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REVIEW ARTICLE

Contestations in the emerging soil-based carbon economy: towards a research agenda

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Abstract

This paper highlights the need to consider the processes and relations in the political, knowledge, technical and socio-material complex that underpins the emergence of a soil-based carbon economy. This economy, characterised by the proliferation of voluntary soil-based carbon markets, carbon farming policies, supply chain and other initiatives, operates through private mechanisms (offsetting, insetting) and public policy instruments. This emerging economy entails a number of inherent political and knowledge contestations associated with claims around the mitigation potential of soil carbon sequestration and carbon farming. We adapt a social ecological systems (SES) framework to understand these contestations and draw on a corpus of agricultural, ecological, political and social science literatures to identify and pose critical questions for future research. We conceptualise the emerging soil-based carbon economy as interactions and outcomes among actors embedded within a defined SES (governance, resource systems, resource units, actors). Five themes are identified: Marketisation, abstraction and technogovernance; Power relations and expert knowledge; Disputing the meaning and value of soil carbon; Disruptions: new interfaces, configurations and actor relations; Uncertainties and capabilities. These underpin a research agenda proposal. We argue that an integrative conceptualisation is essential to equitably account for the broad mix of social, technical, economic, political, and ecological contexts in which soil carbon is embedded and present options for operationalising the conceptualisation.

Keywords Soil-based carbon economy · Social Ecological Systems · Soil carbon markets · Carbon farming · Governance · Power

Introduction

Green finance has become an essential element in helping governments to meet their commitments to climate change mitigation and net zero, and biodiveristy (Benton et al. 2021), and in driving new bioeconomy and green business models (CBI Economics 2024; Davies et al. 2021). These private sector sources of finance are increasingly looked on to fill government funding gaps. For example, the government in England has set a target for private finance into nature recovery to reach over £1 billion a year by 2030 (Defra 2023), with the green finance strategy (HM Government 2023) outlining how they intend to achieve the step change needed. This green finance is envisaged to help quickly upscale a farming transition towards net zero (Green Finance Institute 2023). Private sector finance can be mobilised for this transition through banks, retailers and the supply chain, and as buyers of and investors in ecosystem services. Globally, there are now an increasing number of opportunities to access new funding streams through private nature markets for enacting nature-based solutions (and land-based natural climate solutions), including funding for carbon sequestration, improving water quality, and enhancing biodiversity (Reed et al. 2022; Buck and Palumbo-Compton 2022; UNEP 2021). The COP28 UAE partners agreed to scale up and enhance access to all forms of finance to transform agriculture in response to climate change (COP28, 2023). The European Commission's EU Carbon Farming

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initiative[1] is based on a green business model that rewards land managers through private and public mechanisms (European Commission 2021) (Bogojević 2024). With this increase in interest, however, are growing concerns about the potential environmental and social impacts and the influence of private sector actors to define what and how to govern, which is an inherently 'political act' (Hirons 2021; Chausson et al. 2023; Battersby et al. 2022).

Soils provide a natural capital that is essential for our well-being, and which is reflected in global initiatives to protect soils for climate change mitigation, food production, and biodiversity conservation (Bardgett and Van Wensem 2020; Lal 2016). Promoting soil as an enhanced carbon sink that absorbs anthropogenic greenhouse gas emissions while provdiing co-benefits has become an increasingly prominent narrative (Bossio et al. 2020), underpinning international scientific and political interests in carbon sequestration, the "4 per 1000" proposal endorsed by the COP 21 Steering Committee in 2015 (OECD 2015) and given formal recognition in the UNFCCC process in 2017 (COP23 decision 4/CP.23) (Rumpel et al. 2018; Vermeulen et al. 2019; Minasny et al. 2017). In particular, there is high expectation as regards transformative potential of agricultural practices to store soil carbon. As such, soil carbon is emerging as a key agricultural resource. As Keenor et al. (2021, p1) observe "[t]he establishment of a soil-based carbon economy has the potential to deliver a paradigm shift that will accelerate climate change mitigation, and concurrently realise net gains for soil health and the delivery of soil ecosystem services". Furthermore, scholars argue for a rapid scaling up of carbon removal through carbon farming and a range of land-based approaches to compensate for the large food system GHG emissions (Crippa et al. 2021).

This soil-based carbon economy operates through private mechanisms and public policy instruments that reward farmers for carbon farming practices that store soil carbon, recarbonise soil, and/or reduce GHG emissions (Keenor et al. 2021; FAO 2019). Such practices can be incentivised through private sector voluntary markets where carbon farming credits become an additional product that land managers can sell; supply chain standards for land management (insetting to meet Scope 3 net zero targets)[2] as well as public sector policy measures such as EU CAP instruments (Bossio et al. 2020; Battersby et al. 2022; Baumber et al. 2020; European Commission 2021); direct financial rewards from governments (Fleming et al. 2019) and potentially government subsidies and taxes (Frank et al. 2024). Of these, voluntary soil carbon markets (VCM) have attracted most attention, increasingly viewed as mechanisms to enable and scale the adoption of carbon farming practices in the UK and internationally with a growing global marketplace (Buck and Palumbo-Compton 2022; Black et al. 2022; Paul et al. 2023; Cevallos et al. 2019). This carbon offsetting approach is an appealing instrument for markets to generate new revenue streams for a range of supply chain actors, financial institutions, and farmers (Reed et al. 2022; Buck and Palumbo-Compton 2022). However, the increase in agri-food companies setting net zero targets for Scope 3 emissions by 2050 such as major food retailers (e.g. in the UK Tesco, 2021; Sainsbury's 2023), processors, and international corporations (e.g. Nestle) represents another dimension of the soil-based carbon economy. As part of this, farm businesses may need to demonstrate reduced emission or increased sequestration to access existing supply chain markets.

The last few years have witnessed a proliferation of voluntary markets, new investors, traders and brokers, project developers, and public and private sector carbon farming initiatives, networks, and projects with soil carbon becoming part of the lexicon of supply chain actors and policy makers, both internationally (Saifuddin et al. 2024) and in the UK (Reed et al. 2024).

