The economic impact of carbon farming practices at farm level: a systematic literature review mapping

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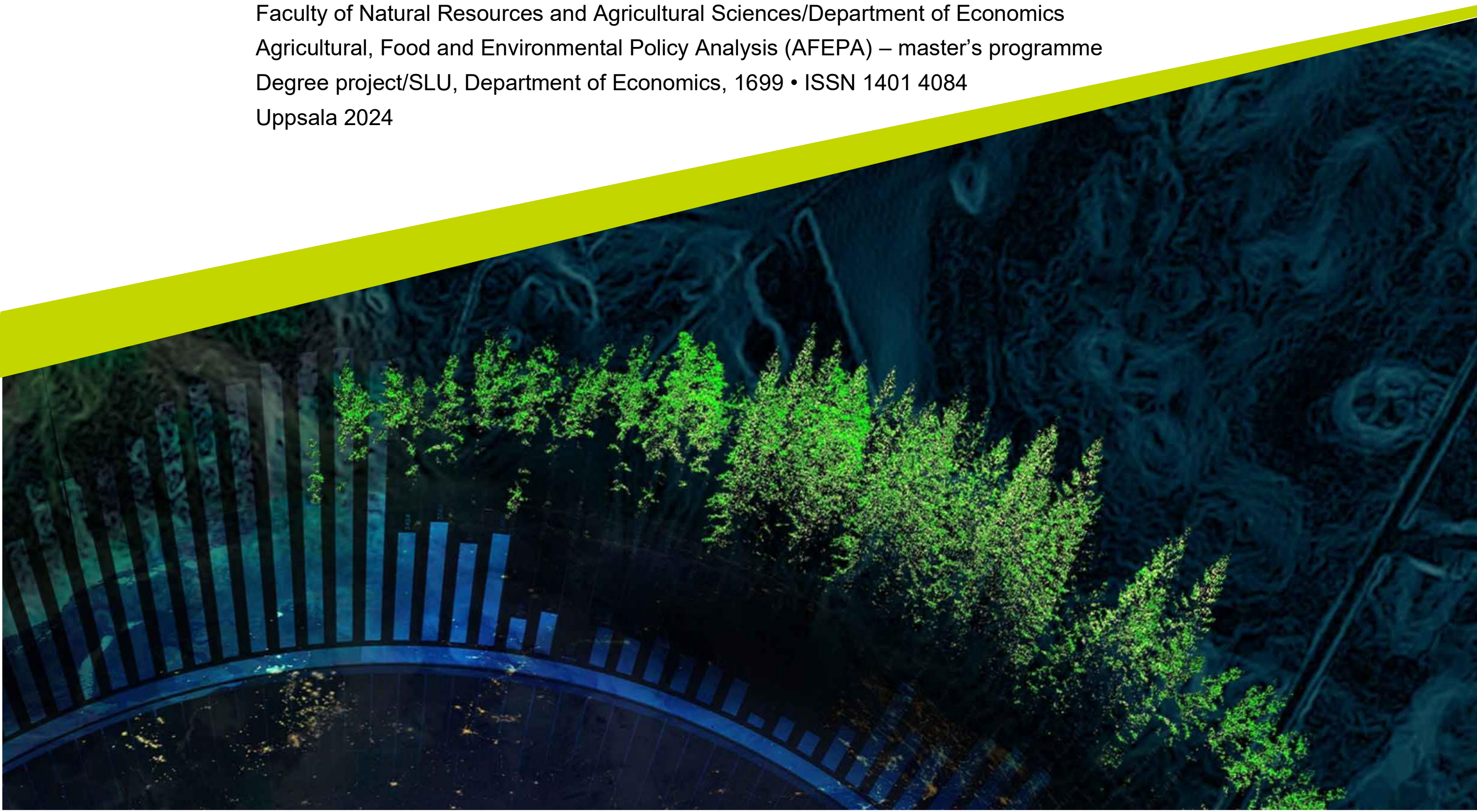

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Abstract

This thesis investigates the economic impacts of carbon farming (CF) practices at the farm level through a systematic literature mapping of developed countries. CF practices offer promising pathways for agricultural mitigation, though past literature has highlighted trade-offs that hinder their adoption. However, recent studies suggest these trade-offs are not universal. Our research synthesises empirical findings, revealing that CF profitability varies based on specific determinants. Adverse economic outcomes can be mitigated when CF practices improve efficiency, even long-term, or create beneficial synergies. In cases where profitability is limited, policies like ecosystem service payments or developing high-value certification schemes may offset losses. The study also identifies gaps in the literature, particularly in causal investigations, peatland management, economic risk assessment, and the impact of climate change on CF practices. Our results emphasise the need for targeted policy interventions to enhance farmer knowledge and support environmentally valuable but less profitable CF practices.

Keywords: carbon farming, greenhouse gas emissions, farm economics, agricultural practices

Table of contents

List of tables

List of figures

Abbreviations

SOC	Soil organic carbon
CF	Carbon farming
ES	Ecosystem services
GHG	Greenhouse gas
SLM	Systematic literature mapping
SLR	Systematic literature review
EU	European Union
NPV	Net present value
USA	United States of America

1. Introduction

1.1 Background and research problem

The objective of this thesis is to explore how the adoption of carbon farming (CF) practices affects the economy of farms, according to the quantitative literature from developed countries. The underlying hypothesis of the entire work is that the economic impact of CF can no longer be considered a universally unprofitable solution. Economic outcomes might shift depending on the context, the type of analysis developed, and the economic variables analysed. If CF practices can be economically viable under specific settings, policies can be adjusted accordingly, increasing the adoption rate and fostering their consequent environmental externalities.

Agriculture, while essential for food production, is also one of the sectors responsible for a significant portion of greenhouse gas (GHG) emissions. One-third of the overall global emissions come from the food system, and 71% of these are determined by modern agriculture and related practices (Crippa et al., 2021). At the same time, the intensive practices used by farmers in the last seventy years have had significant impacts on the environment, damaging the soil's biodiversity as much as the water quality (Ontl, T. A. & Schulte, L. A., 2012; Thompson et al., 2023; Webb et al., 2001). Explanatories are the consequences of modern agricultural practices on the Baltic Sea, where fifty years of intensive agriculture in its bordering countries damaged its ecological integrity (Archambault, 2004).

However, agriculture holds the potential to transition from a net emitter to a net sequester of GHGs through the adoption of specific practices (Borzęcka-Walker et al., 2018). These include CF practices, seen as farming and land use change strategies, such as agroforestry, management of peatland, or conservation tillage, that can be adopted by farmers and land managers to reduce, avoid, or mitigate their agricultural emissions (Mcdonalds et al., 2021). This outcome is usually followed by diverse environmental co-benefits, such as improving soil fertility, water balance on fields, long-term field productivity, or resilience to extreme events, providing numerous positive environmental externalities to society (Aertsens et al., 2013;Rempel, 2023; Scheid et al., 2023; Sharma et al., 2021).

Despite the significant environmental benefits of CF, the decision to adopt these practices ultimately lies with farmers. The economic viability of the farming practice is a main determinant in the producer adoption decision (Beer & Theuvsen, 2020; Dumbrell et al., 2017; Kragt et al., 2017). Therefore, following economic thinking, farmers would guide their decisions towards those practices that improve rather than diminish their farming economic results. The relevancy of economic considerations in agricultural production made researchers focus on how farmers' results may be affected by adopting environmentally sustainable practices such as CF (Tang et al., 2016). This developed a consensus in the literature that CF, by reducing yields and/or increasing costs, imposes mitigation costs on farmers with diverse intensity according to specific pedoclimatic conditions (Antle, 2001; Pretty et al., 2005; Tang et al., 2016). Given the research perspective, numerous developed countries included CF in their GHG mitigation support policies to enhance their adoption and the consequent environmental externalities provided (Tang et al., 2016). These interventions usually consist of subsidies or certification schemes, bounded to emission-related payments, that aim to provide additional revenues for CF farmers to compensate for potential losses (Raina et al., 2024). Despite the policy effort, countries with a long history of public interest in CF, such as Australia, recorded a low adoption of it due to a lack of understanding and effective promotion to farmers of its economic implications (Kragt et al., 2017).

Recently, the willingness of decision-makers to improve existing mitigation policies in the field of agriculture, as suggested by the "Fit for 55" package from the European Union (EU), brought a renewed interest in the investigation of the economic implications of CF (Mcdonald et al., 2021). Following the policy need, new articles have been written highlighting that the negative economic outcome of CF is not a sure thing. Authors suggest that results may vary depending on the time frames considered, the level of analysis (e.g. at farm level rather than field), the potential interaction between different practices, and the economic variable taken into account, as in the case of risk (Che et al., 2023; Huang et al., 2020; Tang et al., 2016). In addition, technological advancement, e.g. genetic improvements, developed new practices that might balance farmers' economic and environmental sustainability (Morgan-Davies et al., 2021). Therefore, CF's traditional negative economic view seems enriched by a more diversified literature that could provide new economic perspectives.

