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BURYING THE CARBON TO DIG UP THE FUTURE: REVIEWING THE ROLE OF GEOGRAPHY IN VALUING SOIL CARBON ECOSYSTEM SERVICES

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ABSTRACT. Soil carbon sequestration presents a pathway towards climate change mitigation and adaptation while also fostering sustainable socio-economic development. The emergence of soil carbon markets, which monetize carbon capture and land management practices, has given new impetus to this area of study. However, the intersection of environmental, social, and economic systems inherent to soil carbon markets introduces significant complexities. To understand the research landscape and the prevailing themes within the field, we conducted a systematic literature review, sourcing articles from the Web of Science and SCOPUS databases that focused on soil carbon markets, published between January 2017 and august 2023. Our analysis revealed three primary research themes emerged: 1) Soil Ecosystem Services (61%), closely associated with the agricultural and environmental sciences; 2) Environmental Economics (21%) show the growing focus on economic valuation of ecosystem services since the Paris Agreement; and 3) Exploratory Analyses (18%) highlight recent efforts in dealing with the complex network of environmental, social, economic, political and cultural factors. However, these areas of research are often treated separately, reflecting a broader disconnect between natural and social sciences: Geography, uniquely positioned at the intersection of natural and social sciences, could bridge this divide. Through a geographical lens, one can better comprehend drivers behind land management and land-use changes and how they relate to environmental indicators and soil carbon markets. In the social sciences, cultural aspects that shape soil management practices, farmers' relationships with land and markets, and their engagement with soil carbon markets could be examined to predict actions towards improving environmental performance indicators. These settings are highly local, influenced by factors like land tenure rights, landscape ecology, political settings, and power dynamics. Geography's role extends beyond merely understanding these local factors. It also involves studying 'space' and 'place', concepts that are crucial in the context of soil carbon markets. Within the framework of complexity theory and spatial agent-based modelling for socio-ecological systems, Geography can provide valuable insights into how different entities within soil carbon markets interact and influence each other. In the context of climate change, soil ecosystem services, and by extension soil carbon markets, can influence social and economic vulnerabilities. An integrated study of land use, management practices, and their impact on soil ecosystem services, using both quantitative and qualitative approaches, can provide insights into social behaviour and ecosystem responses over time.

Enterrando el carbono para desenterrar el futuro: Revisando el papel de la geografía en la valoración de los servicios ecosistémicos de carbono del suelo

RESUMEN. El secuestro de carbono en el suelo puede ser un camino hacia la adaptación y mitigación del cambio climático, al mismo tiempo que puede fomentar el desarrollo socioeconómico sostenible. La aparición de los mercados de carbono del suelo, que monetizan la captura del carbono y las prácticas de gestión de la tierra, ha dado un nuevo impulso a esta área de estudio. Sin embargo, la intersección de los sistemas ambientales, sociales y económicos inherentes a los mercados de carbono del suelo introduce complejidades significativas. Para comprender el estado de la investigación y los temas predominantes en este campo, se realizó una revisión sistemática de la literatura científica, obteniendo artículos de la Web of Science y de las bases de datos de SCOPUS centrados en los mercados de carbono del suelo, publicados entre enero de 2017 y agosto de 2023. Nuestro análisis reveló tres ámbitos principales de investigación: 1) Servicios ecosistémicos del suelo (61%), estrechamente relacionados con las ciencias agrícolas y ambientales; 2) Economía ambiental (21%) que muestra el creciente enfoque en la valoración económica de los servicios de los ecosistemas desde el Acuerdo de París; y 3) Análisis exploratorios (18%) que resaltan los esfuerzos recientes en el tratamiento de la compleja red de factores ambientales, sociales, económicos, políticos y culturales. Sin embargo, estas áreas de investigación a menudo se tratan por separado, lo que refleja una desconexión más amplia entre las ciencias naturales y sociales: la Geografía, posicionada de manera única en la intersección de las ciencias naturales y sociales, podría salvar esta brecha. A través de una visión geográfica, se puede comprender mejor los impulsores que están detrás de la gestión de la tierra y de los cambios en el uso del suelo y cómo se relacionan con los indicadores ambientales y los mercados del carbono del suelo. En las ciencias sociales, los aspectos culturales que configuran las prácticas de gestión del suelo, las relaciones de los agricultores con la tierra y los mercados, y su compromiso con los mercados del carbono del suelo pueden ser examinados para predecir las acciones de mejora de los indicadores de comportamiento ambiental. Estos parámetros son altamente locales, influenciados por factores como los derechos de tenencia de la tierra, la ecología del paisaje, los entornos políticos y las dinámicas de poder. El papel de la Geografía va más allá de la mera comprensión de estos factores locales. También implica estudiar el espacio y el lugar, conceptos que son cruciales en el contexto de los mercados de carbono del suelo. En el marco de la teoría de la complejidad y la modelización espacial basada en agentes para sistemas socioecológicos, la Geografía puede proporcionar información valiosa sobre cómo interactúan e influyen entre sí diferentes entidades dentro de los mercados de carbono del suelo. En el contexto del cambio climático, los servicios de los ecosistemas del suelo y, por extensión, los mercados de carbono del suelo pueden influir en las vulnerabilidades sociales y económicas. Un estudio integrado del uso de la tierra, las prácticas de ordenación y su impacto en los servicios de los ecosistemas del suelo, utilizando enfoques cuantitativos y cualitativos, puede proporcionar información sobre el comportamiento social y las respuestas de los ecosistemas a lo largo del tiempo.

Keywords: Soil carbon sequestration, soil carbon markets, environmental Geography, climate change mitigation, land management practices.

Palabras clave: Secuestro de carbono del suelo, mercados de carbono del suelo, Geografía ambiental, mitigación del cambio climático, prácticas de gestión de la tierra.

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1. Introduction

The global discourse surrounding Climate Change Mitigation and Adaptation has been gaining momentum since the early 1990s. This increased attention is primarily fuelled by the collective understanding of a changing climate that is predicted to become warmer and drier. Consequently, the scientific community's focus has gravitated towards strategies to mitigate climate change's causes and adapt to its inevitable effects (Lobell *et al.,* 2013; Smith *et al.,* 2020; Tubiello, 2012). In response to these pressing concerns, according to the International Panel to Combat Climate Change (IPCC), mitigation strategies are typically classified into two distinct categories. The first pertains to efforts to reduce emissions of greenhouse gases, and the second involves the removal of a proportion of the existing atmospheric greenhouse gases. In contrast, adaptation to climate change involves comprehending the potential responses of natural ecosystems to climate forcings and designing strategies to navigate these changes.

The Agriculture, Forestry and Other Land Use (AFOLU) sector is at the forefront of climate change mitigation options. This sector accounts for over 24% of global greenhouse gas emissions, second only to the Energy sector (IPCC, 2014), and directly impacts the three fundamental components of the global carbon cycle, namely soil, biomass, and the atmosphere. The carbon storage capacity of soils surpasses the combined total of atmospheric and biomass pools (Lal, 2010; Scharlemann *et al.,* 2014). This capacity is maintained for extended periods, thereby making soil an essential tool in carbon sequestration (Lal and Ussiri, 2017).