However, the expectations for soil carbon sequestration (Buck and Palumbo-Compton 2022), the urgency to address climate change (Bradford et al. 2019), and the expansion of unregulated soil carbon markets (Reed et al. 2022) into the so-called 'wild west' territory of offset markets, along with public and private sector attempts to scale up carbon farming, creates multiple cultural and scientific challenges which coalesce to make this a highly contested and dynamic arena. In particular, this emerging soil-based carbon economy entails a number of inherent political and knowledge contestations associated with claims around the mitigation potential of soil carbon sequestration and carbon farming (Henderson et al. 2022; Sykes et al. 2020). Described as a 'speculative and promissory climatic regime' (King et al. 2018), and as 'overly optimistic and inherently flawed' (Amundson and Biardeau 2018), scholars argue that the existing knowledge base does not justify the current trend to set global agendas focusing on soil carbon sequestration (Moinet et al. 2023). Critics argue that, not only are there fundamental flaws in the logic of these markets to reach climate neutrality, but also environmental justice concerns (Saifuddin et al. 2024). Furthermore, VCM are controversial, and are criticised and championed by various groups in equal measure (Miltenberger et al. 2021). VCM thus present significant governance challenges (Black et al. 2022) and potentially risk marginalising soil's wider value and meaning. Additionally, the social, economic, and political barriers

[1] Carbon farming practices refer to those agricultural activities that can sequester carbon and/or reduce GHG emissions for example cover crops, reduced tillage, manure and fertiliser management.

[2] For companies to gain the benefits of shared value, they need to engage in carbon insetting, in which the carbon credits generated by farmers are marketed directly to buyers within the same supply chain.

to the implementation of soil carbon sequestration and carbon farming are only just becoming apparent (Amelung et al. 2020; Amundson and Biardeau 2018), as evidenced in the relatively small scale and slow progress in investment and action in this area (Vermeulen et al. 2019).

Against this backdrop, this paper highlights the need to consider the processes and relations in the political, knowledge, technical, and socio-material complex that characterise the emergence of a soil-based carbon economy. We adapt a social ecological systems (SES) framework to understand contestations in this emerging economy and draw on a corpus of agricultural, ecological, political, and social science literatures to identify and pose critical questions for future research.

These studies reveal persistent and related themes which to date were not always connected or applied to soil carbon (Table 1). Drawing on these insights, we identify a number of intersecting contestations relevant to the emerging soil-based carbon economy. We argue that an integrative conceptualisation (i.e. pluralist ontology that combines disciplinary perspectives) is essential to equitably account for the broad mix of social, technical, economic, political, and ecological contexts in which soil carbon is embedded.

Social ecological systems framework

A framework for analysing a soil-based carbon economy needs to draw on sociotechnical systems, where social elements (such as regulations, trading mechanisms, and stakeholder interests, goals, and values) and technical elements (such as carbon accounting methods, verification technologies, and IT platforms for trading) come together, and it needs to incorporate agroecological perspectives of soil systems and the multiple variables and processes acting within and between the ecological, political, economic, and social components. The social ecological systems (hereafter 'SES') framework provides a means to do this, bringing together ecological and social systems by focusing on four high tier components: *the governance system* (formal and informal rules), *the resource system* (particular ecosystem types and biophysical processes), *resource units* (part of and interact with the resource system), *actors* (public and private actors within a governance system). *Interactions* between the above components take place and are mediated by broader system relations within which the SES is embedded and produce outcomes. SES can be employed to organise arguments and analyses from the distinct perspectives relevant to a soil-based carbon economy (Bennett and Gosnell 2015; Amin et al. 2020). We conceptualise the emerging soil-based carbon economy (Fig. 1) as a set of *interactions* and *outcomes* among actors operating in an *action situation* embedded within a defined SES in which market and policy intermediaries negotiate, manage and trade in *resource units* with the intent of enhancing or maintaining carbon sequestration within the *resource soil system;* and *actors* such as land managers and farmers, and those who influence and support them, navigate changes, implement new practices, and deliver soil carbon within a *governance* system that legitimises, enforces, and monitors agreements among these actors. Employing the SES framing shows how the soil-based carbon economy is a highly contested set of interactions and outcomes. First, we synthesise literature concerning the four components of the SES, and in the following section we identify the five key interactions and outcomes which underpin our research agenda proposal. We acknowledge that there are many different frameworks for social–ecological systems and conceptual and methodological ambiguities (Binder et al. 2013; De Vos et al. 2019; Schlüter et al. 2019), but for this high level conceptualisation we take the key dimensions where there is agreement (Partelow 2018).

SES components and relevance to soil-based carbon economy

Governance

Governing the many dimensions of sustainable soil management brings new demands (Helming et al. 2018). These are especially acute with soil carbon governance where a lack of monitoring, problems in ensuring additionality, permanence, and safeguarding against leakage effects, and poor accountability are prominent (Battersby et al. 2022; Paul et al. 2023).

Soil carbon trading, supply chain governance, and policy implementation all require consensus on certification instruments used for long-term soil carbon storage, and the development of robust institutional agreements and processes (Rodrigo-Comino et al. 2020; Keenor et al. 2021; Amin et al. 2023) and an agreed method for valuation (Baveye 2023). International soil carbon codes are in operation, but exhibit differences in governance, scope, rules, methods, and marketplace and as such are not easily transferable (Black et al. 2022). Whilst more developed in Australia and USA, voluntary markets for soil carbon in Europe and the UK, for example, are currently unregulated. With the absence of regulation, significant controversy remains over the claims that are made with respect to gains or losses in soil carbon sequestered, and there are accusations of corporate "greenwashing". Central to this is the lack of transparency, environmental integrity, and standardisation in the methodologies and rules for monitoring, reporting, and verifying (MRV) and the use of different methods, benchmarks, technologies, and rules to deliver and generate carbon credits (Elliott et al. 2020; Smith et al. 2020). Currently, there are many models

Table 1 Summary of previously disconnected bodies of research in soil science, climate science, ecosystem services, and social and political studies

