, before describing current trends (Section 3.2), SES components (Section 3.3), knowledge gaps and methodological challenges (Section 3.4) in soil carbon management research. Section 4.1 and 4.2 introduces the SES components of soil carbon management and proposes a conceptual SES framework, before discussing the future research direction for soil carbon management research in Australia.

2. Methodology

2.1 Search terms and article selection approach

Our systematic review followed a two-stage process (SI Figure 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 the literature to journal articles, and book chapters. The literature search was undertaken between August and November 2018 using the search terms provided in SI Table 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, and 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 (SI Figure 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 had 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 4 (SI Figure 1). The list of articles used in the review are included as supplementary materials with full bibliographic details.

2.2 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 (Figure 1). The word frequency query corroborated the main 'search terms', such as: 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 (Figure 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 aspect together e.g. 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 was matrix coding queries and crosstab queries. These functions allowed examination of interactions between articles' source classifications and a coded theme. The relationship between the source classification "SES component" and the "soil carbon management co-benefits" theme were examined using matrix coding queries. Crosstab query function was used to explore the number of articles that examined each spatial scale soil carbon management co-benefits (theme), as well as the type of perspective. 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 3.2).

3. Results

3.1 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 on the national level, 12 articles on local or farm level, and two articles that had no specified level. The highest number of articles for agricultural soil carbon management were at the regional level (Figure 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) (Figure 2).

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 (Figure 2). This slight decline in research output might be due to changes in research funding under the ERF and its implementation in 2015 (Figure 2).

3.2 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 either focused on 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 (SI Table 2). These studies revealed that management practices were less influential on soil carbon stock compared to environmental variables (e.g. climate and soil type), however, under long-term management increases in soil carbon are likely (Rabbi et al., 2015; Chappell and Baldock, 2016). Modelling and auditing of soil organic carbon, using the Agricultural Production System Simulator (APSIM) model, Rothamsted Carbon Model (RothC), Agro-C, Full carbon Accounting Model (FullCAM) in order to simulate SOC content in agricultural lands was the most researched topic (21 of 66 articles) (SI Table 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 (SI Table 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 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) (SI Table 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 (SI Table 2). Studies on grain cropping systems revealed that the marginal economic value of SOC depends on the crop type and cropping zone, this economic value was sensitive to fertiliser price (Petersen et al., 2016). 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 2.3). 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 importance of management practices, cover crops, and pasture for storing carbon (Chan et al., 2011; Bajgai et al., 2014). Regional scale soil carbon management research focused also on soil management (e.g. zero tillage, conservation tillage), organic amendments (e.g. biochar) (McHenry, 2009a; Drake et al., 2015), 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) (Thamo et al., 2013; Sinnett et al., 2016). 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 offsetts, 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 practices effects on biodiversity (Bradshaw et al., 2013).

3.3 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) (SI Figure 2A). The dominant land use 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 (SI Figure 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 (SI Table 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 (SI Table 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, farmer's 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 (SI Table 3).

Under half (43%) of the reviewed articles identified the co-benefits of soil carbon management. The co-benefits examined in those articles were from a scientist's perspective (40 articles) and only 2 articles examined the co-benefits of soil carbon management from a farmers' 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. Farmer participation in research was low with only 10% of articles gathering information directly from farmers (8 articles) or using information provided indirectly through use of farmers' fields for sampling (2 articles) (SI Figure 3A). Similarly, 68% of articles examined did not consider farmers' capacity needs (resources, knowledge and skills) when examining soil carbon management (SI Figure 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 (Figure 4). Of the 43% of research examined 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 research were uncommon. Given that few studies (2 articles) involved farmers then the dominant perspective was from a scientist. Thus, the cross tab 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 occurs at their level (Figure 4), and the results of research conducted at a national and regional level would be difficult to scale to the level relevant for local application.

3.4 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 (Rochecouste et al., 2015, Longmire et al., 2015). Research in Australia on soil carbon management has been initiated for many reasons 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 (Wang and Dalal, 2006; Dean et al., 2012). 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 (Maraseni et al., 2008; Luo et al., 2014).

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 (Grundy et al., 2016; Evans, 2018), However, these attitudinal variables (e.g. how farmers perceive 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 et al., 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 (McHenry, 2009b; Kragt et al., 2012; 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. Methods employing social techniques (e.g. survey and interviews), meanwhile 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 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 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 e.g 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 fifties (Dumbrell et al., 2016) and they were interested in carbon farming initiatives. However, farmers with interest in adoption of these prescribed practices, and 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).