Historical land use changes, including the transition from natural vegetation to agricultural and urban areas, have led to increased carbon emissions (Arneth *et al.,* 2017). These changes have driven biomass burning and soil erosion, thereby reducing carbon from these vital pools and subsequently releasing it into the atmosphere (Bristow *et al.,* 2016; Drews *et al.,* 2020). Population growth in recent decades has added further pressure on natural ecosystems. The increasing demand for food production often extends to marginal lands, accelerating desertification and leading to productivity and income loss (Kirkby, 2021; Shukla *et al.,* 2019). Consequently, the cycle of intensification and the search for new arable lands continue.

Early research suggested the potential of poor and degraded lands worldwide to capture and store half to two-thirds of historical GHG emissions (Lal, 2004). While contemporary studies challenge the magnitude of this potential and the complexity of soils as adaptive systems introduces uncertainties, there is consensus about the pivotal role of soil carbon sequestration in climate change mitigation (Salvati *et al.,* 2015). The political landscape is gradually aligning with these perspectives, as demonstrated by the "Soil Carbon 4perMille Initiative" of the Paris Agreement (Lal, 2020; Rumpel *et al.,* 2020; Zomer *et al.,* 2017).

The mechanism of carbon trading, originating from the Cap-and-Trade emission reduction schemes of the Kyoto Protocol, has evolved over the years. The growing environmental concerns have paved the way for Voluntary Carbon markets where individuals or corporations can buy carbon offsets for their emissions. However, issues surrounding the additionality, permanence, monitoring, and validation of sequestered carbon have given rise to greenwashing concerns (Fleischman *et al.,* 2020). Despite its reduced presence in voluntary markets, agricultural land remains a potential platform for emission reductions and net atmospheric removal of CO_2, albeit questions about its dimensional relevance and complexity issues arising from working complex adaptive systems with non-linear response to both natural and human forcings (Fearnehough *et al.,* 2020; IATP, 2020; Michaelowa *et al.,* 2019; Venmans *et al.,* 2020).

Although efficacy and relevance concerns surround carbon offset schemes in agricultural land, the potential benefits of land restoration, climate change adaptation, and the redistribution of income from pollutant urban areas to low-density rural regions cannot be overlooked. This is especially true for regions with arid, semiarid, and dry subhumid climates. Areas of the globe that demonstrate environmental sensitivity to climate change and desertification often coincide with low-income developing countries, where the potential benefits of ecosystem services and food security amplify the necessity for soil carbon sequestration approaches.

The complexity of Soil Carbon Sequestration for Climate Change Mitigation and Adaptation requires interdisciplinary understanding, as it intersects environmental, social, economic, and political issues. Navigating this complexity can benefit greatly from the field of Geography, which excels in addressing complex relations within time and space (Cerqueira, 2021). This review explores recent scientific literature on soil carbon capture and storage, its relation to ecosystem services valuation, and carbon markets, as interpreted by the Social Sciences. The objective is to illuminate the potential contributions of Geography and geographical thought.

2. Methods

This study implemented a structured literature review adhering to the PRISMA Guidelines to screen and analyse results from a Web of Science (WoS) Social Science Citation Index (SSCI) and SCOPUS search query that focused on publications from January 2017 to August 2023. Both data sets were processed using an R script to exclude duplicates and organize the articles in alphabetical order of the first author, as well as creating a screening document with the following details: Author(s), Year, Title, Abstract, DOI.

We initiated the first systematic search in December 2021 and updated the final list on August, 2023, ensuring that we captured any additional relevant studies that were published during this period. The exact queries used in the SCOPUS and WoS searches are provided below:

SCOPUS (81 results):	**WoS (97 results):**
Title-Abs	Social Sciences Citation Index (SSCI),
(Soil AND Carbon AND Market*)	From 2017 to 2023.
AND (PubYear > 2016)	(((TI=(soil AND carbon AND market*))
AND (Limit-to(SUBJAREA, “Soci”)	OR AB=(soil AND carbon AND market*)))

In addition to this, a secondary search was executed on the SCOPUS database to estimate the volume of scientific work exploring the valuation of soil carbon as an ecosystem service within the Social Sciences discipline. We conducted three different queries on the title and abstract content: “Soil AND Carbon”, “Carbon AND Market*”, and “Soil AND Carbon AND Markets”. The rationale behind this was to assess the thematic variability of the subject, thereby enabling more accurate and informed future queries that can potentially eliminate field biases in the literature search.

3. Results

Our results showed that the interplay between the three keywords indeed allowed different approaches to be taken towards problems of a similar nature. The results and the analysis over the last five years are depicted in Tables 1 and 2, and Figure 1, providing a comprehensive overview of the search findings.

Table 1. Percentage of works associated with each research field in three different queries. at = All Time; 2017-p = 2017 to present day; 2020-p = 2020 to present day.

	Agriculture and Biology				Environment				Earth and Planetary			
	at	2017-p	2020-p	trend	at	2017-p	2020-p	trend	at	2017-p	2020-p	trend
Soil AND Carbon	**54%**	**52%**	**51%**		**45%**	**49%**	**49%**		18%	18%	17%	
Carbon AND Market*	10%	9%	8%		**33%**	**37%**	**37%**		6%	6%	6%	
Soil AND Carbon AND Market*	**48%**	**45%**	**42%**		**49%**	**52%**	**53%**		10%	13%	13%	

	Engineering				Energy				Social			
	at	2017-p	2020-p	trend	at	2017-p	2020-p	trend	at	2017-p	2020-p	trend
Soil AND Carbon	6%	7%	7%		4%	5%	5%		3%	5%	5%	
Carbon AND Market*	31%	32%	33%		**32%**	**36%**	**37%**		14%	15%	15%	
Soil AND Carbon AND Market*	13%	12%	12%		11%	17%	19%		**13%**	**15%**	**15%**	

Table 2. Percent distribution of published work between January 2017 and August 2023.

	2017	2018	2019	2020	2021	2022	2023	trend
Soil AND Carbon	11%	12%	13%	15%	17%	18%	13%	
Carbon AND Market*	9%	9%	11%	13%	17%	24%	17%	
Soil AND Carbon AND Market*	10%	10%	11%	17%	18%	17%	17%	

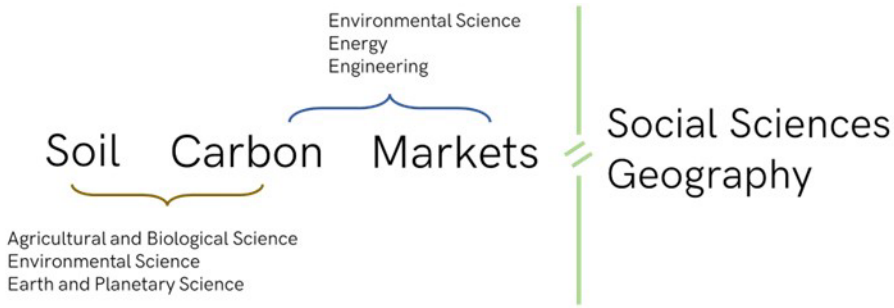

Figure 1. A comprehensive overview of the search findings.