Soil carbon: scientific debates		Social, economic and political barriers to the implementation of soil carbon sequestration			
Ecosystem services, soil carbon sequestration and mitigation		Carbon farming and markets: farmer adoption, governance		Carbon (non-soil) offsetting and markets	
Soil ecosystem services, natural capital (NC), nature-based solutions (NBS)	Soil carbon sequestration and mitigation potential	Carbon farming (CF), soil carbon (SC) markets, farmer perspectives, capability	Governance	Commodification, marketisation	Political ecology, ecosystem services
Soil ecosystem services (Bardgett and van Wensum 2020 (soil as NC); Baggaley et al. 2022 (NBS, UK); Baveye 2023) **Natural capital** (Robinson et al. 2014) **Soil politics and human dimensions** (Krzywoszynska and Marchesi 2020, Gosnell 2022;Granjou and Meulemans 2023) **NBS** (Hirons 2021; Chausson et al. 2023)	**Role of soil carbon in mitigation** (Smith et al. 2012; Banwart et al. 2014 (SC, global); Bossio et al. 2020; Paul et al. 2023; Minasny et al. 2017; Smith et al. 2020; Yumashev et al. 2022 (UK)) **High expectation—SOC sequestration** 'win-win', co-benefits, few trade-offs (Rumpel et al. 2018; Amelung et al. 2020; Rodrigo-Comino et al. 2020; IPCC WG1, 2021; Miltenberger et al. 2021; McGlade and Morris 2023; Frank et al. 2024) **Contested role** (Bradford et al. 2019; King et al. 2018; Keenor et al. 2021; Moinet et al. 2023) **Mitigation potential of land management practices and knowledge gaps** (Smith et al. 2012; Powlson et al. 2011; Paustian et al. 2016, 2017; Oldfield et al. 2022)	**Co-benefits and trade offs** (Tang et al. 2016 (review GHG incentives, USA); Fleming et al. 2019 (CF, Aus); Keenor et al. 2021, McGuire et al. 2022; Buck and Palumbo-Compton 2022 (review SC, USA)) **Carbon certificates** (Paul et al. 2023) **Adoption barriers and incentives for farmers** (Kragt et al 2017 (CF, AUS); Sykes et al. 2020 (SC); Amundson and Biardeau 2016 Dumbrell et al. 2016 (CF, Aus); Frelih-Larsen et al. 2020 (CF, EU); Gosnell 2022; Baumber et al. 2020; Barbato and Strong 2023 (CM, USA); Amin et al. 2023; Phelan et al. 2022 (SCM, UK) **Knowledge and capacity** (Ingram et al. 2016; Kragt et al. 2017 (Aus); Aslam et al. 2017; Ingram and Mills 2019 (EU); Guan et al. 2021 (GHG, China); Macdonald 2022 (EU); Mattila et al. 2022)	**Soil carbon governance and MRV** (Elliott et al. 2020 (UK); Kragt et al. 2017 (Aus); Battersby et al. 2022; Jackson Hammond et al. 2021 (USA); Black et al. 2022 (UK); Reed et al. 2022; in press; Paul et al. 2023) **Techno-politics/Techno-governance (standards and metrics)** (Freidberg 2014; Rosin et al. 2017; Konefal et al. 2022)	**Green finance, climate capitalism, NBS** (Chausson et al. 2023) **Neoliberal processes, marketisation, calculative and performative work, materiality, subsumption of nature** (Mackenzie 2009; Callon 2009, Bumpus 2011; Twyman et al. 2015; Blok 2016 Ferreira 2017; Nel 2017; Cavanagh et al. 2021) **Fantasy of carbon offsetting, integrity, governance** of traded credits (McAfee 2016; Watt 2021) **Abstraction. Datafication. politics** (Scheidel 2019; Gabrys et al. 2022) **Carbon storytelling and new actors** (Kröger 2016; Chartier and Demaze 2020)	**Carbon colonialism and injustice** (Lawhon and Murphy 2012; Bennett and Gosnell 2015; Berbés-Blázquez et al. 2016) **Political ecology** north-south REDD+ (Leach et al. 2014 Lyons and Westoby 2014; Schumacher 2023 **Power asymmetries** (Giller et al. 2009; Kosoy and Corbera 2010; Leach et al. 2014 (biochar and markets); Newell and Taylor 2018; Carton 2020) **Private sector, corporates and offsetting** (Vermeulen et al. 2019; Battersby et al. 2022) Carbon farming **licence to operate** (Baumber et al. 2020)

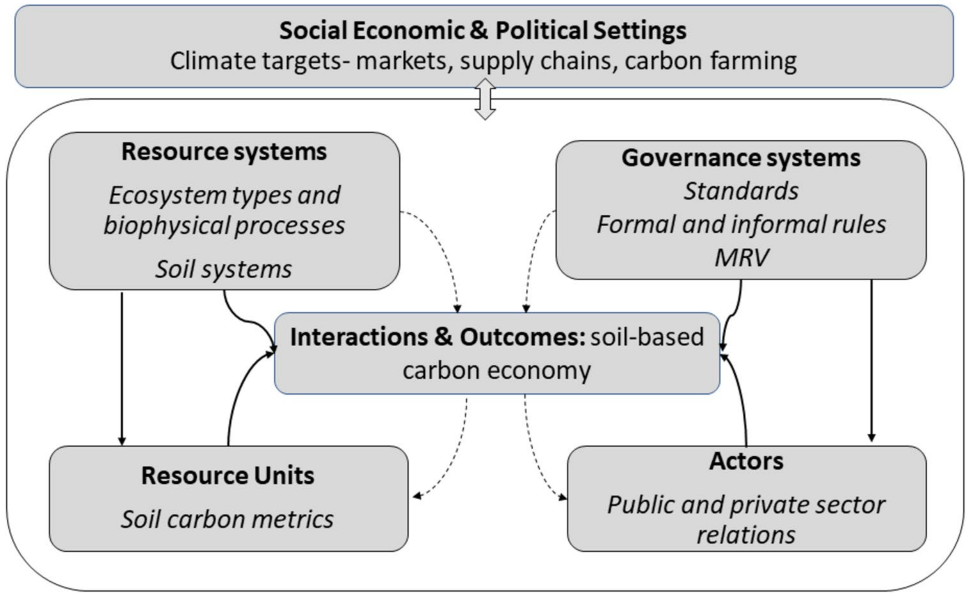

Fig. 1 SES framework for soil-based carbon economy (adapted from McGinnis and Ostrom 2014)

for carbon farming payments and mechansims in Europe and the UK, linked to different levels of MRV with associated risks and adminsitrative costs to farmers, and levels of certainty of mitigation (Macdonald 2022).