Although there is a potential public interest in the just-provided consideration, recent literature on the topic is highly scattered, with no knowledge of synthesis. Existing reviews focus on specific subgroups of CF practices, such as agroforestry (Thiesmeier & Zander, 2023), or gather papers on the economic settings and the mitigation mechanisms in force (Raina et al., 2024; Tang et al., 2016). The absence of an organised overview of the literature does not provide a firm knowledge base for research and policy developments (Snyder, 2019). This condition prevents researchers from addressing relevant gaps or recognising specific literature trends. In addition, policymakers cannot benefit from the synthesising power of literature review to improve nowadays CF policies. A synthesis of the literature presents decision-makers with the current state of the art on the economic impact of CF, highlighting both contrasting and common findings to support scientifically well-grounded decisions that individual papers alone may not provide. To our knowledge, no paper in the literature has synthesised and mapped recent literature to provide an overall picture of the economic impact of different CF practices at the farm level.

1.2 Aim and research questions

This paper aims to systematise the current scientific evidence regarding the economic impact of CF at the farm level in developed countries. This is done through a systematic mapping of the recently published literature.

The research questions guiding the analysis are outlined as follows:

1. What is the impact of carbon farming on farming economic results?

Leading to the following question:

2. If the economic impact is positive for the farm, what factors affect it, and how?

1.3 The structure

The work is structured in five chapters. The second chapter consists of an overview of the literature to highlight the definitions of CF, followed by a conceptual framework necessary for interpreting the economic effect of CF at the farm level. Chapter three defines the methodology adopted for the systematic literature mapping. Chapter four illustrates the results of the mapping exercise, which are later discussed in Chapter five, defining the literature trend, the gaps, and the implications of the conclusions on policy developments.

2. Carbon farming definitions and economic effects

Before defining the method used to systematise the literature, it is essential first to establish a clear understanding of the object of analysis. In the literature, various approaches and definitions may exist for a specific research topic, such as CF and its economic outcomes, as in our case. Developing prior knowledge of the definitions and approaches relevant to our elements of interest is crucial to build a robust literature review. This basic understanding is necessary to create the search string to guide our literature search, ensuring we capture articles that accurately address our research question. By doing so, we can avoid skewing our sample toward articles that rely on commonly accepted definitions and instead focus on a broader, literature-based sample.

Given our objective, this chapter will focus on our paper's two critical elements of interest: CF and its economic consequences on the farm. The first subchapter will clarify the definitions of CF and identify the practices recognised by the literature. The second subchapter will present a conceptual framework to highlight the economic impacts of CF, suggesting how the existing literature might approach these impacts from an agricultural production economics perspective. This is essential to ensure the subsequent analysis is comprehensive, accurate, and scientifically grounded.

2.1 Carbon farming definitions

CF is an aggregate of agronomic practices, land use change, and technical solutions that farmers and landowners can adopt to control the fluxes of GHGs in agricultural and land management activities (European Commission, 2021). The GHG control capacities of CF practices are obtained through strategies capable of avoiding potential emissions, reducing the emissions of farming activity, and/or fostering the agricultural sequestration of atmospheric carbon (Mcdonald et al., 2021; Smith et al., 2007; Tang et al., 2016). Given this definition, the scientific community recognises numerous practices that can be included in CF (Mcdonald et al. 2021, Tang et al. 2016). Mcdonald et al. (2021) classify these practices into five subcategories, using “umbrella terms” according to the nature of the practice, the type of consequent change needed at a farm level, and its effect on GHG fluxes. These subcategories are defined as the management of peatland, livestock, and manure management, nutrient management on cropland and grassland, agroforestry, and practices that maintain and enhance soil organic carbon (SOC). Different examples of practices included in these categories are shown in Table 1. Of these, only one, the *management of peatland*, determines a condition of land use change concerning specific waterlogged land ecosystems (i.e. rewetting former peatland areas) to avoid potential GHG losses (Minasny et al., 2023; Rana et al., 2024). The other four subcategories identified by Mcdonald (2021) regard agricultural systems independently from the type of ecosystem where the farmer operates, affecting management-related elements.

Management of livestock and crop nutrients represents a series of management strategies aiming at increasing the efficiency in the flow of carbon and nitrogen from agricultural activities, hampering their consequent GHG emissions (Smith et al., 2007). On the other hand, *agroforestry* and *agricultural SOC-enhancing techniques* act on GHG fluxes by fostering carbon sequestration from soils. *Agroforestry* influences the management through the integration of woody vegetation with crops or animal systems on the fields, affecting the amount of tree litter on the soil and providing large portions of organic carbon pool to it (Baah-Acheamfour et al., 2015; De Stefano & Jacobson, 2018). While *agricultural techniques that aim to enhance carbon sequestration* support the role of soil as a sink through farming practices that reduce soil disturbances by intensive techniques or natural erosion (Kane, 2015). Reduced and minimum tillage, the use of cover and catch crops, perennial cropping system, and rotational grazing are just some of the potential strategies a farmer could adopt from this category to reduce the quantity of carbon in the atmosphere (COWI, 2021). All the identified subcategories have been analysed thoughtfully in the literature to understand how they affect farms through different perspectives.

Table 1. Examples of practices within the subcategories defined by Mcdonald et al. (2021)

Categories of practices	Practices
Managing peatland	Peatland rewetting
	Paludicolture
Livestock and manure management	Technologies to reduce enteric methane
	Manure management
	Increase herd efficiency
Nutrient management on cropland and grassland	Improve nutrient planning

	Timing and application of fertilizer
	Reduction of fertilizers
Agroforestry	Creation of silvopastoral systems
	Management of woody futures such as alley cropping
Practices that maintain and enhance soil organic carbon	Conservation tillage
	Cover cropping
	Improved crop rotation
	Conversion from arable land into grassland
	Organic farming

2.2 Conceptual framework of carbon farming economic effects

While having a GHG mitigation function, CF has diverse implications for farms' economies. Its mitigation capacity is supported by public interventions that, as suggested by Antle et al. (2001), can influence the farm-level economic analysis. Given the large number of countries implementing CF policies, due to their diverse nature and to maintain a general perspective, the conceptual framework will focus primarily on factors that may be common in different contexts of analysis and so not on policies.

From a production point of view, a CF practice can be seen as a specific production method adopted by farmers to provide a defined output. Consequently, according to the type of method applied, the type and quantity of input chosen by the farmer to pursue a production will change. In the specific case of CF, this might determine two side effects. On one side, it will allow the generation, as already seen from the definition subchapter, of positive environmental externalities also in terms of GHG regulation. On the other, the practice and the consequent changes in the production method will impact the final output quantity, increasing or decreasing it. The direction of the effects on the output differs according to the type of product considered and the substitutability of the input involved in the change of practice (i.e. a polluting input may be substituted with a more environmentally friendly one, incapable of providing the same effect on the production). For example, reduced tillage may improve soil health but reduce yields for certain crops, like sugar beets, due to their need for well-ploughed soils that this production technique cannot provide (see Van den Putte et al., (2010)). The effects of a practice on production are often summarised in empirical papers with the term productivity or yield, showing the amount of output produced given a set of inputs (FAO, 2017).

The impact that CF has on production reflects on farmer's profits. In other words, a farming practice alters the relationship between inputs and outputs, affecting costs, revenues, and ultimately profits when assuming constant prices. Following the neoclassical economic principles, the farmer aims to maximise profits (Debertin, 2012). Therefore, the changes in costs and revenues a production method will imply may guide farmer's profit-maximising decisions. Following this line of thought, when considering the farming practices to adopt, farmers would opt for the ones that either minimise costs by using fewer or cheaper inputs and/or maximise output levels, increasing the gap between revenues and costs. Different CF practices may impact costs and revenues differently, affecting the final profit and, consequently, farmers' decisions. Many empirical studies estimate these effects through indicators such as profitability or net return at the field or farm level or for specific activities through gross margin, calculated as variable costs minus revenues for specific farm branch activities (Davis et al., 2021; Bavorova et al., 2020).

The economic relevance of the practices also varies depending on the time perspective. CF practices can require a long-term view that goes beyond the upcoming farming season, with high initial investments and long-term benefits. For example, purchasing new farm machinery requires more time to recoup expenses. Expanding the time horizon allows for adjustments by selling and purchasing fixed assets, turning fixed costs into variables. In addition, some environmental co-benefits CF determines, such as improved soil health and water retention, may have an explicit production implication over a longer timeframe, providing economic benefits. For example, Cusser et al. (2020) found that despite higher initial expenses, no-tillage practice costs were recovered in 13 years thanks to higher yield developed in later periods with higher relative profitability than traditional practices in the same time frame. Thus, the temporal dynamics of CF practices can significantly affect the final farm economics considerations.