It was observed that issues bridging the environmental and social realms were anticipated to spread research topics across different fields. As depicted in Table 1, "Soil Carbon" was predominantly associated with Agricultural and Biological Sciences, Environment, and, to a lesser extent, Earth, and Planetary Sciences. "Carbon Market*", on the other hand, was associated largely with Environmental Sciences, but also significantly with the Energy and Engineering fields.

When all three keywords were combined in the query, there was a concentration of results within Agricultural and Biological, and Environmental fields, with Social Sciences emerging as a more relevant field. Although the relative importance of Social Sciences was still minimal (13 to 15%), the introduction of the term "Soil" in the query drastically decreased the significance of the Energy and Engineering fields.

We then screened the articles by their titles and abstracts to gauge their relevance to this study, discarding articles that met the following criteria: 1) that were out of scope of the goals of these research but managed to be included in the search by having simultaneously the terms "soil", "carbon" and "markets" in the title or abstract (for example energy papers on biomass fuel such as wood pellets or agronomy papers on animal husbandry production); 2) that did not focus on soil carbon sequestration directly or indirectly as an ecosystem service (for example pure agronomic studies of crop performance); 3) focused on soil carbon emissions (either by land use change or other sources such as rice paddy emissions and erosion). This resulted in 56 documents being discarded (Table 3), leaving 77 for further analysis. These 77 documents were classified into three categories: 1) Soil Ecosystem Services (in agricultural land, integrated systems, forests, and coastal environments), 2) Environmental Economics (including topics like carbon pricing and trading mechanisms), and 3) Exploratory Analyses. The sections that follow will delve into the results of the review following the above classification, and the relevant articles can be found in a table at the end of each respective category.

Table 3. Screening and Analysis Results.

Articles (n = 133)		Soil Ecosystem Services (n = 47)				Environmental Economics (n = 16)		Exploratory Analyses (n = 14)
Discarded	*56*	*Agricultural Land*	*Integrated Systems*	*Forests*	*Coastal Environments*	*Carbon Pricing*	*Trading Mechanisms*	
Relevant	**77**	19	7	17	4	8	8	14

3.1. Soil Ecosystem Services

Soil resources play a critical role in the fast turnover domain of the carbon cycle, serving as the most significant carbon pool (Lal and Ussiri, 2017). However, these same resources are also responsible for the majority of carbon emissions in the Agriculture, Forest, and Other Land Use (AFOLU) sectors, primarily due to changes in land use. Furthermore, the intensity of land use and the resulting degradation creates both an opportunity and a necessity to refine management practices, with a view to bolstering carbon stocks in biomass and soils alike.

The sequestration of carbon has an intrinsic value within the context of ecosystem services, due to its beneficial impact across the board. Provision services are improved as a result of increased agricultural productivity; regulation of climate and surface temperature becomes feasible due to the net removal of atmospheric carbon and alterations in surface albedo; biodiversity and pedogenesis are promoted, thereby providing additional support; and cultural values are enriched through the preservation and propagation of local species, which are often tied to educational, aesthetic, and spiritual or religious activities. Furthermore, this also enables the production of local goods (such as specific honey varieties) and the development of tertiary activities, including tourism and sports.

The process of Soil Carbon Sequestration induces a shift in the carbon cycle, allowing terrestrial ecosystems to absorb more carbon from the atmosphere than what they lose through respiration, oxidation, or erosion. Such a shift can be achieved through the application of recommended management practices, such as enhanced tillage, the use of cover crops and green manure, or prolonged fallows. Extensive reviews on soil and land management practices have already been conducted (Aguilera *et al.,* 2013; Cerqueira, 2021, Chapter 4; Sanz-Cobena *et al.,* 2017).

Articles focusing on Soil Carbon Dynamics and Sequestration explore management practices and changes in land use, with the aim of optimizing and augmenting carbon sinks, boosting carbon pools, and addressing questions concerning the capture of carbon and the volume that can be stored. It should be noted that the methods employed for soil carbon sequestration vary according to land use type, particularly between forest and agricultural land. In the context of forests, carbon can be stored more effectively through improved management practices, regenerated through reforestation efforts, or 'saved' via the conservation of natural capital and its valuation against changes in land use and economic applications.

3.1.1. Agricultural Land

Changing land use from natural vegetation to arable land is a significant source of greenhouse gas emissions within the Agriculture, Forestry, and Other Land Use (AFOLU) sectors. This transition results in carbon loss from both soils and biomass, due to clearance and exposure to erosion processes. Mitigation measures for climate change in this sector encompass soil carbon sequestration in arable lands – often referred as ‘carbon farming’ (Marks, 2020; Sharma *et al.,* 2021) – facilitated by management practices that help restore some of the carbon stocks lost during conversion. These practices work by augmenting cover protection (through cover crops and straw deposition), increasing organic and nitrogen inputs (via compost and green manure), and reducing soil erodibility (through improved tillage).

The use of organic amendments such as biochar (a specific type of coal produced by emission-controlled pyrolysis) can augment soil carbon stocks while minimizing CO_2 emissions from the burning of excess biomass and N_2O from mineral fertilization (Liu *et al.,* 2020). Anticipated adaptation benefits include enhanced water retention capacity and yield (Otte and Vik, 2017). Nonetheless, the economic viability of biochar is hampered by a lack of scale, and production CO_2 emissions may outweigh the ecological advantages (Rodrigues and Horan, 2018). This could be mitigated by more efficient straw pyrolysis (Liu *et al.,* 2020). Other organic farming procedures also show benefits compared to conventional farming, providing ecosystem services of carbon and cycling, biodiversity, soil health and erosion control, especially when associated with other practices than enhance soil protection (Persiani *et al.,* 2023). However, some setbacks include high adoption costs (Auerbach, 2018) even though there is the possibility of added profitability (Beni *et al.*, 2021).

Land clearance and land use change significantly contribute to GHG emissions, however, some transition patterns are associated with carbon sequestration and increased income (Roy *et al.,* 2022). In Southeast Asia, oil palm cultivation is a primary driver, but using fruit bunches as a mulch can counterbalance some of these emissions by increasing carbon sequestration and reducing carbon emissions (Rudolf *et al.,* 2021). However, employing organic amendments for carbon sequestration may create competition between ecosystem services. As an example, a study found that using crop residue for soil carbon sequestration (regulatory service) diminishes its potential for bioenergy (provisioning service). Therefore, to harmonize climate change mitigation with other sustainability objectives, crop residue management needs to be designed in an integrated, site-specific manner (Mouratiadou *et al.,* 2019). Recent trends in land use change in some western countries include farmland and agroforestry abandonment, due to a complex network of changes in socioeconomic, environmental, political, and cultural factors, inducing soil and biomass carbon sequestration and other ecosystem services (Carlos Alias *et al.,* 2022; Yang *et al.,* 2020)

Recommended management practices also include improved tillage (null, reduced, or shallow) to reduce runoff erosion and organic matter loss; green manure to increase soil nitrogen and decrease the application of mineral fertilization and N_2O emissions; and compost to enhance soil organic matter and water retention capacity *(Bhattacharyya et al.,* 2021; Chopin and Sierra, 2021; De Leijster *et al.,* 2020). The effectiveness, scalability, and profitability of implementing these management practices could be improved through a socio-organizational framework that combines people, infrastructure, technology, culture, and knowledge (Johansson *et al.,* 2022). This approach could have a positive effect on Net Present Value and the willingness to adopt these measures, which are further enhanced by input from local stakeholders and land managers (De Leijster *et al.,* 2020; Feliciano, 2022; O'Sullivan *et al.,* 2018; Otte and Vik, 2017). Improved governance mechanisms such as a standardized framework for sustainable biomass, more efficient assessment of land management best practices, and better scaling opportunities may ensure the enhancement of co-benefits and coupling of negative emissions with 'net-neutral' practices (for instance, biomass management for biofuel that concurrently stores carbon in the soil) (Torvanger, 2019).