Furthermore, the implementation of insetting measures by supply chain companies is currently only rudimentarily established with no precise rules on how insetting should be accounted for. The lack of uniform accounting rules, clear definitions and methodologies to account for carbon and emissions, questions the integrity of companies' emission reduction and net zero targets (Ebersold et al. 2023; Stoll et al. 2019). The low investment in sustainable supply chains is in contrast to the number of 'hazy' voluntary business commitments made (UNEP 2021). To compound this, there is a high level of divergence in the farm carbon calculators on the market to support monitoring, as evidenced in a recent report for the UK (RSK ADAS Ltd 2023).

This leads to concerns that in the long term, mitigation will not be achieved and soil carbon certificates are likely to fall short of providing the certified emission offsets (Paul et al. 2023; Oldfield et al. 2022). In addition, markets might expose farmers and investors to unnecessary financial risks, leading to hesitancy and low confidence amongst farmers and other agri-food actors (Kragt et al. 2017; Buck and Palumbo-Compton 2022). Only when delivered with high integrity can carbon offsetting have an important (but small) role to play in achieving net zero (Committee on Climate Change 2022). However, in response to these critiques, some argue that 'the perfect can be the enemy of the good' and given the urgency of the situation they assert that such issues are resolvable and that VCM for example are a first, but urgent step in the transition (Miltenberger et al. 2021; Bernstein 2023).

Governance arrangements are forming to respond to the above, with a European framework for carbon removals in development (European Commission 2021) (Günther et al. 2024), and in UK principles for a Farm Soil Carbon Code (UKFSCC) recently identified (Black et al. 2022) as well as developing a range of nature investment standards which provide clear rules for how farmers can access payments from nature markets (BSI 2024). These are independent of standards already applied globally (Jackson Hammond et al. 2021). The lack of integration and potential conflict in the UK between public funding and voluntary markets for natural capital, and limited analysis about how they might be blended, has also been highlighted (Reed et al. 2024). To address this, each of the UK governments are working towards integrating public payments to complement nature markets (e.g. Defra 2023).

Resource systems

Soils are critical to agroecological systems, providing multiple interlinked ecosystem services and operating at the interface of agriculture, climate science, and natural capital (Baggaley et al. 2022). Soil organic carbon (SOC) in the form of organic matter is a key component of soil ecosystems. Envisaged as stocks and flows, SOC dynamics are particularly complex with many feedback loops. Soils have the capacity to both release and sequester carbon and other greenhouse gases and, as King et al. (2018) argue, a rather restrictive vision of soil as a global stock of carbon that we could monitor, model, manage, and enhance largely downplays this complex dynamic. Net soil carbon sequestration occurs when the difference between CO_2 removals and emissions is positive and contributes to mitigation when sequestration results from a net gain of carbon from the atmosphere. There are a range of approaches for achieving this (Sykes et al. 2020). However, debates over the role of SOC in mitigation are long-standing and have been described as adversarial (Bradford et al. 2019; Saifuddin et al. 2024). Equally, the impact of carbon farming practices such as conservation tillage, cover cropping, and residue management in arable systems is questioned (Buck and Palumbo-Compton 2022; Oldfield et al. 2022; King et al. 2018; Sykes et al. 2020; Powlson et al. 2011). For the UK, there are multiple contextual considerations (Yumashev et al. 2022). Furthermore, SOC responds slowly to changes in agricultural management, and in ecosystem terms it is called a 'slow' variable (Smith et al. 2012). Claims that carbon sequestration provides a win–win solution for mitigation and food security are also contested (Saifuddin et al. 2024; Moinet et al. 2023). However, others argue that despite the difficulty of ensuring long-term storage and sequestration of carbon, to overlook this potential opportunity does not make sense, pointing to evidence of some practices succeeding (McGlade and Morris 2023). Calls from the scientific community for a global-scale soil climate mitigation strategy and an agenda for collective action demonstrate the growing momentum in support of this view (Amelung et al. 2020; Vermeulen et al. 2019).

Resource units

There is a large body of work looking at how complex socioecological realities concerned with farm soils are made legible and governable by translating scientific knowledge into tools that markets and policymakers can use (Granjou and Meulemans 2023). This stems from soil systems having multiple properties and functions that have been disaggregated, measured and monitored by scientists. A soil-based carbon economy necessitates both quantifying soil carbon changes and determining a trading value. Soil organic matter (SOM) and soil organic carbon (SOC) are the most commonly measured variables; however, some argue that they provide little insight into carbon sequestration (Moinet et al. 2023). This is because measuring SOC reliably is challenging with high spatial and temporal variability of stocks and multiple management and context variables (Smith et al. 2012). A range of tools, technologies, and methods (measurement based, model based and remote sensing based) are used by markets and policy instruments to measure and predict soil carbon change, while farmers are rewarded according to actions, outcomes, or both (Macdonald 2022). Different methods are critiqued, for example a sociology of modelling perspective argues that modelling practices construct an inevitably selective reading of and gaze upon the world (Leach et al. 2014). Carbon payment is often in the form of "offset credits" that equate to a removal or reduction of 1t CO_2e. As such, as Carton (2020, p. 1355) observes that for carbon offsetting, a 'technocratic toolbox' is required which is "an assemblage of carbon dioxide equivalents, carbon credits, baselines, carbon measurement methods, monitoring, report and verification (MRV) methodologies".

Actors

Soil systems are socio-natural systems. In agriculture, they are managed systems that hold together farmer and soil material relations, and consequently have important human and cultural value (Granjou and Meulemans 2023; Baveye 2023; Gosnell 2022; Krzywoszynska and Marchesi 2020). Soil system management and governance is enacted by a multiplicity of traditional actors in the agri-food system (farmers, land managers, advisers, researchers across public and private sectors) (Ingram and Mills 2019; Bumpus 2011; Chartier and Demaze 2020). Most interest has been directed at farmers, and evidence from Australian (Kragt et al. 2012; Fleming et al. 2019; Dumbrell et al. 2016), international (Buck and Palumbo-Compton 2022), and US (Barbato and Strong 2023) studies show that co-benefits are more important drivers of farmer adoption of soil carbon sequestration practices and participation in carbon markets or programmes than receiving offset credits. Synergies may arise if participating farmers start to rethink soil management and increase soil organic matter, which can lead to improved soil health, fertility and resilience (Paul et al. 2023). However, some question the additionality that such markets can bring for farmers already implementing soil health practices, while a UK study suggested that such farmers may even be excluded due to regulations (Phelan et al. 2022). Furthermore, there is a risk that selling credits will harm farmers' own decarbonisation efforts and penalise them when supply chains start to require net zero farm status (Elliott et al. 2020). Overall, there is low confidence amongst farmers and agri-food actors in the governance of carbon farming due to policy and market complexity and uncertainty (Elliott et al. 2020; Kragt et al. 2017), which Baumber et al. (2020) argued was threatening the social licence of carbon farming in Australia. Information shortcomings across the Agricultural Knowledge and Innovation Systems (a framework for understanding supporting organisations, actors, and linking mechanisms) limit effective advisory support. Opportunity costs (including transaction and measurement costs) (Kragt et al. 2012; Tang et al. 2016) may lead to overestimates of income. Cultural, agronomic, and knowledge deficits are further barriers as well as concerns related to credibility, relevance, and legitimacy (Mills et al. 2019; Ingram et al. 2016).