In addition, farming outcomes are not always sure in a real-world situation. Farmers, in their production decisions, also aim, in most cases, to reduce the uncertainty and variability of an outcome following a risk-averse behaviour (Debertin, 2012). Limiting factors (i.e., diseases, climatic conditions, soil characteristics) may reduce the certainty of an outcome from a specific production, which may be fostered or reduced by the type of practice adopted. For example, certain CF practices may increase the incidence of crop diseases and pests, increasing yield variability over time (MAO et al., 2023). On the other hand, if risk is seen as the distribution of an outcome (Debertin, 2012), then the decision to adopt a specific practice might affect it. This may also be true for uncertainty when the probability of an outcome remains unknown due to various factors, such as a lack of knowledge or unpredictable environmental conditions. Literature indicates that CF practices show uncertainty regarding the impact of diverse climatic conditions or soil types on yields in the farmer's decisions, suggesting it is a potential element for further economic consideration (Mondal & Chakraborty, 2022).

In conclusion, CF practice may have diverse effects on production, profits, time perspective, uncertainty, and risk. The terms used by the researcher to show these effects can be summarised in Table 2, potentially useful for the subsequent systematic review.

Table 2. Summary of economic terms

Economic context	**Terms to define the economic outcome**
Production function	Yield
	Productivity
Profit function	Costs
	Gross margin
	Net returns
	Net revenues
	Profitability, profits
Time	Long term
Risk and uncertainty	Risk
	Variability
	Uncertainty

3. Method

Systematic literature mapping (SLM) is a method developed in social sciences and medicine to gather results from empirical evidence (James et al., 2016). In agricultural economics, this method has already been implemented (e.g., see Thompson et al. (2023)), also in the specific case of CF to outline the incentive mechanisms in force (Raina et al., 2024). SLM is helpful to those researchers who aim to explore a broad policy theme by gathering literature on it to identify thematic trends and research gaps (Soaita et al., 2020). Its application and general definitions suggest that SLM differs from the traditional systematic literature review (SLR) method (James et al., 2016). SLR is the gold standard of reviews, which tries to answer a specific question by gathering and confronting research and its data (Snyder, 2019). Conversely, by approaching a broad research question, SLM overcomes potential limits determined by the heterogeneous characteristics of the literature, exposing its mosaics of diverse features (Soaita et al., 2020). The broader perspective is reached by following a systematic collection, description, and catalogue of the existing literature, outlining potential knowledge or cluster gaps that could be relevant for upcoming research or policy development (James et al., 2016). This outcome is reached by extracting a sample of articles from the literature screened and analysed according to already set criteria and coding variables of interest.

The literature on CF is known to be diverse depending on the biogeographical locations, the type of CF, and the methodology used (see Tang et al. 2016). For these reasons, SLM is the most adequate methodology for our research question, allowing us to avoid the risk of SLR that, by narrowing the research to a specific question, may not account for the diverse reality of the literature. Due to the systematic nature of the review, the literature proposes different checklists and guidelines to guide researchers in increasing the reproducibility level of their review, as in the case of the most common 2020 PRISMA statement (see Rethlefsen et al., (2021)) and the recently developed ROSES (RepOrting standards for Systematic Evidence Syntheses) (see Haddaway et al., (2018)). This study follows the ROSES checklist because of its higher specificity for SLM and its successful implementation in another SLM exercise by Raina et al. (2024). On this matter, it is necessary to underline that we did not consider the critical appraisal section, which is optional due to time constraints, as much as the development of a peer-reviewed protocol, given the nature of the study.

3.1 Exclusion and inclusion criteria

To provide the most relevant literature for the SLM, it is necessary to identify, a priori, a series of specific criteria that will allow us to select articles meaningful to answer our research question. The criteria adopted for this work are extensively illustrated in Table 3 and were developed to direct the research on finding ideal articles covering CF practices and farmer economics. These had to be peer-reviewed and in English to ensure the quality of the work and due to language limitations. In addition, we aimed to find quantitative articles to facilitate the comparison between the results and methodologies applied in the final analysis.

Table 3. Exclusion and inclusion criteria used in the screening process to determine which study to include in the SLM

Exclusion criteria
1. Wrong country: study taken outside the countries of interest. 2. Wrong population: study do not regard farmers' economics but other subjects such as the impact of a policy or the agronomic implications of a specific intervention. 3. Wrong study design: the study is a review, meta-analysis, or a qualitative study. 4. Wrong language: the study is not in English. 5. Wrong practice: the article focuses on practices that cannot be included in the definition of carbon farming. 6. Wrong publication: the paper is not a peer reviewed. 7. Wrong outcome: the paper does not investigate the economic outcome at farm level. 8. Wrong time: the article has been published before 2016.
Inclusion criteria
1. The paper is a quantitative study using primary or secondary data. 2. The paper discusses carbon farming practice coherent with the definition provided in the literature. 3. The paper is written in English. 4. The paper analyzes farmers or farm level economic outcomes.

5. The paper is a peer reviewed.
6. The paper is included within the time frame considered (2016- 2024).
7. The paper considers at least one of the countries of interest.

It is necessary to point out that restrictions were imposed to limit the research on papers regarding specific countries in a given period, as previously done in other SLM (see, e.g., Thompson et al., 2023 and Raina et al., 2024). The countries of interest for this work were developed countries considered member states of the EU, neighbouring or similar countries (United Kingdom, Norway, and Switzerland), the United States of America (USA), Canada, New Zealand, and Australia. This location restriction was necessary to provide studies that covered farms and farmers operating in agricultural systems with comparable characteristics (e.g. highly mechanised production, developed markets, and organised supply chains) to simplify the comparability of their results.

From the time perspective, the author focused on a time frame ranging from 2016 to the 6th of April 2024 (the research date). The year 2016 has been chosen for two main reasons. One year before (2015), the Paris Agreement was signed as a legally binding treaty to act internationally on climate change, setting a starting point for the global political commitment to fight climate change and pushing international research on this matter (Raina et al., 2024). 2016 is also the date of the last comprehensive literature review covering the economic settings of CF by Tang et al. (2016).

3.2 The search string

Once the exclusion criteria were defined, a search string was developed to extract the articles of interest from the literature databases. The search string is based on section 2, which provided numerous valid literature-based terms by accounting for CF's definition and economic implications on the farm (e.g. see Table 2). These were paired in different ways through trials to develop a search string capable of identifying an adequate sample of articles for our analysis and given the initial aim. Specifically, in this process, the author consulted an expert from the “Swedish Agricultural University Library” to be advised on how to increase the accuracy of the research. The advisory session brought to the development of several search strings tested in the database “Web of Science Core Collection” to verify potential hits. The trials led to a final search string, illustrated in Table 4, chosen considering the usefulness of the output articles according to our final aim and to develop the SLM.

Table 4. The search string as used in Web of Science Core Collection and adapted accordingly to the other databases' search functions

Category	Search limit	Keywords
Population of interest	Title	farm* OR agr*
Type of intervention	AND topic (Title, Abstract and Keywords)	("carbon farm*" OR "carbon sequester*" OR " Greenhouse gas emission*" OR "avoid* NEAR/3 emission*" OR " red* NEAR/3 emission*" OR "emission* NEAR/3 mitigation*")
Type of outcome	AND topic (Title, Abstract and Keywords)	(econom* OR perform* OR product* OR cost* OR profit* OR risk* OR "econ* analys*" OR return* OR "gross margin*" OR "production econ*")
Country	NOT topic (Title, Abstract and Keywords)	Africa OR Argentina OR Bangladesh OR Brazil OR Cambodia OR Chile OR Colombia OR Africa OR Guatemala OR India OR Iran OR Kenya OR Lebanon OR Malawi OR Mexico OR Nepal OR Nigeria OR Pakistan OR Senegal OR south AND Africa OR Tanzania* OR Thailand OR Uganda OR Vietnam OR Zambia OR Zimbabwe OR Bolivia OR Uzbekistan OR chin* OR Ethiopia* OR Philippine OR Honduras OR costa AND Rica OR Mozambique OR Laos OR Malaysia* OR Ghana OR Singapore* OR Asia
Time	Filter	2016 - 2024

Table 4 can be briefly summarised as follows. The final search string limited the research to articles related to agricultural activities by searching only for those papers with farming or agricultural-related words in their titles. In addition, to recognise an article treating the economic impact of a CF practice, it had to include in its titles, abstracts, or keywords a set of words that describe the GHG impact of the practice and its potential economic outcome. To further limit the research output, we imposed a filter to consider papers within the 2016-2024 time frame and exclude those papers that mentioned in their titles, abstracts, or keywords, the most common not developed countries.

The final Search string illustrated in Table 4, has been applied to different databases: "Scopus" "Web of Science Core Collection", "Green Files" and "Econlit". "Scopus" and "Web of Science Core Collection" were selected to perform the research because of their interdisciplinary nature and relevance within the research field. At the same time, "Green Files" and "Econlit" were chosen respectively for their specialisation in sustainable agriculture and their relevancy in the field of economics.