Table 4. Relevant articles within Soil Ecosystem Services - Agricultural Land.

Author	Year	Short Summary
Auerbach	2018	Compares conventional and organic farming effects on small-scale farmers, highlighting organic's benefits for soil health and biodiversity
Beni *et al.*	2021	Mediterranean organic farms turn to natural agriculture for environmental benefits and better profitability, contrasting soil erosion and enhancing soil health.
Bhattacharya *et al.*	2011	Examining global soil carbon sequestration practices in developing countries, the study highlights agroforestry's promise and policy implications.
Carlos Alias *et al.*	2022	Global market pressures lead to unprofitable agroforestry abandonment, increasing forests and transforming soil into carbon sinks.
Chopin and Sierra	2021	Feasibility of 4‰ increase in soil organic carbon assessed for Caribbean agricultural soils, limited by soil types and practices.
De Leijster *et al.*	2020	Agroecological practices enhance almond orchard sustainability, yet economic incentives and policies are crucial for wider adoption.
Feliciano	2022	UK horticultural farmers respond to rising demand by adopting sustainable practices for environmental and economic benefits.
Johansson *et al.*	2022	Transforming Swedish farms into carbon sinks requires agroecological practices, fostering biodiversity, soil health, and sustainable food systems.
Liu *et al.*	2020	Straw biochar application improves crop yield and reduces N2O emissions but faces economic challenges.
Mouratiadou *et al.*	2019	Maximizing bioenergy from crop residues while mitigating soil carbon decline requires integrated, site-specific management strategies.
O'Sullivan *et al.*	2018	Functional Land Management (FLM) integrates soil functions for sustainability. Catchment challenges engage stakeholders and bridge science-policy gaps.
Otte and Vik	2017	Biochar enhances soil fertility, crop yield, and carbon capture. Challenges remain in implementing functional biochar systems, requiring socio-technical strategies for sustainable adoption.
Persiani *et al.*	2023	Identifying cost-effective measures to reduce agricultural emissions in France, emphasizing efficiency and investments.
Rodrigues and Horan	2018	Biochar emerges as a sustainable solution for agriculture, carbon sequestration, and climate change mitigation, with varying global economic viability.
Roy *et al.*	2022	Various land-use systems (LUSs) were assessed for CO2 sequestration, C stocks, and income potential. Forest-based LUS showed highest benefits.
Rudolf *et al.*	2021	Empty fruit bunch (EFB) mulching in oil palm plantations enhances yields and soil organic carbon, benefiting sustainability.
Sharma *et al.*	2021	Carbon farming enhances sustainability by diversifying natural farming methods, sequestering carbon, and integrating agroforestry for soil health.
Torvanger	2019	Biomass energy with Carbon Capture and Storage (BECCS) is vital for achieving climate targets but requires careful governance.
Yang *et al.*	2020	Abandoned farmlands globally hold potential for carbon capture and storage and can be facilitated by biodiversity management and biochar application.

3.1.2. Integrated Systems

Apart from traditional and conventional agricultural practices, some authors refer to integrated systems as a win-win approach regarding environmental protection, and social and economic development, which are the three pillars of sustainability. These systems include complex patterns of agriculture and forestry (agroforestry), agriculture, forestry, and pasture (agrosilvopasture) and forestry and pasture (silvopasture). These measures tend to be associated with poorer and more degraded and marginal lands since they are reportedly effective in reducing land use change and intensity-related soil erosion and mitigating losses in organic matter and carbon emissions.

Integrated systems such as agroforestry and agrosilvopasture are especially promising on their potential role of increasing soil organic carbon, reduce greenhouse gas emissions, increasing yield and fostering biodiversity (Aba *et al.,* 2017), all while reducing labour costs and providing marketing advantages to farmers, providing climate change mitigation, adaptation, food security, and provision of cultural and recreational benefits (Partey *et al.,* 2017; Ryschawy *et al.,* 2021; Sollen-Norrlin *et al.,* 2020). The introduction of tree crops in agricultural production, even though yielding positive environmental results, often requires financial incentives to drive change (Englund *et al.,* 2020), as it may interfere with traditional cropping practices (Felton *et al.,* 2023).

Apart from the more traditional integrated systems, some studies also show a positive feedback from integrating feedstock crops in marginal agricultural lands in Europe to provide biofuel and other ecosystem services such as erosion control and carbon sequestration (Von Cossel *et al.,* 2020). The value of the adoption of these mechanisms increases when they target more marginal lands, where the primary agricultural activity creates a degradation gradient that is mitigated by the protective and organic properties of perennial cropping systems. In these approaches, the integration of feedstock crops not only addresses biofuel production needs but also contributes to the restoration and enhancement of ecosystem services, making significant strides towards sustainable land management practices.

Table 5. Relevant articles within Soil Ecosystem Services - Integrated Systems.

Author	**Year**	**Short Summary**
Aba *et al.*	2017	Planting trees mitigates climate change by capturing carbon and conserving nature.
Englund *et al.*	2020	Multifunctional perennial production systems can balance biomass demand with environmental benefits, needing proper compensation mechanisms.
Felton *et al.*	2023	Agroforestry offers benefits like carbon storage, soil health, and additional income, but barriers hinder its adoption.
Partey *et al.*	2017	Improved fallows in Africa enhance food security, soil fertility, carbon sequestration, and livelihoods but require policy support.
Ryschawy et al.	2021	Agroecological integrated sheep-vineyard systems show promise for reducing inputs, improving soil quality, and enhancing sustainability.
Sollen-Norrlin *et al.*	2020	Agroforestry systems offer benefits like productivity and carbon sequestration, but adoption faces challenges like costs and awareness.
Von Cossel *et al.*	2020	Cultivating perennial biomass crops like Miscanthus can enhance carbon neutrality and environmental services, requiring subsidies to bridge the gap with biofuel economics.

3.1.3. Forests

The adoption of the suggested management practices mentioned earlier enables market valuation of various soil ecosystem services. This includes the provision service, which involves boosting yield, the regulation service for climate change mitigation, and the support service that aids climate change adaptation (Chen *et al.,* 2022). However, achieving an optimized carbon cycle through these practices presupposes that a prior transition from natural vegetation to agricultural land has occurred. As a result, these endorsed agricultural practices serve as ways of estimating the value of strategies that mitigate the impacts of land use changes, essentially aiming to repair previous degradation.