Contested interactions in the SES: towards a research agenda

The emerging soil-based carbon economy is conceptualised as a set of interactions and outcomes among actors embedded within this SES as defined above by the high tier components. We identify *five interconnected key themes* in this SES framework which provide the basis for a research agenda and research questions (Fig. 2). Drawing on commonalities across different perspectives and literatures, the themes were identified iteratively by the authors as foci of contestation.

Marketisation, abstraction, and technogovernance

This theme centres on marketisation processes and the abstraction and governance activities that accompany them. A large body of literature, examining the politics of offsetting and its character as a market instrument, can inform our analysis. This critiques the assumptions, values, and expert knowledges that underpin carbon as a tradable commodity (Watt 2021), explored along themes of climate capitalism, commodification of nature, the integrity and governance of traded credits, 'the fantasy of carbon offsetting', and fetishisation of carbon (Watt 2021; Carton 2020; McAfee 2016). Kosoy and Corbera (2010) identify three 'inherent invisibilities' relevant to the commodification of soil carbon: simplifying the complexity of natural ecosystems; prioritising a single exchange value; and masking the social relations embedded in the process of 'producing' and 'selling' ecosystem services. With commodification, new meanings are conferred on carbon by the neoliberal processes of marketisation (Twyman et al. 2015; Callon 2009) which express a global technocratic order of enviromental governance (Blok 2016). Such marketisation brings multiple controversies which relate to abstraction, measurement, and governance (Callon 2009). The processes of abstraction and datafication (Gabrys et al. 2022; McKenzie et al. 2013; Nel 2017), and the constructed nature of ecosystem markets, obscure crucial social and ecological differences that have been the focus for carbon offset research (e.g. Bumpus 2011). The new imaginaries around soil carbon as a tradable commodity turn it into an abstracted 'value of equivalence', which counters the common understanding of a more holistic soil system and risks reinforcing the disconnect between people and nature. As Leach et al. (2014, p. 49) observe with respect to the new carbon economy in Africa "soil carbon is 'chopped out' of its ecosystem and social contexts and revalued as exchangeable pieces of carbon nature. Farmers are hailed as green actors and market winners, provided they discipline their practices according to these new technical and market logics". This singular focus on carbon has been criticised as marginalising the many other benefits managing soil health can deliver (McGuire et al. 2022).

Sciences and technology studies scholarship takes a marketisation perspective on the creation and performance of carbon markets (Callon 2009; Bumpus 2011; Ferreira 2017). Carbon markets are regarded as ongoing collective experiments that are assembled as carbon is 'brought into being' as a commodity (Callon 2009). As such, the emerging soil-based carbon economy may be conceptualised as a 'market-in-the-making' (Callon 2021), by which we mean a combination of farm-level mangement practices and emerging

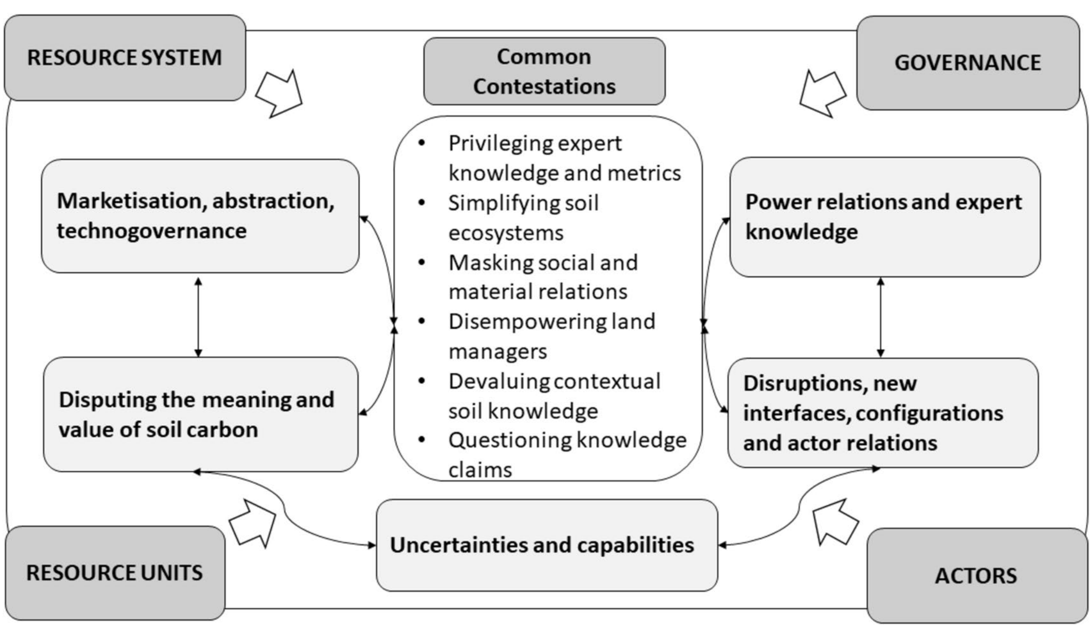

Fig. 2 SES interactions in the soil-based carbon economy

government and private forms of investment, regulation, and codification that collectively, but by no means in unison, 'frame' what is 'valued' to form a 'soil-based carbon economy'. The essential point therefore is the need to pay close attention to the social and material relations that 'make' markets over and above the markets themselves.