3.3 Screening

The articles found after applying the search string in the selected databases were screened following a strategy of three main stages. The output of the database was first imported into the "Mendeley Reference Manager" software (Mendeley, n.d.) and into the systematic review web app "Rayyan QCRI" (Ouzzani et al., 2016). In "Rayyan QCRI" all the duplicates were identified and removed with the support of its detecting duplicate function. The second step consisted of screening the remaining articles by title and abstract, following the criteria given in Table 3. The articles considered as not relevant for the research purpose were coded as "excluded" in Rayyan QCRI, while the ones of interest were tagged as "included". The articles the author judged as difficult to categorise according to the selection criteria were kept for a more detailed analysis in the complete screening phase. The third and last phase included the full-text screening of those papers tagged as "included" in the previous stage. After an extensive reading, papers aligned with the exclusion criteria were removed from the sample.

3.4 The coding

During the full-text screening phase, the author developed a coding protocol in an Excel Table (see Appendix 1) to systematically gather data on each article's methodology, practice covered, comparator used, and results. The protocol was then applied to the articles, creating the sample after the full text screening phase and gathering codes of interest into a unique Excel file.

3.5 Analysis of the sample

The data gathered from the coding process were used to analyse the selected papers. Initially, a descriptive statistic was conducted to identify an overview of the general characteristics of the sample. This analysis focused on addressing and summarising the origins of the articles in the sample, the categories of CF practices studied, and the metrics and methodologies used by the different authors. Once the general characteristics of the treated sample were evident, the articles were grouped according to the CF practices categories identified in Chapter 2 to analyse them according to a similar technical context. We used a vote count approach to recognise the evidence of the economic impact of carbon farming from the results of each sample article (as done by Thompson et al., 2023). Specifically, we identified how often, per each category, a positive or a negative economic outcome was shown and the variable responsible for this outcome. The general trend of the articles' results led to a narrative synthesis (Campbell et al., 2020) necessary to interpret the direction of the findings across the different articles, highlighting the determinants influencing specific economic variables and outcomes. These determinants were then summarised in a table, showing the frequency of their positive impact on the economic results within the considered categories.

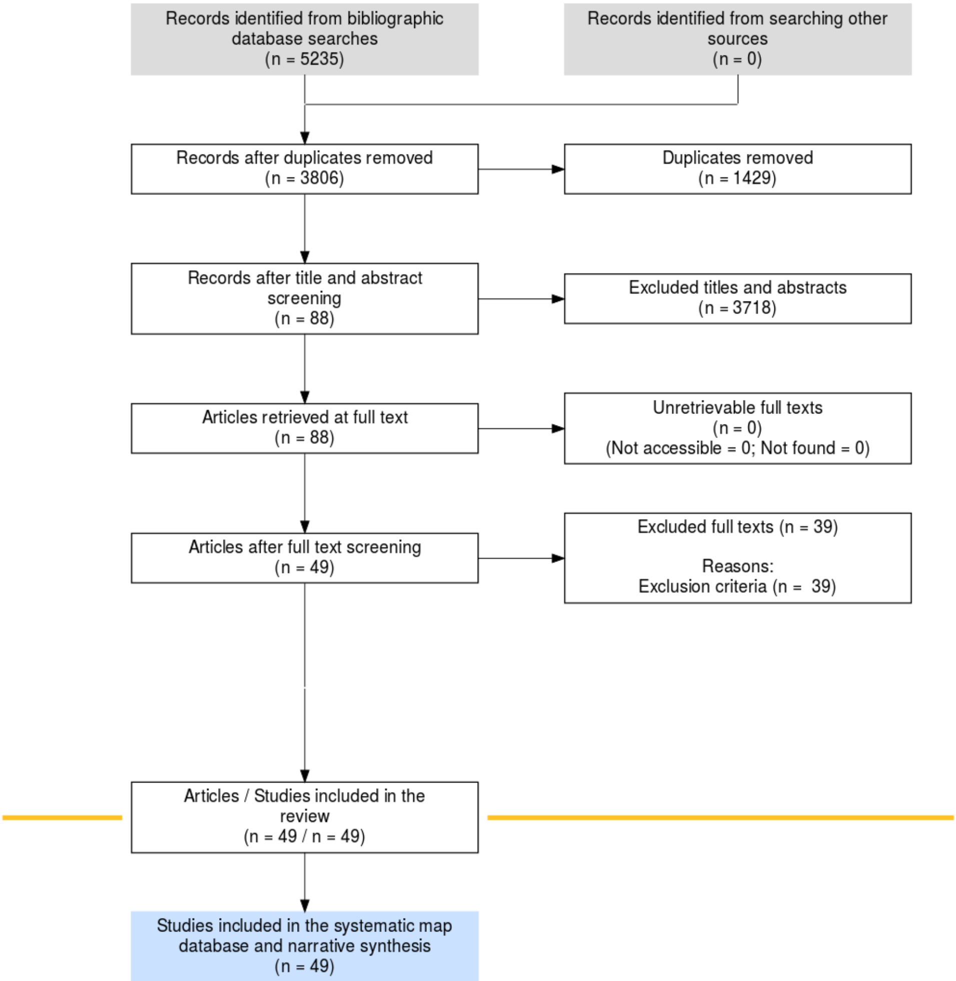
4. The results

This section illustrates the mapping of the gathered literature following a specific line of thought. First, the general characteristics of the sample will be provided and described. Subsequently, the articles' results will be illustrated, highlighting the factors that affect different CF economic outcomes.

4.1 Searching results

The application of the already described methodology brought stepwise results that can be briefly summarised in Figure 1. The search string in Table 4 provided 5235 articles, of which 2488 were from “Scopus”, 2321 were from “Web of Science Core Collection”, 403 were from “Green Files” and 23 were from “Econlit”. Once imported in Rayyan CQRI, 1429 duplicates have been identified and removed. Screening the remaining 3806 articles by title and abstract brought a final output of 88 eligible articles for the full-text screening. The large number of articles excluded was due to the high number of papers that covered study areas outside the scope or were not quantitative. At the full-text screening stage, 39 articles were excluded because covering only the environmental impact of specific practices and not the economic ones, were not peer-reviewed, in a foreign language, or outside the geographical scope. This brought to the final sample of 49 articles used to develop the narrative synthesis of the SLM, summarised in Appendix 2 with their general characteristics and results.

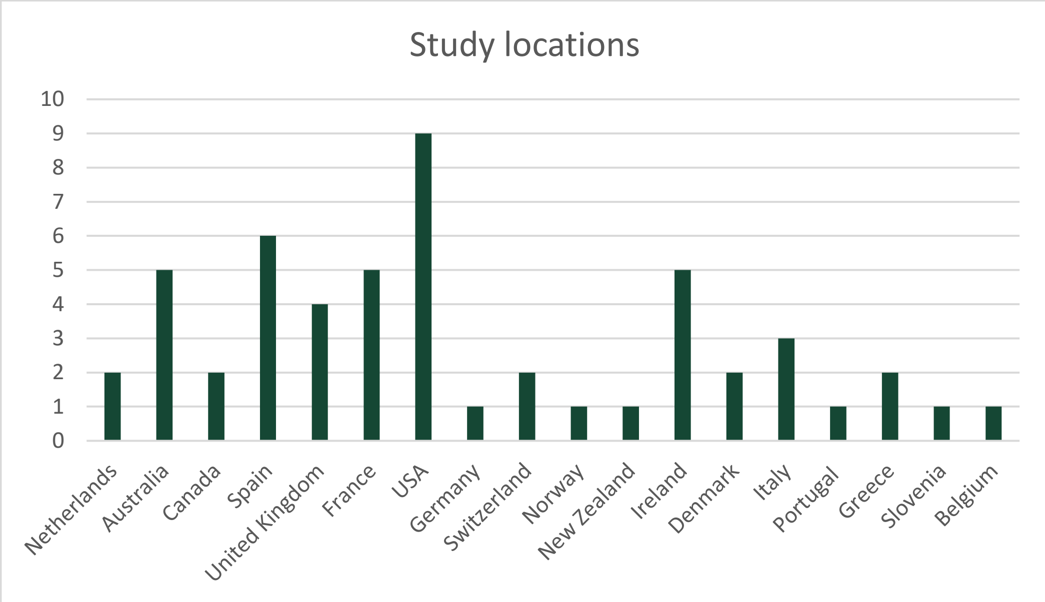
Figure 1. ROSES flow diagram to explain the results based on the official website



4.2 General overview

The final sample of 49 articles spans 17 different countries worldwide. As shown in Figure 2, the USA holds the record for the most articles produced. However, if the EU was considered a single entity, it would account for more than half of the total sample, with 26 articles.