Nonetheless, it's crucial to note that natural ecosystems such as forests, grasslands, and shrublands offer ecosystem services that could be valued without triggering the detrimental effects of land use change. These services include climate regulation, support for biodiversity, and cultural values. We can estimate the value of conserving and maintaining the dynamics of natural ecosystem services either through direct conservation efforts or by valuing these services at a rate comparable to, or higher than, those achievable via land use and land cover changes. The studies categorized under this topic aim to address questions on how to assign a value to carbon in natural ecosystems, making the capital in these natural areas a preferred option over triggering degradation.

Valuing forest conservation starts with assessing the baseline scenario to comprehend the carbon stocks and balances in soils and biomass. This step is essential to gauge the emissions avoided by preserving natural vegetation instead of converting it into arable land (Santini *et al.,* 2020). The same consideration applies to certain less profitable tree crops like the carob-tree (Ceratonia siliqua L.), which may be replaced by more profitable but environmentally harmful crops/practices if ecosystem service valuation is not implemented (Correia and Pestana, 2018). When carbon farming via reforestation efforts, there are cost-effectiveness differences between plantation, restored and second-growth forests as carbon accumulation rates and implementation costs vary with the degree of human intervention, even though soil carbon contents appear to remain comparable (Brancalion *et al.,* 2021).

Forest conservation, restoration, and enhancement of land management practices could potentially mitigate up to 21% of the United States' annual emissions (Fargione *et al.,* 2018), and regional cost-share programs allow for compensating landowners for the provision of market and non-market ecosystem services (Chizmar *et al.,* 2021). These practices can concurrently achieve positive effects on biodiversity (Dybala *et al.,* 2019), water retention, soil erosion (Jafarzadeh *et al.,* 2021; Kitaibekova *et al.,* 2023; Wu *et al*., 2022) as well as providing recreational services related to landscape tourism, sometimes exceeding the economic value of wood harvesting (Lopes and Amaral, 2021). In the Amazon, restoration projects are expected to yield various socioeconomic impacts, including the protection of water resources, reduction of soil erosion, income from carbon programs, and sales of timber and non-timber products. However, a conflict exists between reforestation and the demand for land clearance for agriculture and cattle ranching. This tension is amplified by the lack of market volume for commercial products from restored areas (non-timber, non-cattle, non-agriculture) (Nunes *et al.,* 2020). When evaluating the three dimensions of sustainability in forest product production, i.e., environmental measures, economic development, and social impacts, integrated assessment modelling techniques can help forecast soil carbon sequestration, greenhouse gas emission savings, financial profits, and job creation over a specific temporal and spatial scale (Jin and Sutherland, 2018). However, there are challenges and limitations to this approach, including model validation, complexity, and non-linearity of land use change.

In parallel, technological advancements, including increasingly available precision farming solutions and artificial intelligence, equip researchers, farmers, polluters, and decision-makers with superior data, information, and knowledge about soil management practices and their implications for nutrition and human health (Camarena, 2021; Costantini *et al.,* 2020; Lal, 2020). Moreover, the improving quality of environmental assessment tools like soil sampling, soil organic carbon mapping, and remote sensing applications make comprehensive benchmarking analyses possible, leading to better decision and policymaking. These tools also empower landowners by assisting them in assigning value to their ecosystem services (Baumber *et al.,* 2019).

Table 6. Relevant articles within Soil Ecosystem Services – Forests.

Author	Year	Short Summary
Baumber *et al*.	2019	Carbon farming in Australia potentially offers co-benefits like biodiversity conservation, improved soil and water quality, increased productivity, and cultural services.
Brancalion *et al.*	2021	evaluates carbon accumulation cost-effectiveness in Brazilian forests, revealing plantations' higher initial storage but lower cost-effectiveness compared to second-growth forests for carbon farming.
Camarena	2021	AI impacts food systems, offering sustainability benefits, but also raises concerns like carbon footprint and inequalities.
Chen *et al.*	2022	Valuing Pudacuo National Park’s Forest ecosystem services informs conservation efforts and ecological compensation criteria.
Chizmar *et al.*	2021	US Southern Forest cost-share programs compensate landowners for timber and ecosystem services, facing funding challenges and evolving objectives.
Correia and Pestana	2018	Extreme climatic events limit agriculture in Southern Portugal. Carob trees provide alternative income and carbon sequestration potential.
Costantini *et al*.	2020	Operational Groups in the EU promote tailored strategies for increasing and maintaining soil organic carbon in arable farming.
Dybala *et al.*	2019	Reforestation for carbon storage and biodiversity can have synergies and trade-offs, requiring optimized design and management.
Fargione *et al.*	2018	Natural climate solutions (NCS) in the US can mitigate 21% of emissions through carbon storage and land management improvements, yielding multiple benefits.
Jafarzadeh *et al.*	2021	Assessing land-use allocation in western Iran, focusing on ecosystem services, trade-offs, and optimization.
Jin and Sutherland	2018	Co-firing Forest residues in US bioenergy contributes to renewables, ISM model assesses economic, environmental, and social outcomes.
Kitaibekova *et al.*	2023	Examining forest ecosystem services in Kazakhstan's Burabay National Park, emphasizing their economic value and conservation importance.
Lal	2020	Industry adoption and global initiatives are crucial for accelerating soil carbon sequestration and NET's but require market incentives, innovative soil sampling, and a "Healthy Soil Act."
Lopes and Amaral	2021	Azores forest recreational ecosystem services assessed using travel cost model, with a value exceeding wood production.
Nunes *et al.*	2020	Large-scale forest restoration in the Amazon can mitigate biodiversity loss, enhance ecosystem services, and promote sustainability through native species reforestation.
Santini *et al.*	2020	Montane ecosystems in Mexico provide vital services, including carbon and water storage, but face threats from deforestation.
Wu *et al.*	2022	Liquidambar plantations offer valuable ecosystem services including wood, carbon fixation, and biodiversity, with significant economic impact.

3.1.4. Coastal Environments

Beyond agricultural and forest lands, the valuation of soil carbon is also a pertinent topic in other natural habitats, including coastal environments such as salt marshes and tidal flats. These areas house substantial quantities of carbon within their deep organic soils. However, due to anthropogenic pressures and land use changes, these regions have experienced degradation and substantial loss of their stored carbon. Moreover, they continue to face risks from sea level rise induced by climate change.

To counteract this, conservation strategies like transplanting vegetation and planning with future sea level changes in mind can both restore some of the lost carbon and guard against future losses. Given their impressive potential for carbon sequestration, these coastal environments have gained popularity in carbon valuation schemes. This is particularly notable in voluntary markets where 'blue carbon' projects, which focus on carbon captured by coastal and marine ecosystems, are becoming increasingly prevalent.