Through this marketisation perspective, then, both offsetting and insetting necessitate a form of 'techno-political governance' (Freidberg 2014) where new practices of soil carbon metric governance are authorised and enacted. Arguably like food footprinting, soil carbon metrics 'do technopolitical work', in that they serve as a tool for achieving certain political ends, which markets and supply chain actors use to govern and legitimate their ideas (Konefal et al. 2022; Freidberg 2014; Rosin et al. 2017). This raises the following research questions:

> What are the implications of soil carbon commodification and abstraction processes for farmer and practitioner communities? How does the apparent 'simplification' of soil carbon dynamics impact soil health and ecosystem services management more widely? What and how are private forms of governance emerging and which stakeholders are involved?

Power relations and expert knowledge

Both offsetting and payment for ecosystem services literatures foreground political ecology and political economy perspectives, highlighting issues of injustice, carbon colonialism, corporate control, and power asymmetries (Berbés-Blázquez et al. 2016; Bennett and Gosnell 2015; Battersby et al. 2022; Newell and Taylor 2018; Kosoy and Corbera 2010; MacKenzie 2009). Political ecology theory can show how power relations manifest themselves, how governance practices emerge, and how knowledge is built, negotiated, and authorised (Van der Horst and Evans 2010). It explicitly questions the expert-led framings and challenges theorists to more carefully and widely consider who is knowledgeable about particular environmental issues (Lawhon and Murphy 2012).

Marketisation and expanding carbon farming policies involve mobilising knowledge claims and discourses that construe offsetting as scientifically valid and legitimate. This can lead to reliance on expert knowledge which authorises the technocratic toolbox and acts to maintain the "hegemonic position that carbon markets enjoy in climate policy, in that knowledge claims inevitably come imbued with values, interests, and power relations" (Carton 2020, p. 1355). Power asymmetries have been observed in North–South relations in past programmes such as REDD+ (reducing emissions from deforestation and forest degradation in developing countries framework), and in contemporary carbon finance initiatives (Cavanagh et al. 2021; Schumacher 2023; Lyons and Westoby 2014), where political framings and commercial interests steer the promotion of practices such as conservation agriculture and climate smart farming despite weak evidence of beneficial impact (Giller et al. 2009). This is positioned within the increasing corporate influence over the governance of food systems and their role in nature-based solutions which is seen as a threat (Chandrasekaran et al. 2021), for example, the Bayer Carbon Initiative. Farmers have inherently had weak political capabilities in such contexts where policy, corporate pressure, and markets act to reinforce existing inequalities (Cavanagh et al. 2021). Political capabilities analysis highlights the significance of underlying relationships and processes to an individual's ability to achieve outcomes, including those that are personal (for example, skills, experience, health), social (power, social norms, gender roles), and environmental (institutions, public goods) (Ensor et al. 2021). There are also warnings that emergent technopolitics around measurement and simplification can provide new powers of legitimisation for corporate or state-planned land uses (Scheidel 2019). Narratives of anticipated or imagined carbon benefits or 'carbon storytelling' can be fundamental to achieving political support (Kröger 2016), whilst crisis narratives can be equally powerful in steering governance (Hirons 2021). Further balance between the benefits and costs, and their distribution across different stakeholders, are critical factors in determining whether carbon farming is able to obtain a 'social licence to operate' from the communities affected by them (Baumber et al. 2020).

It is important therefore with respect to a soil-based carbon economy to show how power relations manifest themselves in the particular institutional spaces where climate change and agriculture overlap (Newell and Taylor 2018; Saifuddin et al. 2024), to avoid further entrenching power asymmetries (Chausson et al. 2023), and to use inclusivity and legitimacy approaches to give farmers a voice (Ingram et al 2016; Hirons 2021). Already, it is recognised that farmer and community capacity to deal with markets is mismatched with the growth of natural capital investors and project developers, with calls for a fairer, more just, and responsible investment in natural capital (Scottish Land Commission 2023). Market value will depend on several factors, including carbon prices and demand for the credits, but based also on current value this is not high in the UK at present (Elliott et al. 2020). The complexity and uncertainty, high MRV costs of carbon markets, and open market structure lower the cost for buyers and other market actors, but raise costs for participating farmers (Elliott et al. 2020). Farmers also have different levels of control about selling certificates, and the type of certificate or credit created can affect claims farmers are able to make about their own impact. Furthermore, tenant farmers and smaller farmers cannot take full advantage of new natural capital (Benton et al. 2021). Assumptions that 'market-forces' will generate shared prosperity overlook the challenges of ensuring distributional and procedural equity (Moinet et al. 2023). However, opportunities for creating shared value with insetting are highlighted by some (Banerjee et al. 2013). This raises the following research questions:

> Who implements and authorises the technocratic toolbox for soil-based carbon and who governs the political and markets arena? Whose agendas are represented and advanced, and which activities and methods are deemed to count? What assumptions, values, and expert knowledges underpin soil-based carbon markets? How can transformational change come about when power asymmetries exist? How can farmer political capabilities be strengthened?

Disputing the meaning and value of soil carbon

This theme is characterised by the contestations associated with different values attributed to soil carbon and is closely linked to marketisation, abstraction, and technogovernance. Soil scientists have struggled to quantify or provide monetary valuation of soil services/functions (Baveye 2023; Robinson et al. 2014) and some question the "appropriation of soils as natural capital" (Bardgett and Van Wensem 2020). From the perspective of farmers and practitioners, their situated meanings of soil carbon are unlikely to match the abstracted, globalised knowledges of soil carbon as a marketable, tradable commodity (Twyman et al. 2015). Soil, not carbon, will have a tangible history and socio-material relation for farmers; their experiential knowledge, care practices, and values they hold about the wider benefits of soil health are potentially threatened (Fleming et al. 2019; Tang et al. 2016). Defining practices in terms of soil carbon risks marginalising and negating the many other benefits managing soil health can deliver and the non-monetary value of soil (Keenor et al. 2021; McGuire et al. 2022) and distracts from ongoing material relations, knowledges, and care practices that farmers have with their soil. A stronger interest in co-benefits (soil health, fertility, resilience) of markets or carbon farming demonstrates this (Buck and Palumbo-Compton 2022; Fleming et al. 2019; Sykes et al. 2020; Baumber et al. 2020). This resonates with calls for a shift from a myopic lens on carbon towards a more holistic approach (Harrison et al. 2021), and for a deep cultural and systemic shift, resetting human–soil relations (Chausson et al. 2023). As Moinet et al. (2023) observe, when nature becomes a provider of monetisable services, this can crowd out values and intrinsic social motivations driving stewardship. However, arguably market mechanisms can enable and scale up the adoption of carbon farming practices, bringing wider ecosystem benefits. How carbon is understood and valued by farmers and practitioners, and how standards and metrics are transcribed onto the material realities of daily lives need further investigation, as does the opposing needs of farmers and investors around permanence, and the constraints on future management that this may impose. This raises the following research questions:

> How do different actors make sense of value and give meaning to soil carbon? How is carbon understood and valued by farmers and practitioners, and how are soil carbon metrics transcribed onto the material realities of daily lives of the farming community? What is the burden of work associated with MRV or interacting with market intermediaries who do the MRV? How does the abstract nature of soil carbon affect assessment of risk in decision-making around participating?