3.5 The use of 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 of SES for soil carbon management in Australia. Van Oosterzee et al. (2014) argued that 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 (SI Table 1). Our systematic review revealed that SES and soil carbon management is still an unexplored area of research and only 4 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 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 (Méndez et al., 2009; Karamesouti et al., 2015; Tittonell et al., 2015).

4. Discussion

4.1 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 critical to soil carbon management in the agricultural field. Furthermore, understanding how these interconnections in a SES affect soil carbon management and farmers' capacity to manage it, could help them 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 over 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 (Rochecouste et al., 2017; Evans, 2018). 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).

4.2 SES components and underlying variables for soil carbon management

In our proposed SES framework, the system components are social, ecological, ecological and social as defined in the methodology, with ecological and social components as the focus of soil carbon management (Figure 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 (Figure 5). In this SES framework, the components have key variables that influence soil carbon management in Australia (Figure 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 (Figure 5). We have provided some example indicators that could be measured to determine the influence of these key variables on soil carbon management (Table 1).

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 (Figure 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 stock (, Rabbi et al., 2015). Land use interacts with other key variables under ecological components such as climate, soil properties and soil biodiversity (Figure 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, 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) (Figure 5). Key variables under the social component include governance and policy settings, carbon markets, 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 (Figure 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.

5. 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, 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 social components of 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 in 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 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 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 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 operationalization 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 SES, which may enhance the process of achieving SDGs such as offsetting carbon emissions.

Declaration of interest

The authors declare that they have no conflict of interest.

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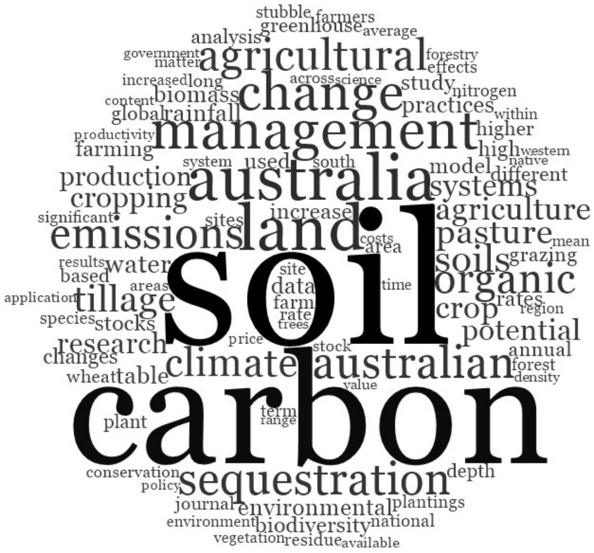

Figure 1. Representativeness of scientific literature in relation to the study theme by using NVivo12 Plus word frequency query. This word cloud shows the clear representation of the search term used in Stage 1 of the systematic review (SI Table 1).

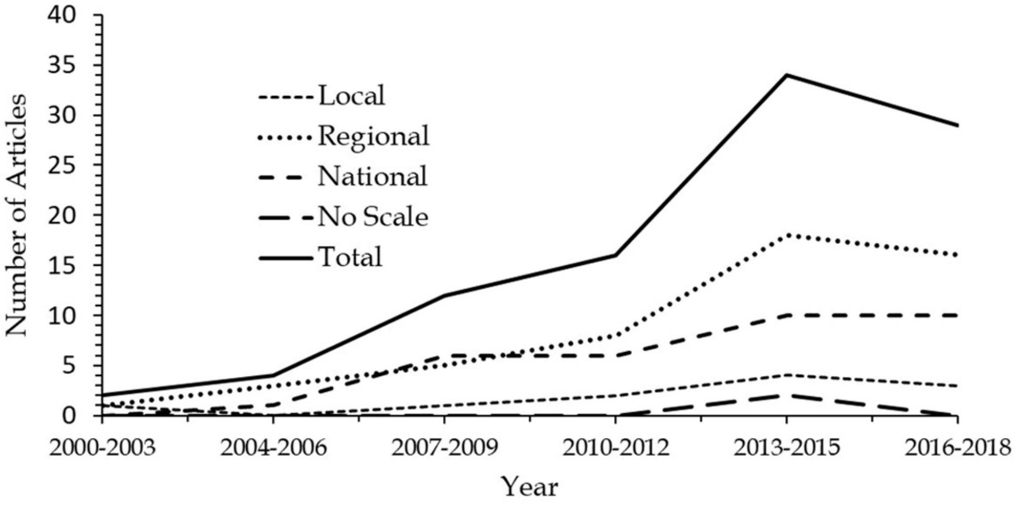

Figure 2. Since 2000, the spatial management levels and temporal distribution of soil carbon management articles from Stage 1 of the systematic review.