As with forest ecosystems, establishing baseline scenarios and ensuring data availability are crucial for understanding carbon stocks and fluxes. These insights can guide the creation of policies and management practices. Understanding the relationships and dynamics among different types of coastal ecosystems, such as mangroves, salt marshes, and wetlands, and their carbon sequestration and emissions in both soil and biomass is fundamental for designing and implementing blue carbon projects (Hutchison *et al.,* 2018). However, the return on investment for the mitigation potential of both soil and biomass carbon sequestration programs is uncertain, due the complex relation between implementation costs and carbon sequestration rates in both soils and biomass (Duncan *et al.,* 2022), and there are political challenges that can be overcome by institutional frameworks that prioritize ecosystem management (Odote, 2019).

Bridging the gap between our knowledge of these ecosystems' environmental performance and the carbon market prices and environmental policies could be instrumental for the socio-economic development of the protected areas. For instance, in the Western Bay of Bengal (India), the value of carbon stored in mangrove ecosystems has been estimated to be $192,442 at a relatively low valuation of $10.90 per ton (Banerjee *et al.,* 2021). This highlights the potential of these ecosystems to contribute to climate change mitigation while also providing substantial economic benefits.

Table 7. Relevant articles within Soil Ecosystem Services - Coastal Environments.

Author	**Year**	**Short Summary**
Banerjee *et al.*	2021	Carbon storage and cycling in Indian mangroves, analysing five dominant species' carbon capacity, soil, water parameters, and carbon emission impact, aiming to inform sustainable marine resource management and carbon trading.
Duncan *et al.*	2022	Enhancing blue carbon sequestration in abandoned aquaculture ponds can boost climate change mitigation and adaptation, but ROI remains uncertain.
Hutchison *et al.*	2018	Operationalizing blue carbon in Gulf Coast wetlands by addressing knowledge gaps for effective management.
Odote	2019	Kenya's legal framework for coastal wetland management aims to adopt an ecosystem approach for sustainability.

3.2. Environmental Economics

The notion of valuing soil carbon as a driver of ecosystem services has taken cues from the early models of cap-and-trade and compliance emission reduction schemes. The premise is to trade carbon capture and storage against a defined volume of emissions, denoted in financial terms, in a similar vein to trading investments in cleaner energy sources. Despite its many criticisms, the complexity and nuance of this approach will be further explored later in this discussion. For this review, the articles grouped under the environmental economics category primarily concentrated on two key aspects: 1) Carbon Pricing; and 2) Trading Mechanisms. These studies provide insights on 'what' to do with the captured carbon.

These two aspects help to elucidate the relationship between soil and land management aimed at enhancing intangible goods and services, and their commodification into marketable terms at regional, national, and international scales. Essentially, it allows for pricing both the value of gaining carbon and the cost of losing it, so that, on one hand, recommended management practices are favoured over conventional or business-as-usual practices, and on the other, the conservation of natural ecosystems remains as profitable, or even more so, than land use changes.

Moreover, it helps understand how these new 'goods' can be integrated into the market for trading between landowners and polluters alike, using both compliance mechanisms and voluntary markets. Finally, understanding the spatial, social, and economic constraints of market placement, product availability, and policy design can benefit from spatial modelling of complex systems centered around the three pillars of sustainability. These modelling approaches provide a means to predict and mitigate potential hurdles in the deployment and optimization of carbon trading schemes.

3.2.1. Carbon Pricing

Assigning a monetary value to carbon in soils and biomass is a multifaceted task. It encompasses an evaluation of the investment required to capture and store carbon through the adoption of specific management practices, and the potential cost of carbon loss due to diminished environmental performance such as yield, biodiversity, and regulation. A study examining the effects of changes in agricultural practices on the natural resource base and livelihoods of farmers estimated that the opportunity cost of soil mismanagement under soil carbon valuation fluctuates between 95 and 168 USD per ton of CO_2 equivalents (Berazneva *et al.,* 2019).

Typically, soil carbon valuation refers to soil organic carbon. However, an important facet of the carbon cycle is the presence of inorganic carbon. This form of carbon takes longer to stabilize and is also susceptible to loss due to mismanagement and erosion, thereby resulting in negative externalities. Some researchers argue for the recognition of the ecosystem services of climate regulation provided by soil inorganic carbon, which currently remains unaccounted for in existing market pricing mechanisms *(Groshans et al.,* 2018).

However, the implementation of these management practices must account for the farmers' willingness to accept the necessary investment and change. A survey of farmers in Indiana, US, revealed that those who had not yet adopted recommended tillage practices would require a net revenue increase of $40 per acre to change their practices. They expressed a preference for government payments, which are typically less subject to price volatility, over other carbon financing solutions such as voluntary markets (Gramig and Widmar, 2018). Given that current carbon prices significantly exceed $40 per ton of CO_2 equivalents, and that effective management practices can sequester over 3 tons of CO_2 equivalents per hectare per year, these values are achievable if trading mechanisms ensure fair valuation among project managers, farmers, and carbon brokers. In France, a study found that 10% of agricultural emissions could be mitigated at a cost under €25 t CO_2eq (Pellerin *et al.,* 2017). Conversely, a separate study with German farmers discovered a high motivation for promoting soil carbon sequestration, regardless of whether the compensation originates from a government subsidy or a market certificate approach (Hermann *et al.,* 2017). On the other hand, the demand side also has been found to have a willingness to pay for land management changes that would provide ecosystem services regarding biodiversity, soil conservation and carbon storage, and aesthetics, which is was found to be around €18-93 per household in a study conducted in Brazil (Parron *et al.,* 2022).

A study centered on the economic performance of marketable (e.g., biomass, provision) and non-marketable (e.g., groundwater, nutrient, carbon) ecosystem services compared agroforestry to conventional agriculture across 11 European countries. Agroforestry demonstrated reduced externalities in terms of pollution, nutrient, and soil loss, along with added benefits of carbon capture, which makes it profitable. By adopting a market approach such as penalties for disservices and compensation for services, the services provided by agroforestry can be commodified, thereby enhancing their appeal and profitability (Kay *et al.,* 2019). The land's capacity to provide soil and water ecosystem services can be used to estimate the economic value of farmland (Priori *et al.,* 2019).

Table 8. Relevant articles within Environmental Economics - Carbon Pricing.

Author	Year	Short Summary
Berazneva *et al.*	2019	Examining soil carbon management's impact on rural livelihoods, a model reveals the opportunity cost of mismanagement.
Gramig and Widmar	2018	Economic viability crucial for carbon sequestration in soils; Indiana study shows farmers' preference for government payments over carbon markets.
Groshans *et al.*	2018	Soil databases assess soil inorganic carbon value for ecosystem services, estimating replacement cost and regional values.
Hermann *et al.*	2017	Subsidies and certificates encourage farmers to sequester soil carbon for climate protection and sustainability.
Kay *et al.*	2019	evaluating economic benefits of agroforestry through marketable and non-marketable ecosystem services, highlighting multifunctional advantages.
Parron *et al.*	2022	Growing international demand for sustainable agriculture in Brazil, valuing ecosystem services, highlights consumers' preferences for improved biodiversity, soil, and carbon management.
Pellerin *et al.*	2017	Agricultural GHG emissions in France can be reduced by cost-effective measures, focusing on efficiency and carbon storage.
Priori *et al.*	2019	An approach for economically evaluating irrigated croplands by considering soil functions and spatial variability.