Disruptions: new interfaces, configurations, and actor relations

In this theme, the focus is on the reconfiguration of actors and the implications for knowledge and discourse. The emerging soil-based carbon economy is already heralding new actors, interfaces, configurations, and social and material relations. Its 'market-making' is enacted by a constellation of new actors such as developers of projects generating carbon credits, credit retailers, wholesalers and/or investment funds, certification bodies, brokers, entrepreneurs, and customers (Demaze and Moïse 2021; Bumpus 2011), who have their own roles, expectations, conceptions, projects, and interests (Callon 2009). New intermediaries are deployed to discipline and frame the individual subjectivities of all actors and act to distribute accountabilities (Freidberg 2014). They potentially disrupt existing actors and services, markets, institutions, and practices. Traditional roles and analytical categories (farmer, adviser, supply chain actor, researcher) of those in the agri-food system can be challenged and redefined and social and professional relations reconfigured. Such reconfigurations can disrupt and destabilise 'meso-scale' actors' (e.g. advisers) routines and practices that are critical for supporting farmer learning as observed for digital agriculture (Eastwood et al. 2019).

Networks of actors (socio-natural and technical configurations) can be assembled in the soil carbon context, as observed for offsetting (Bumpus 2011). How these networks encounter and negotiiate practices, knowledges, and technologies, create discourses, and assemble capabilities (knowledge and political capabilties) should be key questions for research. The intersections of politics and knowledge with definitional and governance struggles create different visions or storylines of how soil carbon can be measured, governed, and managed. Carbon has its own language that circulates between sciences, markets, the public, and governments; the term 'carbon' carries a plurality of meanings with associated values (Twyman et al. 2015). Storylines cohere around groups of actors or networks that exist at a given point in time indicating the relative strengths of social, technical, economic, and political interest groups. Market actors construe offsetting and the commodification of soil carbon as scientifically valid and legitimate; traditional agri-system actors perceive high risks due to the unregulated nature of markets and question market credibility (Elliott et al. 2020; European Commission 2021), while policy makers position soil carbon markets as part of a broader geopolitical discourse associated with neoliberal environmental governance. This raises the following research questions:

> What are the new interfaces and cross sector linkages that facilitate the expansion of these markets? To what extent do carbon market actors and new relations disrupt or invigorate established roles and relations? How do different groups of actors create storylines around soil-based carbon economies to make sense of and give meaning to them? And how do they legitimise particular knowledge claims and practices?

Uncertainties and capabilities

This theme draws together notions of credibility, capabilities, and situated literacy linking them to empowerment. Land managers (farmers, advisers, and support services) face burdens and new demands in engaging in carbon accounting, voluntary soil carbon markets, and carbon farming (Buck and Palumbo-Compton 2022; Kragt et al. 2017; Green Finance Institute 2023). They struggle to assess the inherent uncertainties and credibility of different knowledge claims about soil carbon (Ingram et al. 2016). They have to navigate market, policy and supply chain mechanisms, negotiate different narratives, and understand complex concepts, terms, and metrics. Limited farmer knowledge and advisory capacity with respect to soil carbon management practices has been previously revealed (Kragt et al. 2017; Aslam et al. 2017; Ingram and Mills 2019), specifically their understanding of soil carbon dynamics and the relationship between soil carbon stocks and flows, and between fast and slow variables (Mattila et al. 2022; Frelih-Larsen et al. 2020). It has also been found that those who are more knowledgeable can be the most sceptical about carbon sequestration (Ma and Coppock 2012).

Baumber et al. (2020) found that shared values, worldviews, and land use norms strongly affected community acceptance of carbon farming. Hence, the importance of building soil capabilities and facilitating farmer learning networks and communities for soil management and social capital (Ingram 2010; Guan et al. 2021; Skaalsveen et al. 2020) takes on a new significance in the context of this emerging soil-based carbon economy. Furthermore, carbon farming options need to be designed for specific soil, political, economic, and ecological contexts (Moinot et al. 2023; Chausson et al. 2023) and take into account the farmers' behavioural control capability (Guan et al. 2021). This is recognised by the government in the UK who acknowledge that accessing nature markets can be complicated and may be a new experience for most farmers. They have commissioned an online toolkit to help farmers identify and access private payments for environmental benefits building on previous work (GFI 2023). Using toolkits like these, it is possible that a move to a soil-based carbon economy could help to build knowledge about soil and carbon markets, offering net gains for soil health and the delivery of soil ecosystem services.

Although previous studies have developed carbon capability frameworks for the public (Whitmarsh et al. 2011; Wei et al. 2016) and for farmers (Guan et al. 2021), these ignore the wider ecosystem services from soil and existing relationships with soil. There is a strong argument for building knowledge capabilities as part of a wider soil carbon literacy. Literacies are seen as 'socio-technical'; this is particularly the case with soil carbon as skills are implicated in wider socio-political (regulation and governance) and corporate (business models and monetisation) aspects. They can also be sites of struggle, built around the contextual knowledge and diverse experiences that shape relationships (McCosker et al. 2022). By connecting the notion of 'situated literacies' (Barton et al. 2000) to soil carbon, we can emphasise the need to understand transformations in the communicative, social, and relational contexts through which soil carbon knowledge and data are produced and traded. This literacy needs to develop across all actors in the AKIS. This raises the following research questions:

> To what extent do actors have knowledge capabilities to understand soil carbon dynamics, metrics, methods, and markets? How is this understanding of soil carbon as situated literacy distributed across actors in the AKIS? How do individuals develop knowledge and political capabilities, and how do these actions interplay with how carbon is known and valued? Can cross sector interaction strengthen capabilities?