Figure 2. Geographical distribution of the sampled articles

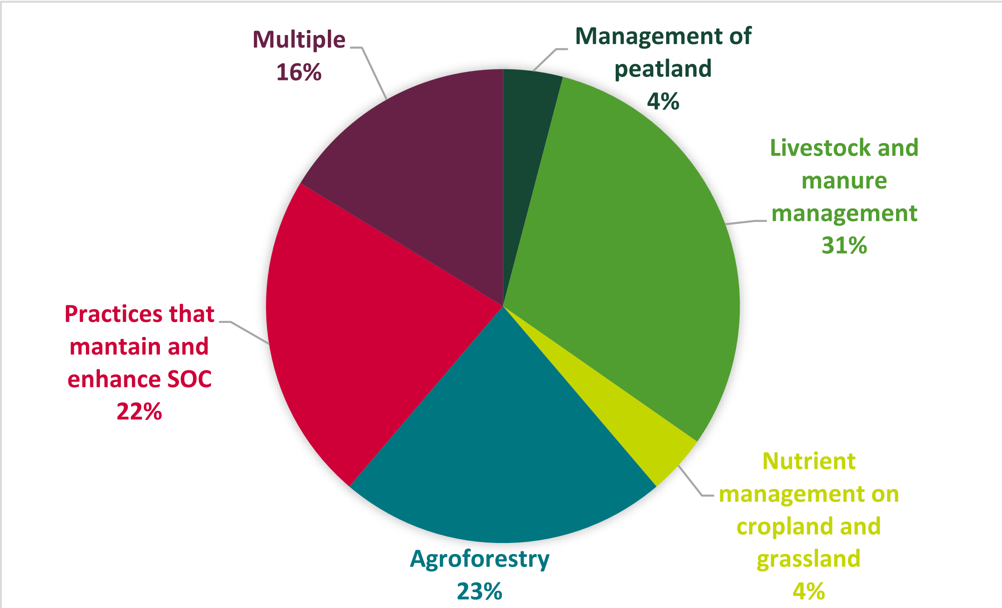


Note: Three articles in the sample covered more than one EU member state. To accurately represent these studies, we treated each country included in these multi-country studies as an individual article in the graphical representation.

The articles analyse different types of CF practices. By grouping the articles according to the categories identified by Mcdonald et al. (2021)[1] (see section 2), as shown in Figure 3, it is possible to see that practices regarding Livestock and Manure management were the most popular. On the other hand, Petland management is the least covered category within the literature (see Fig. 3). A careful reader would notice that Nutrient management also has a low representativeness in the sample. However, with respect to Peatland management, its practices are usually analysed combined with others, entering the Multiple practices category.

[1] The Mcdonald et al. (2021) categories are added by a Multiple category necessary to consider those articles that cover numerous practices from within categories simultaneously.

Figure 3. Distribution of different studies according to the categories defined by Mcdonald et al. (2021)



No matter the category considered, practices are all evaluated addressing their economic and environmental impact compared to the most common agricultural practice of the region studied, usually dairy or arable production. This comparison is quantified through different metrics, as shown in Table 5.

Table 5 The economic and environmental outcome indicators considered for the evaluation of the CF practices within the sample

Economic indicators	**Number of articles**	**Environmental indicators**	**Number of articles**
Net present value	11	GHG emissions	23
Gross margin	9	Nitrogen balance	12
Net return	8	Carbon sequestration	10
Profitability	8	SOC balance	7
Farm net return or income	7	Water quality	3
Abatement cost	4	Soil erosion	3
Farm profit	2	Phosphorous balance	3
Farm worth	2	Pollination	2
Costs	1		
Net margin	1		
Stochastic dominance	1		
Gross mixed income	1		
Expected gross margin	1		
Compliance cost	1		
Financial return	1		

Note: The sum of the number of articles is not equal to the total number of articles screened since some treated more than just one economic and environmental indicator.

Table 5 suggests that a common indicator used to evaluate the environmental impact of agricultural practices is GHG emissions due to its ability to include various emission sources into a single measure. When broken down into specific polluting elements, most authors focus on nitrogen balance and carbon sequestration in categories with specific mitigation potential, such as Agroforestry and Livestock and manure management. On the economic side, researchers' primary interest lies in assessing these practices' effects on profitability. This is typically measured as net return, which accounts for fixed costs at both the field and overall farm levels. In contrast, gross margin is relevant when focusing on specific farm activities without considering variable costs. Additionally, net present value (NPV) is often used to evaluate the long-term worth of investments, especially for practices with extended time horizons like agroforestry. Notably, only two papers did not consider profitability as an outcome; instead, they examined the impact of practices on farmers' risk. This is the case of Brečko & Žgajnar (2022) and Monge et al. (2016), which used stochastic dominance and the expected gross margin to investigate the effect of adopting specific CF practices on economic risk.

The different metrics were applied with specific methodological approaches. The type of method used influences the conclusions and interpretations of the CF results, affecting our analysis. In the considered sample, 80% of the articles (40 in number) use simulation-based methods, while the remaining 20% (9) perform the analysis with non-simulation methods. Specifically, simulation-based articles use representative secondary data on the field or farm level to model fictional scenarios on adopting CF practices (such as N-Cycle by Fournel et al., (2019)). The artificial nature of these simulations benefits the modeller by making it possible to adjust the model artificially according to its interest (e.g. by stating optimising objectives or assumptions of a rational behaving farmer). On the other hand, these adjustments limit results to specific modelling contexts, being hardly applicable in farming situations that do not correspond to these features, as for the case of rational-behaving actors. This limitation of the sample could have been overcome by the non-simulation articles that, through statistical methods, provide generalisable counterfactuals for modelling results. In our sample, a large majority (6) of the non-simulation papers use experimental data gathered at the field level that cannot be easily extended to another production environment, even if accompanied by descriptive statistics (Lorenzetti & Fiorini, 2023; Zhou et al., 2022). The remaining part of non-simulation papers uses econometric approaches based on a large set of secondary aggregate farm data (see Flaten et al. (2019); Lambotte et al. (2023); Zehetmeier et al. (2020)). These articles analyse data through bivariate analysis or statistical regression and provide results on CF and profitability that can be generalised to farmers with similar populations, given the search for the statistical significance of their outcome. However, econometric studies cover only organic practices and can only help support simulations regarding organic production. Despite the limit given by the high amount of simulation articles in the sample, the results of these studies can still be compared, considering the directions of their results rather than their significance.

4.3 Synthesis of the results

The results of the studies in the sample have positive environmental outcomes that change in their nature according to the category of practice considered. In contrast, on the economic side, the results are more heterogeneous.

As shown in Table 5, most of the articles evaluate the economic outcome of CF in terms of profitability. Only Brečko & Žgajnar (2022) focus mainly on the impact on risk, suggesting that increasing the diversification of production in cattle farms reduces farmer risk and GHG emissions. Apart from this exception, all the remaining papers, given their shared interest in profits, can be aggregated and compared to address the effects of CF and the economic variables that drive these. To simplify the analysis, the comparison can be performed according to the technical context provided by already identified CF categories, as summarised in Table 6.

Table 6. Frequency of the articles in the sample showing the effect of CF practices on specific economic variables and profits per each category

CF categories	Economic variable affected considered in the articles						Paper conclusions on profitability[a]		Total Articles in absolute values
	Yield		Costs		Revenues				
	+	-	+	-	+	-	+	-	
Livestock and manure management	33% (5)	26% (4)	55% (8)	20% (3)	33% (5)	-	73% (11)	27% (4)	(15)
Agroforestry	-	-	-	-	18% (2)	90% (10)	18% (2)	82% (9)	(11)
Nutrient management	-	50% (1)	50% (1)	50% (1)	-	-	50% (1)	50% (1)	(2)
SOC practices	18% (2)	9% (1)	36% (4)	45% (5)	36% (4)		55% (6)	45% (5)	(11)

Peatland management	-	-	-	50% (1)	50% (1)	50% (1)	50% (1)	50% (1)	(2)
Multiple	71% (5)	29% (2)	42% (3)	14% (1)	-	-	86% (6)	14% (1)	(7)
						Total	56% (27)	44% (21)	(48)

Legend:

a = Accounting as profitable the articles with at least one practice with a profitable outcome without policy support.

- / + = positive or negative effect of the CF practices considered on the economic variable/profits

(#) = absolute number of articles that show a positive effect of the economic variable on profitability

Note: Each positive or negative variable's frequency is related to the total number of articles in the practice category because some articles consider the effect of more than one economic variable.

Following Table 6, it is possible to see that there is no consensus in the sample about the effect of CF on profitability, even within single categories. In all the categories considered, articles underlying profitable and unprofitable results are driven by the same variables but in opposite directions. The following subchapters will, therefore, focus on how different categories of CF practices affect different economic variables, driving or hampering profitability. The category "multiple" will be discussed within the different categories to avoid repetitions affecting these transversally.