3.2.2. Trading Mechanism

Carbon markets and their associated trading mechanisms have been a critical focus area in climate change mitigation policies. These markets currently operate in two distinct modalities: regulated markets and voluntary markets. Regulated markets require certain sectors to offset emissions exceeding a designated threshold. This offset can be achieved through investments in emission reductions of other companies or in carbon capture and storage projects. Voluntary markets, on the other hand, allow individuals to invest in emission reduction or carbon capture and storage projects to offset their own emissions, such as those resulting from air travel or other consumption habits. These voluntary schemes are bound by marketing strategies and storytelling to create a more successful product (Brill, 2021), even though there are questions of additionality, permanence, validation and monitoring that create conceptual and legal challenges (Davis, 2023).

However, as we inch closer to climate tipping points, driven by thresholds of atmospheric carbon concentrations, the existing emission reduction trading schemes are becoming obsolete. Current climate scenarios underscore the need for negative emission solutions –capturing more carbon than we emit– so that atmospheric greenhouse gas concentrations can be reduced before tipping points are reached. Some researchers argue that nature-based solutions are currently the only scalable solutions available, suggesting that soil carbon could play a pivotal role due to its association with multiple ecosystem service provisions. This perspective anticipates a potential growth of the global carbon market. However, trading mechanisms need to ensure the longevity of carbon storage, fair valuation, rewards for additionality, permanence, co-benefits, monitoring, and transparency across different standards and financing mechanisms (Keenor *et al.,* 2021).

Several studies have explored market design to support landowners in managing their properties for optimal carbon fluxes and balances. They have examined trading systems, land management consultancy, and soil data measurements. Concepts like "Soil Value Exchange" (Blackburn *et al.,* 2018), "Ecosystem Service Market Consortium" *(Biggs et al.,* 2021), and various "Carbon Farming" strategies have been proposed to promote environmental practices, drive sales and investments, and diversify the land sector through the development of an ecosystem service economy (Black *et al.,* 2022; Marks, 2020; Russell-Smith and Sangha, 2018).

Table 9. Relevant articles within Environmental Economics - Trading Mechanism.

Author	Year	Short Summary
Biggs *et al.*	2021	Examining California rangeland soil carbon governance, study assesses impact of corporate-led ecosystem services initiative.
Black *et al.*	2022	Analyses approaches, methods, and governance in emerging soil carbon markets for climate mitigation.
Blackburn *et al.*	2018	Nature-based solutions can store significant amounts of carbon, with the Soil Value Exchange aiming to support soil carbon trading for landowners' benefit.
Brill	2021	Carbon offsets' market challenges are addressed through storytelling, creating links between origin, customer, and value.
Davis	2023	Voluntary carbon market faces legal challenges due to uncertainty in measuring agricultural carbon sequestration.
Keenor *et al.*	2021	Current carbon pricing insufficient for Net Zero. Soil re-carbonization with economic incentives needed for climate goals and soil health.
Marks	2020	Addressing urgent climate challenges through Carbon Farming Certification, integrating carbon sequestration with agriculture.
Russell-Smith and Sangha	2018	Australia's northern savanna offers opportunities for sustainable land use, focusing on ecosystem services markets for economic and environmental benefits.

3.3. Exploratory analyses

Understanding the economic response to environmental and social factors under global climate change involves analysis across various sectors such as agriculture, forestry, and other land uses. The nature of both soil systems, carbon markets and their social, economic, political, and cultural constraints is non-deterministic and non-linear, making predictions challenging for simplistic models. Recently, researchers have started paying more attention to ways of predicting the ecosystem service response to these different variables, as well as modelling their economic performance and reflecting on the social, cultural and political meaning behind these approaches.

Some studies offer diverse perspectives on how exploratory analyses can contribute to a deeper understanding of environmental responses, helping guide future policies and practices in mitigating climate change and conserving ecosystems. One study focused on the balance between sustainable agriculture and carbon sequestration, finding that climate-smart actions like no-till and cover crops can help offset potential yield income losses through carbon credit income (Contasti *et al.,* 2023), while strategic landscape management can offer environmental and socioeconomic benefits, including increased biodiversity and carbon sequestration (Parish *et al.,* 2023). On the other hand, the reliance on negative emissions technologies (NETs) in long-term climate strategies poses a risk that promises of future NETs might inadvertently create a "spiral of delay" in taking current action (Jacobs *et al.,* 2023).

Recent studies have explored innovative approaches to modelling and predicting carbon stocks and prices. For instance, a novel artificial intelligence model for estimating mangrove soil organic carbon (SOC) showed that the use of multisensor earth observation data can significantly improve SOC estimation, providing valuable insights for sustainable mangrove conservation (Le *et al.,* 2021). Another study proposed a hybrid model using ensemble empirical mode decomposition (EEMD), a linearly decreasing weight particle swarm optimization (LDWPSO), and a wavelet least square support vector machine (wLSSVM). This model accurately predicted carbon prices across three different Chinese markets, outperforming 12 other model combinations (Sun and Xu, 2021). Another study found that, within China's cap and trade mechanism, economic costs for grassland mitigation measures could be achieved between USD -6.52 to 3.78 t CO_2eq (with negative values indicating another valuable positive effects aside carbon sequestration) and could be traded at market values between USD 12.7 and 30.90 t CO_2eq (Wilkes *et al.,* 2021).

There's also been progress in developing tools to analyse the economic impacts of various greenhouse gas mitigation practices. For instance, a Field Scale Economic Analysis Software is capable of estimating the net benefit under different mitigation practices (Li *et al.*, 2021). This tool allows researchers to evaluate whether climate change mitigation practices are economically beneficial, or whether they require government subsidies to make them preferable to business-as-usual practices that may contribute to land degradation. Similar approaches have been applied to forest land, incorporating global change scenarios into the adaptive market price of timber and its relation to the co-production of ecosystem services. Examples include a model that assesses the Net Production Value of woodlands considering carbon storage in the forest and harvested timber, carbon substitution, windthrow risk, biodiversity, water quality, and cultural values (Lundholm *et al.,* 2020).

Table 10. Relevant articles within Exploratory Analyses.