Conclusion

This paper highlights the need to consider the processes and relations in the political, knowledge, technical, and socio-material complex that characterise the emergence of a soil-based carbon economy. Conceptualising this emerging economy as a set of interactions and outcomes among the SES tier components of governance, resource systems, resource units, and actors provides a novel means for identifying five research agenda themes, as shown in Fig. 2.

The multiplicity of issues identified shows that relevant research hitherto has been dispersed and addressed from a number of disciplines and perspectives. The interconnection between the themes calls for integration in future research approaches and for combining disciplinary perspectives through trans- and inter-disciplinarity. However, the methodological pluralism that characterises SES and other systems approaches creates challenges in understanding this system complexity (De Vos et al. 2019).

SES is intended here as a high-level conceptual framework to identify research themes through the diagnosis of contestations in interactions and outcomes. With respect to operationalising this concept to address the themes and research questions identified here, it can help scholars deconstruct the system complexity, identify at what conceptual level their research is located, and suggest a logical entry point to analysis that suits their specific research questions of interest (Ostrom 2009). Specifically, the SES framework provides variables (for the four main tiers and the tiers nested below them) which can be used to create theoretically grounded indicators. Although these variables are derived empirically for collective action and sustainable common pool resource use (Partelow 2018; Schlüter et al. 2019), some are relevant to the contestations discussed here. The interactions and outcomes (the action situation) can also be taken as the focal unit of analysis, although decisions about the activities to include, which processes to represent, and where to set system boundaries in an analysis depend on the question or phenomenon of interest (Schlüter et al. 2019). Most SES empirical work is typically more place based (e.g. de Vos et al. 2019), whereas soil-based carbon economy contestations may extend across spatial and institutional scales with important feedbacks between the multiple levels of its constituent scales (Glaser and Glaeser 2014).

Although there are limitations, the framework nevertheless offers a valuable heuristic for operationalising this research agenda to investigate contestations associated with the soil-based carbon economy. Selected variables for the main tiers could include: government, NGO, and supply chain organisations (governance); agricultural/land-based sectors (resource system); economic value and beneficiaries of carbon credits (resource unit); and buyers and sellers of carbon credits (actors). Interaction variables can include deliberative processes and monitoring activities and conflicts, while outcome variables can include some measure of social benefit (empowerment, revenue) and soil carbon sequestration performance. With respect to scale (dimension of analysis) and level (the unit of analysis) (after Cash et al. 2006), higher levels of *spatial* (global, country), *jurisdictional* (national and regional), and *institutional* (laws and regulations) scales can capture the scope and the heterogeneity in meanings, actors, and strategies in this developing economy, while landscape and more local level *spatial* scales, alongside local and regional levels of *jurisdictions* and rules (e.g. MRV) in *institutions*, provide insights at a finer resolution. *Network* scale (levels of family, group, and society) and *knowledge* scale (levels of universal–context and general–expert) are particularly important to reveal the constellation of actors and the power and knowledge processes in this emerging economy. Regarding approaches and methods, given the nascent form of the economy, research methodologies that track ‘market-in-the-making’ processes and practices are important, as assemblages are formed (Konefal et al. 2022), alongside social research methods to better understand how metrics order and structure behaviours and practices (Rosin et al. 2017). Case study approaches (sector and initiative based) using methods such as social network analysis, Netmap analysis, and discourse analysis can reveal knowledge contestations. Critically, such studies can help foreground analysis of power relations that can attend to the human actors and their relations with soils, institutional settings, and broader narratives and discourses, as well as identify how political and knowledge capabilities can be built. Table 2 illustrates how research might be designed for the theme marketisation, abstraction, and technogovernance.

Although this paper has focused on the emerging soil-based carbon economy in the UK, drawing on the international literature and experiences ensures that the analysis has wider resonance and can inform conceptualisations and research agendas in other contexts. Given the significant role of green finance and private sector actors, researchers need to engage with frameworks for anticipatory governance and responsible innovation to envisage and steer future developments (Battersby et al. 2022). This is particularly urgent with the increasing emphasis on green business models in soil carbon sequestration initiatives for mitigation. Looking towards the future, some scholars envisage that by 2050, the “current discrete market-based solutions in climate action will become internalised aspects of our economies rather than separate remediations” (Miltenberger et al. 2021, p1) and should be given leeway to improve and fulfil this. Robust research has a clear role in such a transition, to inform both the public and private forms of governance, both instrumentally by strengthening the evidence base, and conceptually by prompting new thinking and debates about soil carbon mitigation trajectories with respect to sustainability, equity, integrity, and accountability. Equally, those scholars with fundamental concerns about offset markets and environmental justice will need to marshal their research plans to support further advocacy.

Table 2 Research design considerations for the theme: marketisation, abstraction, and technogovernance

Example theme and research question	Main tier—selected variables	Interactions—selected variables	Outcomes—selected variables	Scale—dimension of investigation and level—units of analysis[a]	Approaches and methods
Marketisation, abstraction and technogovernance What are the implications of soil carbon commodification and abstraction processes for farmer and practitioner communities?	Govt., NGO, supply chain, and sector organisations Resource system—sector Resource unit—economic value (distribution of benefit) Actors—buyers and sellers, -type, power and norms	Deliberative processes Monitoring activities Conflicts Investment activities Supply chain activities Standardisation activities	Social performance measures (empowerment, just carbon credit payments) Soil carbon sequestration performance measures	Spatial and temporal (national, regional, local) Jurisdictional (international, national, regional, local) Institutional (regulations, MRV) Networks (individual farmers, intermediaries—constellations of actors) Knowledge (general-expert; scientific-contextual)	Map actors, organisational structures and processes Track 'market-in-the-making' practices and processes as assemblages are formed Case study approach (sectors)—using e.g. metrology to understand how metrics order and/or structure behaviours & practices

[a]Scale is defined as 'the spatial, temporal, quantitative or analytical dimensions used to measure and study any phenomenon' and levels as 'the units of analysis that are located at different positions on a scale' (Glaser and Glaeser 2014). The critical system scales for understanding and responding to human environment interactions, each with their appropriate level (in brackets), include: spatial (areas), temporal (rates, etc.), jurisdictional (administration), institutional (rules), management (plans), networks (links), knowledge (truths), and ecosystems (outputs) (Cash et al. 2006)

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