4.3.1 Livestock and Manure Management

The articles covering practices within the Livestock and Manure Management category show a negative economic outcome from applying the related CF practices in 27% of the cases (see Table 6). These results are driven by high costs and low yields, as shown in Table 6. For instance, the high cost of managing manure in livestock farms or the decrease in yield due to shorter lactation periods drives an overall reduction of profitability, even if they lead to lower GHG emissions (Lehmann et al., 2019; Rotz et al., 2016). On the other hand, 73% of the literature on this category supports profitable results (see Table 6). This result can be reached when authors introduce farming improvements or expand the analysis from a single branch to the overall farm level. Specifically, innovations that enhanced production efficiency, such as better feeding techniques (Pierer et al., 2016) or animal genetics (S. A. Smith et al., 2016), increased profits. This effect was fostered when these practices were combined, thanks to the multiplicative effects resulting from their interactions (Harrison et al., 2016). At the same time, expanding the analysis to the overall farm level provided a holistic view of the outcomes, demonstrating how practices applied in one production area can have economic consequences on other farm branches. For example, manure management practices and improved feeding strategies can yield cost savings by providing cheap organic fertilisers (Rotz et al., 2016) and reducing the need for farmland dedicated to feed production. This, in turn, increases the land available for alternative production, enabling additional revenues while lowering the nutrients leaching from the cultivation of feeding crops (Cong & Termansen, 2016; Mertens et al.,2023). This effect expands when combining livestock-related practices with those from other farm branches, as with no-tillage for crop production, creating synergies that further enhance profitability at the overall farm level (Baccour et al., 2021). These profitable outcomes, even when expanding the level of analysis, can vary in impact depending on the specific pedoclimatic conditions where the farm operates (Ouellet et al., 2021). In addition, in the case of manure management practices, uncertainty may increase due to potential trade-offs between ammonia emissions, phosphorus runoff, and GHG emissions, which can limit the environmental benefits (Cantillon et al., 2024; Fournel et al., 2019). Therefore, while these practices offer economic advantages, their environmental impacts must also be carefully managed.

4.3.2 Agroforestry

Agroforestry practices are found profitable in 18% of the articles (see Table 6) because of the low value of the produced biomass compared to traditional dairy and arable farming systems (Kay et al., 2019; Staton et al., 2022). The profitable articles suggest that high-value production, such as Mediterranean woody cultivations (e.g., olives (Kay et al., 2019)) or combinations of arable land with orchards (Staton et al., 2022), overcome the revenue loss. For the remaining 89% of the papers in the category (see Table 6), the value increment in the final production cannot be obtained. To address these economic shortcomings, the authors account for the economic value of the environmental benefits through hypothetical policy interventions. Agroforestry practices, no matter the profitability effects, provide many ecosystem services (ES) that go over GHG reduction, such as reduced soil erosion and improved pollination. The services are therefore evaluated with “ES payments” based on the quantity of ES produced (Thamo et al., 2019) or on a hectare level (Flack et al., 2022; Laporta et al., 2021). The value of the ES changes according to the services considered and the comparator used in the analysis, as shown in Table 7.

Table 7. The valuation of ES necessary to make agroforestry practices comparable to local agricultural ecosystems

Practice	**Article**	**Comparator**	**ES variable**	**Minimum ecosystem services revenues[a]**
Afforestation	Flack et al., 2022	Pastures	C	273.16 € ha^{-1} yr^{-1}

	Thamo et al., 2019	Infertile land left abandoned	GHG (CO_2, CH_4 and N_2O)	40 $/tCO2-e
	O'Donoghue et al., 2024	Animal production[b]	C	100 €/t CO2
	García de Jalón et al., 2018	Arable	C, N and soil loss	365€[c] ha^{-1} y^{-1}
Silvoarable	García de Jalón et al., 2018	Arable	C, N and soil loss	195€[c] ha^{-1} y^{-1}
Silvopasture	La porta et al., 2021	Land left abandoned[b] or arable intensification	C	134[d] € ha^{-1} , 149[e] € ha^{-1}
	Kay S et al., 2019	Regional typical productions[e,f]	C, N and soil loss	30 € t−1 C , 5€ kg^{-1} N, 12[f] € t−1 soil, 17[g] € t− 1 soil

Legend:
C= carbon sequestration
N= nutrient balance
GHG= GHG reduction
a= minimum evaluation of ES to make agroforestry comparable to the alternative
b= land that is more convenient to be left uncultivated
c= accounting for already existing afforestation grants in England
d= to avoid abandonment of land
e= to avoid arable intensified productions
f= in continental regions
g= in Atlantic regions

Table 7 suggests that the additional revenue provided by ES changes according to the type of practice and the afforestation as much as the ES accounted for in the authors' analysis. Especially to notice is that carbon sequestration is always evaluated as ES in all the articles. This usually acquires a value based on the market price of carbon necessary to reach similar economic results to traditional practices (Thamo et al., 2019) or by considering the societal cost of carbon sequestration over time (Laporta et al., 2021). The estimations of the value of carbon provide values, in all cases, that are higher than the actual policy support. On the other hand, when the evaluation of ES is extended to other services, such as reduction of soil erosion, phosphorus, and nitrate leaching, with values determined in the literature, the comparability is more accessible without changing the carbon price already set by the existing policy. The accountancy of multiple ES increases the societal value of agroforestry systems to social NPV comparable with the regional traditional arable system, as shown by García de Jalón et al. (2018) with silvoarable systems. ES payments can also lower the economic risk exposure of farmers to more price-volatile farming, such as dairy, acting as sure income sources (Monge et al., 2016). These economic results are affected by the species chosen for cultivation, enhancing or reducing ES's positive contribution. Fast-growing trees, for example, sequester carbon more quickly, fostering ES provisioning (Greene et al., 2023). Conversely, some species may present trade-offs between economic value and carbon sequestration outcomes, increasing the complexity of the choice (Ovando et al., 2017). The uncertainty related to agroforestry systems can also change according to future climate change or the region's needs of ES due to its specific characteristics. For example, areas more susceptible to soil erosion value more systems able to reduce soil losses (Kay et al., 2019), while the type of climate change the region will experience affects trees' growth differently and, consequently, their ES capacity (Thamo et al., 2019).

4.3.3 Nutrient management on agricultural cropland and grassland

Nutrient management practices yield mixed economic results, with half of the articles finding them unprofitable and the other half finding them profitable. Regardless of the economic outcomes, these practices can enhance nutrient balance in the field and reduce GHG emissions, though the financial impacts vary. When management focuses on reducing fertiliser use, it leads to decreased yields, which can offset any cost savings from using fewer inputs (Abdul-Salam et al., 2019). The opposite effect comes true when the reduction of fertilisers is accompanied by specific technological innovations that, by increasing the absorption capacity of plants, lower the input needed with no effects on yields (Diacono et al., 2023). This favourable outcome may also be reached when practices are combined. This is the case of practices that substitute chemical nitrogen fertilisers with manure handled from the dairy farming branch of the farm (Rubhara et al., 2024). The synergy between nutrient and manure management practices leads to cost savings, reducing external input purchases without affecting the final production capacity on the overall farm (Pellerin et al., 2017). Although relevant, this positive outcome might be hampered by the pedoclimatic condition of the fields. Geographical location and the consequent soil type change the effectiveness of nutrient management practices, affecting yield improvements and leaching reductions according to the biological interactions between the type of soil, crop, and fertiliser, as underlined by the study of Dumbrell et al. (2017).

4.3.4 Practices that maintain and enhance soil organic carbon

SOC enhancing practices have been shown in all the articles to sequester carbon in the atmosphere and store it in the soil. However, this environmentally beneficial action appears unprofitable in 45% of the papers (see Table 6). Authors found that the increase in the costs of the practices, as for the management of additional cover crops, is not offset by higher yields (Colombo et al., 2024). Parallelly, it is the same for cost-cutting practices, such as no-tillage, that negatively affect profitability due to the reduction of the final crop yields (De Leijster et al., 2020; Martin-Gorriz et al., 2020). The remaining 55% of the articles covering this category (see Table 6) suggest that this negative outcome changes when considering long time frames or combining single practices. Specifically, the SOC enhancing practices' positive effect on soil health needs time to become explicit in higher yields, changing the unprofitable short-run perspective (Zhou et al., 2022). These positive results can also last regardless of the climate change that long-term scenarios may imply (He et al., 2022). In addition, combining different SOC practices supports final yields through a synergistic effect in improving the soil structure, as done for no-tillage combined with cover crops (Lorenzetti & Fiorini, 2024). When yield increments are not possible, the outcome shift can be reached by affecting the final revenues, as in organic productions. In this case, the higher final production value, driven by price premiums, outperforms conventional production's profitability (Wachter et al., 2019). This is also confirmed by Lambotte et al. (2023), who, with a Francois farm dataset, found no statistically significant differences between conventional and organic farms' net returns despite the lower productive capacity.

4.3.5 Management of peatland

In the case of peatland management, a limited number of articles show an ambivalent position regarding the profitability of the practices (see Table 7). On the environmental side, it is always supported that changing the land use of the analysed area avoids significant GHG emissions while restoring entire ecosystems now degraded by agricultural activities. These beneficial actions, although, imply different economic consequences. Liu et al. (2023) find financial trade-off in Dutch farms since wetland favourable systems, such as paludiculture, provide less revenue than traditional dairy farming, with high establishment costs. Deverel et al. (2017) suggest that farmers can achieve better profits in the San Joaquin Delta of the USA by allocating part of their land to high-value crops like rice while restoring portions of wetlands rather than sticking to traditional arable farming. This approach is most effective when the flooded land has organic matter-rich soils, which are unevenly distributed across farms. Therefore, successful implementation requires cooperation among farmers to plan land use changes across the entire peatland area.