Author	**Year**	**Short Summary**
Balume Kayani *et al.*	2021	Examines soil fertility variation among smallholder farms, emphasizing factors like "market distance," "farm typology," and "site," suggesting tailored fertility management.
Contasti *et al.*	2023	Climate-smart practices like no-till and cover crops balance soil carbon storage and yield income trade-offs.
Franceschinis *et al.*	2022	Evaluating soil functions' economic value is crucial for Soil Security concept, influenced by personal and social norms.
Geng and Liang	2021	GEP theory assessed forest ecosystem service and natural resource values in Jiaokou County, China, revealing valuation complexities.
Jacobs *et al.*	2023	Countries' long-term climate strategies include future negative emissions technologies (NETs), possibly delaying immediate mitigation efforts.
Kallio and LaFleur	2023	Regenerative agriculture empowers farmers to combat climate change through soil-centered practices, challenging traditional knowledge.
Le *et al.*	2021	Developed CBR-PSO model estimates mangrove soil organic carbon using remote sensing data, enhancing accuracy for conservation.
Li *et al.*	2021	Software estimates economic viability of greenhouse gas mitigation practices for crops, suggests subsidies to incentivize adoption.
Lundholm *et al.*	2020	Study integrates ecosystem service indicators into Forest Management Decision Support System, accounting for climate change and timber markets.
Moran-Rodas *et al.*	2022	Urbanization and farming practices impact soil organic carbon; farm and household conditions crucial for positive change.
Parish *et al.*	2023	Transitioning to cellulosic bioenergy feedstocks improves carbon management and biofuel production, benefiting economics, environment, and ecology.
Santos *et al.*	2022	This study assesses and values ecosystem services of pasture-based beef farms in Alentejo, highlighting their positive environmental impacts.
Sun and Xu	2021	A hybrid model that improves carbon price prediction accuracy.
Wilkes *et al.*	2021	Improving Asian grassland management benefits livelihoods and carbon sequestration, requiring suitable financial instruments and policies.

Apart from these approaches, there are other economic indicators worth considering when assessing the economic performance of soil carbon. For example, Gross Ecosystem Product theory could be used to evaluate the total value of various final material products and services provided by ecosystems (Geng and Liang, 2021), which, in the case of the *montado/dehesa* systems in Portugal and Spain can account for between 146-176€ ha^{-1} y^{-1}, especially from soil protection (Santos *et al.,* 2022). Also, market distance, farm typology, and site characteristics can serve as proxy measurements for soil fertility in smallholder farming environments (Balume Kayani *et al.,* 2021).

The interplay between income, social and economic aspects of farming sites, as well as environmental characteristics in forest land demonstrates the complexity of these systems. This emphasizes the importance of a holistic approach to understand the intricate relationships within. Recent studies have highlighted the how social norms and personal preferences influence people's values towards soil functions (Franceschinis *et al.,* 2022), as well as the link between farm and household conditions and soil carbon management decisions (Moran-Rodas *et al.,* 2022). Lastly, and focusing on the novel concept of regenerative agriculture, another study challenged conventional ways of understanding agriculture through soil-and-carbon centered knowledge practices. Using ethnographic fieldwork in farms across Finland, Norway, and Italy, they examined the relationships between farmers and landscapes, and showed how farmers engage with their landscapes through complex dynamics of control, care, and rhythm (Kallio and LaFleur, 2023).

4. Discussion: on the role of Geography and Geographical Thought

Carbon sequestration in soil interconnects a myriad of factors that transcends the boundaries of environmental, social, economic, cultural, technological, and political dimensions. It calls for an interdisciplinary approach to decipher this intricate web, as this phenomenon sits at the intersection of various scientific disciplines.

The application of this process in addressing climate change implies a substantial degree of human involvement, therefore, engagement with social sciences is imperative. This includes deciphering cultural nuances that underpin soil management practices, the relationship of farmers to their land and markets, and the socio-cultural dynamics that may influence an individual's willingness to act (Salvati *et al.,* 2015).

These conditions are usually deeply local and intricately tied to factors such as land tenure rights, landscape ecology, political structures, and power dynamics (Santos and Roxo, 2017). A simplistic interpretation that diminishes the importance of soil and climate could result in a misleading narrative.

Geography, being an integrative discipline, stands at a unique crossroad in this discourse. It assimilates a range of scientific and epistemological perspectives, thus lending a holistic understanding of the soil carbon ecosystem services. This involves engaging with the concepts of 'space' and 'place', which embody the meanings and perceptions formed through human interactions (Tuan, 1977).

In the context of climate change, the role of soil ecosystem services takes on a heightened significance. The associated social and economic vulnerabilities might hinge upon land use and management practices. Thus, in-depth analysis and modelling of these changes could provide insights into social behaviour and ecosystem responses (An *et al.,* 2021).

The disciplinary involvement of geography in agent-based models for socio-ecological systems could be particularly beneficial. By combining social and environmental systems in a relational approach, researchers could explore how perceptions and willingness to act might differ under varying climate, policy, and development scenarios (Gomes *et al.,* 2019; Molajou *et al.,* 2021).

The intricacy of soil management extends beyond mere human-centric approaches and requires a holistic understanding of the relationships within farming and soil ecosystems. These include not only the interplay between income, social norms, and personal preferences but also the ecological aspects of land. The emergence of regenerative agriculture further underscores the connection between farmers and their landscapes, highlighting the multifaceted dynamics of control, care, and rhythm. This more-than-human perspective shifts the focus towards recognizing the complex web of relations that shape agriculture, encompassing environmental, social, and cultural dimensions. By acknowledging these rich interconnections, a pathway is forged to better integrate and value ecological livelihoods within the broader context of climate change mitigation and adaptation.

Overall, the assessment of soil ecosystem services for climate change mitigation and adaptation necessitates an integrated approach, blending the wisdom of 'human' and 'physical' geographers. It requires the balanced usage of the epistemological and methodological frameworks that often separate these sub-disciplines. By bridging these divides, we could enable more effective cooperation and devise comprehensive strategies to harness soil carbon sequestration in combating climate change (Gotts et al., 2019).

5. Conclusions

Soil carbon sequestration offers a valuable solution to reducing excess carbon in the atmosphere, promoting climate change adaptation, and combating desertification. The recent scientific literature regarding soil carbon markets has focused on three main lines of research: 1) Soil Ecosystem Services, which is a topic of research closely associated with agricultural and environmental sciences and focuses on ways to promote and maintain the uptake and storage of excess atmospheric carbon and its storage in soils and biomass; 2) Environmental Economics, a topic that has been growing since the 2015 Paris Agreement and the introduction of voluntary carbon markets, which had an initial period of reflection on how to associate an economic valuation to soil carbon and, more recently, to the complex task of implementing trading mechanisms that overcome the challenges of additionality, permanence, monitorization and validation; and 3) Exploratory Analyses, where the most recent works have focused on ways of integrating the complex non-linear nature of environmental, economic, social, political and cultural factors that influence both carbon sequestration and the valuation of its associated ecosystem services. The complex, nonlinear relationship between ecosystem response and human action underscores the need for an interdisciplinary approach that integrates various ecological and socio-economic frameworks. Social sciences play a pivotal role in understanding the cultural, political, and economic contexts surrounding soil carbon markets, land tenure rights, and farmer relationships. Meanwhile, geography provides an integrative platform for diverse scientific perspectives, offering tools like spatial agent-based models to probe deeper into socio-ecological systems and human-environment interactions. Combined qualitative and quantitative methodologies allow us to appreciate and effectively value soil ecosystem services for climate change mitigation and adaptation, paving the way for sustainable land use and management practices. To bridge the gap between human and physical geography, we must embrace a balanced use of epistemological and methodological frameworks. Looking forward, it is imperative to intensify our research efforts and refine our practices to harness the full potential of soil carbon sequestration in our fight against climate change.

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