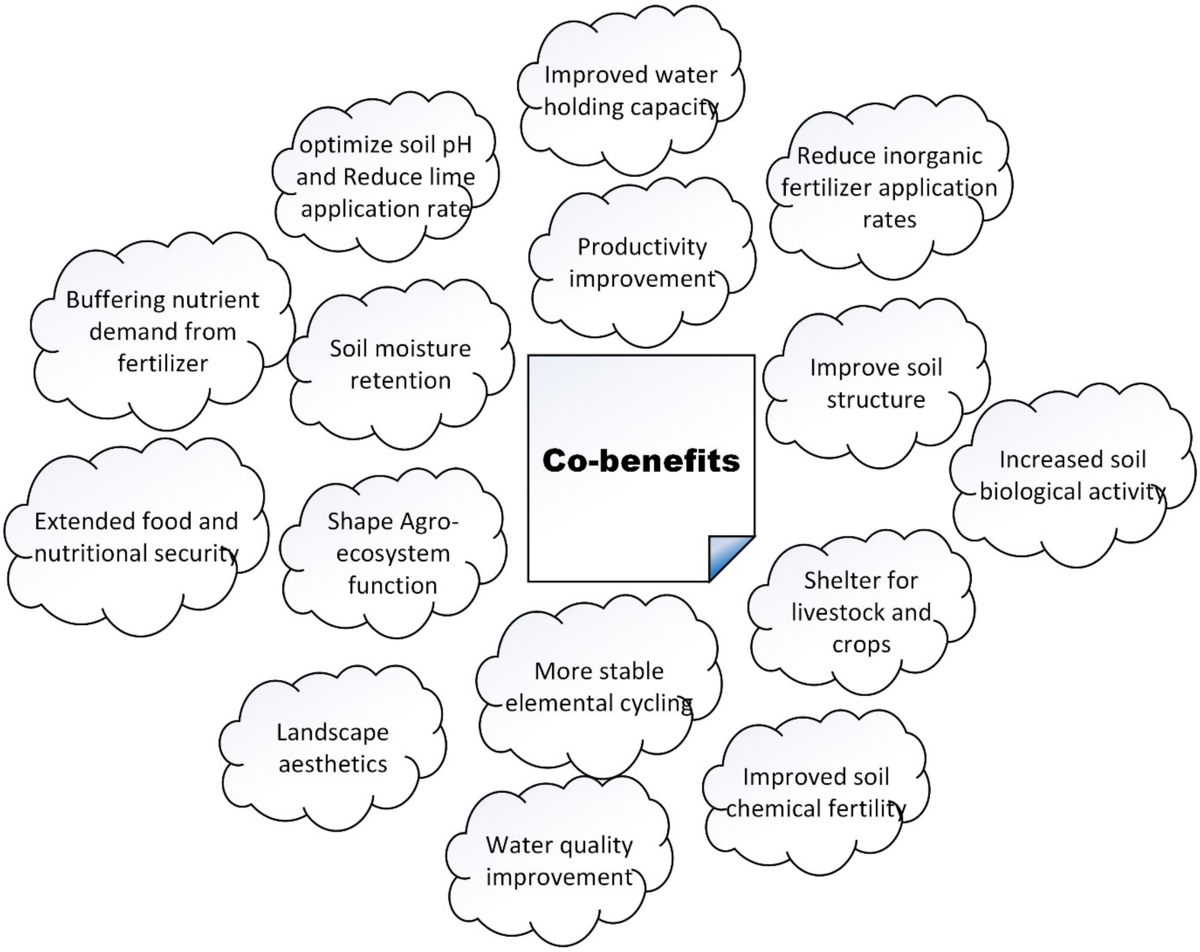

Figure 3. Identified Co-benefits of the soil carbon management in Australia from Stage 1 of the systematic review (n=97)