4.4 Summary of the profitability affecting factors

Considering the narrative analysis previously illustrated covering all the single categories, Table 8 summarises it. Specifically, it illustrates the factors driving the change of profitable outcomes and the number of papers in the sample underlining these drivers for each CF category.

Table 8. Frequency of papers per each category of CF practices highlighting the effect of different factors driving profitable results

Factors affecting profitability	Share of papers per CF category				
	Livestock and manure management	Agroforestry	Nutrient management	SOC practices	Peatland management
efficiency improvements	27% (4)		25% (1)		
long run perspectives				33% (2)	
Increment of output value		18% (2)		50% (3)	
Farm level analysis	45% (5)				100% (1)
Multiple practices	18% (2)		50% (2)	67% (4)	
Inclusion of ES revenues		64% (9)			
Pedoclimatic conditions	18% (2)	9% (1)	25% (1)	17% (1)	
Total	100% (11)	100% (2+9[a])	100% (4)	100% (6)	100% (1)

Legend:

(#) = absolute number of articles that show a positive effect of the economic variable on profitability

a = articles that without policy support are unprofitable but with ES payments become profitable

Note: The sum of the articles within the tables is not equal to the number of articles with a profitable outcome since some articles may be relevant to more than one factor. The category Multiple is not included since it is considered a factor due to its value in the underlying synergic effect of practices.

5. Discussion and conclusions

The mapping of the 49 articles provides a clear picture of the recent literature on the economic impact of CF. Despite the high number of simulation articles, we were able to define the general trend of the literature on the effect of CF on economic outcomes and the factors affecting them.

Our results show a predominant interest in finding the profitability of CF, with mixed results. 45% of the papers suggest that CF imposes economic burdens on farms, aligning with the view supported in the precedent literature (e.g., Kragt et al., (2012); Tang et al., (2016)). Specifically, our result shows that this is the case for practices that reduce externalities, affecting the final profitability by increasing costs, as for manure management, or reducing yield, as for lower use of fertiliser, without being counterbalanced by economic gains. The literature also identifies these practices as those that “do not pay to be green” (Ghisetti & Rennings, 2014). Specifically, the practice application implies costs, setting an economic burden on farms and being adopted only if forced by external regulations (Ibid.). However, the remaining 55% of the papers from our sample diverge from these considerations, suggesting that profitable farm outcomes are possible under certain conditions. This shift in the literature differs according to the categories of CF practices considered, its characteristics or analytical perspectives adopted.

Our results indicate that efficiency gains primarily drive profitability for individual practices that involve agricultural innovations or improved management techniques, such as livestock management, nutrient management, or SOC practices. Specifically, practices like optimised feeding, which reduce resource use per unit of output, deliver positive economic and environmental outcomes. Although previous CF literature has not extensively addressed this aspect, the concept of reducing negative externalities through efficiency is well-established in production literature, as Kemp (2010) discusses in the context of "Eco-Innovations." Practices that enhance efficiency have been shown to offer "win-win" economic advantages, making it profitable for firms to adopt greener practices (Ghisetti & Rennings, 2014). Our findings suggest that this principle can be extended to CF, particularly for practices that improve farm efficiency. However, we saw that it is essential to account for the specific characteristics of the agricultural sector. The biological interactions between farming activities and the surrounding environment are often realised over extended timeframes (Cusser et al., 2020; Nunes et al., 2018). For example, practices that enhance SOC may improve efficiency over the long term due to the slow impact of CF practices on the soil's productive capacity.

When efficiency improvements are not possible, our findings suggest that other factors enhance CF's profitability. One of these is access to niche markets that offset the negative burdens of CF through higher prices. For instance, we saw that organic farming practices that lead to lower yields could offset their productive losses due to higher revenues driven by the additional market value for organic products. This outcome follows an already consolidated perspective of the literature. It is, in fact, well established that organic production has similar or higher revenue efficiency than conventional (Hansen et al., 2021). This result is possible because organic products, through certification systems, guarantee that the production method adopted provides environmental externalities, acting as leverage for sustainability-concerned consumers to pay higher prices (Brito et al., 2022). Although this is a win-win solution, certification schemes for agricultural products recognised by governments (e.g., the EU or the USA) are limited, and the organic market is the only well-developed market that accounts for environmental certifications to the final consumers (Reganold & Wachter, 2016). Despite this, organic production allows us to understand that CF's economic viability can also be tied to market dynamics. Recognised certification schemes can be used to internalise externalities in consumer prices, making the demand for sustainable products a driver for an eventual shift in production methods.

Our findings suggest that the profitability of CF practices, which do not directly result in efficiency gains, can also be enhanced by adopting a whole-farm perspective or combining multiple practices. This insight addresses the gap identified by Tang et al. (2016), demonstrating that the literature on CF has evolved since their review. Specifically, our research shows that integrating different practices can create production synergies, particularly in the context of SOC practices, thereby boosting overall yields. Additionally, strategies like livestock, manure, and nutrient management can improve economic performance when assessed together at the whole-farm level. These interactions between different farm branches (e.g., crop and livestock production) are determined by complementary effects that enhance economic outcomes. The benefits of such integration in sustainable practices have also been recognised in other contexts. Wilkins (2007) argues that mixed farms are better equipped to achieve resource sustainability due to the interactions between diverse farm branches. As de Roest et al. (2018) suggested, farms focusing on a single production may benefit from economies of scale and improved technical capacities while being more vulnerable to changes. Conversely, diversified farming systems create economies of scope, where the complementarities between different productions can lead to enhanced economic outcomes, especially when sustainable production methods are applied. Our results support that diversified farms are more effective in implementing CF practices, thanks to the complementarities these practices can enhance across different productive branches. Therefore, CF practices will be more likely to succeed in un-specialised farms with a more diversified production approach.

When the economic loss is determined by the low value of the final biomass, as for agroforestry, we found that providing additional revenues through policy intervention drives profitability. In line with current literature on agroforestry (see e.g. Thiesmeier & Zander, 2023), internalising ES economic value allows to reach the results of alternative traditional practices. We extend this consideration to the fact that this payment would compensate the farmer and provide sure sources of income that reduce his/her exposure to economic risk. Although there is agreement in the literature on the success of ES in supporting CF practices, nowadays, policies still need to be improved (Nath et al., 2023). Where present, in a limited way, e.g. EU or USA, they provide economic incentives for adopting CF through action-based (i.e. predefined payment per hectare) or results-based payments (i.e. depending on the quantity of ES produced) (Bartkowski et al., 2021). No matter the payment method adopted, more than the current ES value is needed to support a change in the profitability of agroforestry systems (Coderoni et al., 2014). Therefore, even if ES payments for the literature are the best way to provide additional revenues, the policy is still underestimating the "True price" of ES-rich CF practices, as agroforestry, missing the opportunity of internalising its externalities to benefit the overall society.

A factor that consistently influences the outcomes, regardless of the category of CF practices, is the pedoclimatic conditions in which the practice is applied. Previous CF literature has highlighted this issue, emphasising that cost-effectiveness varies spatially, even when considering environmental outcomes (Plastina et al., 2024; Tang et al., 2021). The biological nature of agriculture means that soil type and weather conditions significantly impact farming practices' capacity to generate positive externalities and their economic results (Hutchinson et al., 2007; Pretty et al., 2005). As a result, there is no one size fit for all CF practices that can be effectively implemented across all regions. Instead, successful CF implementation must consider the unique environmental context of each location. The variability in soil and weather conditions across different regions implies tailoring CF practices to local conditions to maximise environmental and economic outcomes.

Although the successful identification of different trends within the literature regarding the outcomes and the factors driving profitability, we identified several gaps that future research should address.

The predominant use of modelling techniques limits the generalizability of findings to assumptions and parameters defined by the researcher. Employing econometric approaches could provide more robust insights into the causal relationships between CF practices and economic outcomes, guiding policy design applicable across diverse farming contexts.

Secondly, our research identified limited articles on peatland management, with varying perspectives on its economic outcomes. This scarcity of studies makes it challenging to draw definitive conclusions about the economic impact of peatland related CF practices and the factors influencing these outcomes. Although peatlands occupy a relatively small portion of agricultural land, they offer significant positive externalities (Girkin et al., 2023). This highlights the need for further research to thoroughly assess their economic implications, identify potential financial trade-offs, and inform policy development to let society maximise the enjoyment of CF externalities.