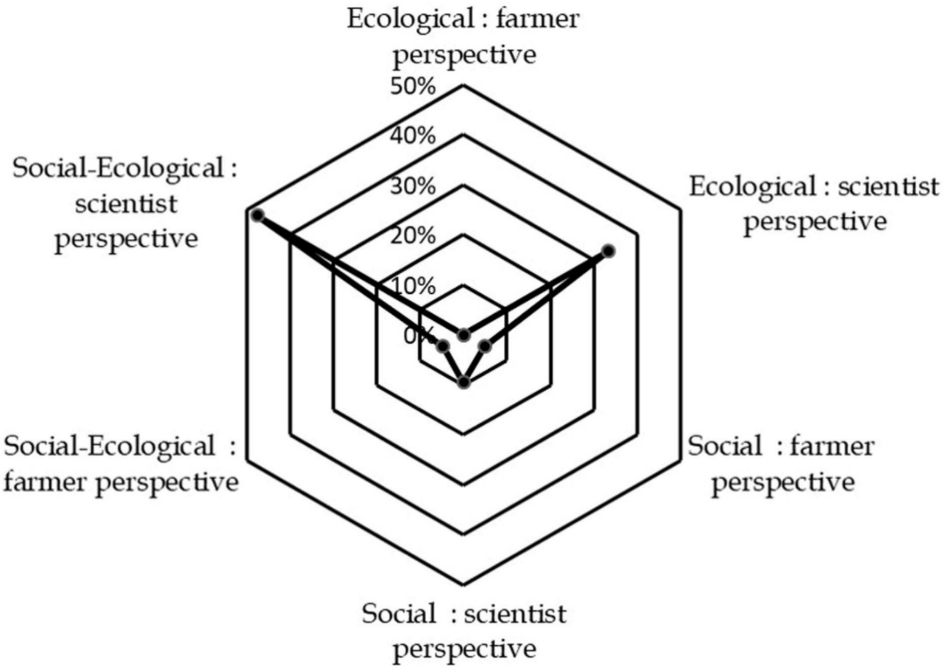

Figure 4. The relationship between a farmer's and scientist's perspective with Social-ecological component (ecological, social and social-ecological) in articles identified as examining potential co-benefits of soil carbon management

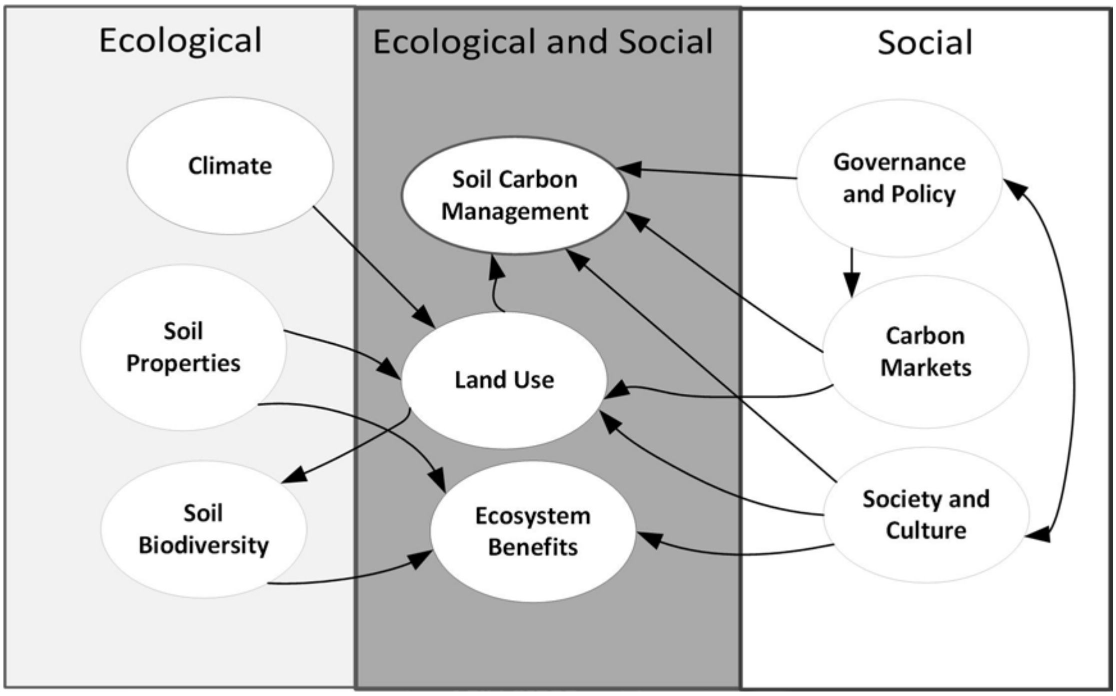

Figure 5. Social-ecological System key components (Ecological, Social, Ecological and Social), with corresponding key variables (e.g. Climate, Land Use and Society and Culture) and proposed interaction of key variables for soil carbon management in Australian agriculture (n= 97). Direction of arrows indicates a potential interaction between key variables and could be a positive or negative relationship.

Table 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)