Finally, a relevant gap regarding uncertainty and risk has to be defined. The effect on the economic risk of CF and the uncertainty related to climate change have shown to be relevant topics but have been considered in few studies. Given that the results underscored a potential influence of these factors by CF, there is a need for a deeper investigation of these matters. For economic risk, more studies need to be done to highlight how CF affects farmers' risk perception and to address whether it plays the role of choice leverage at the time of the adoption decision. On the other hand, considering climate change is necessary for future studies, especially because of the long-term effect of CF practices and its potential consequences on their economic and environmental outcomes.

5.1 Limitations

We acknowledge that, for its nature, the SLM presents different potential limitations.

First, the literature can be limited by the research databases consulted. To overcome this, we decided to include the "Web of Science" in the selected database due to its renowned reliability and richness in the amount of literature gathered (Li et al., 2018). However, we still recognise that the databases used might not have considered a small portion of articles.

Secondly, developing a search string in this methodology may narrow the results by limiting the search to articles with only the words included in them. To avoid this risk, as provided in section 4, we developed trials that helped recognise potential synonyms within articles and include them in the search string, reducing the risk of articles skewed by the terms considered.

Third and last, the screening procedure might have been limited by the reviewer's capacity to select the final articles to include in the analysis. Having a single reviewer is not a common practice within the SLM literature (e.g. af Sandeberg et al. (2023)), bringing potential biases in the selection of papers due to a lack of counterfactuals and discussions with other researchers. To avoid selection biases, we developed narrow exclusion criteria. We followed a systematic procedure in the reading, as shown in the method section, to guide the single reviewer choices with lower risks of biases.

5.2 Policy implication

In developed countries, CF is generally supported through voluntary or compliance-based carbon markets, such as the Australian Carbon Farming Initiatives, or by hectare subsidies, as in the agri-environmental schemes of the European Union. However, these interventions are not efficiently designed, causing farmers' low willingness to adopt these practices (Raina et al., 2024). Our research provides different suggestions to enhance existing policies, aiming to increase the potential profitability for carbon farmers. These are based on the assumption that profitability is a crucial driver of adoption (Pannell et al., 2006) and that the government's goal is to improve the environmental sustainability of agricultural production.

First, governments must recognise CF's spatial variability and understand the pedoclimatic conditions in which they operate. This knowledge is essential for identifying practices that maximise environmental and economic outcomes in specific contexts.

Our findings suggest that CF practices that improve farm efficiency create win-win scenarios for farmers. Their potential profitability can thus be a strong incentive for adoption, reducing the need for additional economic support. However, for these practices to be integrated into farming operations, farmers must be aware of the opportunities they present (Pannell et al., 2006). Therefore, it is essential to develop knowledge transfer initiatives that provide farmers with the information they need to select practices with the best economic and environmental outcomes for their specific production contexts.

Moreover, policies supporting specific farm structures may facilitate the transition toward CF. Diversified farming systems, in particular, tend to achieve relevant economic success when adopting sustainable practices. Thus, incentives to diversify farm production can enable the profitability of practices that previously may not have been accessible to specialised farmers.

Finally, policymakers should consider implementing ES payments for practices that do not generate immediate economic gains but offer significant societal benefits, such as agroforestry. While such payments already exist in some countries, they must be more consistent and better supported by well-defined ES markets and conditions. Alternatively, policymakers could adopt a bottom-up approach similar to that used in organic farming. By developing specific certification schemes, decision-makers can empower consumers to demand sustainable products. This would allow price premiums to ensure farmer profitability, even with the uncertainty related to shifting the responsibilities to consumer preferences.

All in all, policymakers' approach to making carbon farming economically attractive should be practice-specific. In this way, producers can choose to adopt practices that reduce their environmental impact without damaging their economic sustainability.

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Popular science summary

The document discusses the economic impacts of carbon farming practices at farm level, focusing on agriculture's significant contribution to greenhouse gas emissions. It examines various carbon farming practices, including agroforestry, peatland management, livestock and manure management, soil organic carbon enhancement, and nutrient management. These practices have a relevant effect on the mitigation of greenhouse gas emission but with diverse economic implications on farms.

Our study shows that the literature tried to account for this impact mainly using farm simulations in specific context and with different approaches.

In general practices applied alone appear to have a positive economic outcome only when giving to the farmer higher market prices, as in organic production, or better yields than the conventional alternatives, as for herd management improvements.

Although this positive outcome, most of the practices, due to high costs for farmers showed to be economically unavailable, especially the richest one in terms of environmental benefits, as agroforestry and peatland management.

Shifting the analysis to a whole farm level or multiple practices applied simultaneously within one farm causes management interaction that overcomes potential negative economic outcomes and provides greenhouse gas reductions.

This underlines the need for two main approaches to new policy development. Decision makers should enhance farmers' training on practices that are economically relevant when combined or profitable at a whole farm level, while more support is needed for practices with higher environmental value.

Further research is necessary to account for climate change uncertainty and economic risks for farmers who decide to apply CF, accompanied by more investigations on practices, such as peatland management, that have been shown to be under-researched.

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Appendix 1

Table showing the protocol used in Excel to code the articles found in the searching

Coding variable	Record
Reference	Title, author(s), date and publisher
Study country/region	Name of the country
Data source	Primary or secondary
Aim	Aim of the study
Practice investigated	Type of practice
Unit of analysis	Location or population
Sampling strategy	Strategy applied to develop the study
Length of the study	Time
Method applied	Type of model or method used
Comparator	Comparator Used
Independent variables	Type o variable used
Dependent variable	Type o variable used
Economic indicators	e.g. Yield, productivity…
Outcome	Type of outcome
Significant	Yes/no

Appendix 2

Table illustrating summarising each article

Source	Location	Practice	Category	Type of production	Methodology	Economic indicator	Environmental indicator	Economic effect	Environmental effect
Fournel et al. (2019)	Canada, southwestern and eater Quebec	Cover on manure storages, Implementation of solid-liquid separation, digestion with gas treatment, composting of solid manure, manure incorporation in soil	Livestock and manure management	Dairy	Modelling using N-CyCLES model on synthetic data	Farm net income	N balance; P balance; GHG emissions	Diverse : depending on farm effects on inputs savings, output produced, investment and operational costs	GHG emission reductions
Harrison et al. (2016)	Australia, Central Queensland	Feeding nitrate supplements, feeding forages, increase female fecundity, optimize herd structure	Livestock and manure management	Beef	Modelling using commercial models on synthetic data	Gross margin	GHG emissions	Positive: Increase in yield covering higher management costs	GHG emission reductions
Smith et al. (2016)	USA	Changing calving period	Livestock and manure management	Beef	Modelling using FORCAP on synthetic data	Net return	CH_4; CO_2 and N_2O emissions	Positive: Increase in yield due to lower breeding failure, higher quality forage and selling at prices peak period	GHG emission reductions
Mertens et al. (2023)	Europe: Belgium, France and Italy	Crossbreeding, fast rotational grazing	Livestock and manure management	Beef	Modelling using FarmDyn on synthetic data	Farm profit	GHG emissions	Positive: More land available for cash crops covering higher labour costs	GHG emission reductions with both practices combined
Zehetmeier et al. (2020)	Germany, Bavaria	Increase feed use efficiency, optimize calving time, livestock density	Livestock and manure management	Dairy	Modelling using BASES and MLR on a sample of 92 farms data	Profitability	GHG emissions	Diverse: Only increment in feed efficiency positively correlated with profits	milk yield and calving interval: negatively correlated with GHG emissions
Cantillon et al. (2024)	Ireland	Increase productivity, optimize calving time, slurry tank cover, Low emission slurry spreading, pasture management, crude protein reduction.	Livestock and manure management	Dairy	MACC on representative farms and practices synthetic data	Marginal abatement costs	GHG emissions	Diverse: Costs changes affect the outcome depending on practice	GHG emission reduction

Mack & Huber (2017)	Switzerland	Concentrate reduction	Livestock and manure management	Dairy	Modelling using SWISSland and regression analysis	Compliance cost	N balance	Negative: Reduction of milk yield	Reduction of nitrogen surplus
Pierer et al. (2016)	European union with 28 states	Optimize feeding time, increase forage quality	Livestock and manure management	Pig and dairy	Modelling using synthetic data	Gross margin; abetment cost	N balance	Positive: Reduction of feed costs and higher yields	Reduction of nitrogen surplus
Rotz et al. (2016)	USA, New York State	Manure solid separator, open lined manure storage, closed manure storage burning in a flare, Anaerobic digester, Anaerobic digester with injection of manure on fields	Livestock and manure management	Dairy	Modelling using IFSM combined with LCA synthetic data set and accounting for climate change scenarios	Net return	GHG emissions	Diverse: depending on the effect on input for other branches and investments, labour and energy costs	GHG emissions reduction
Cong & Termansen (2016)	Denmark	Optimize feeding	Livestock and manure management	Pig	Modelling using experimental and synthetic data	Profit	N balance	Positive: Reduction of feed costs and provisioning of farmland for alternative productions	Reduction of nitrogen surplus on farmland
Castaño-Sánchez et al. (2022)	USA, Central Pennsylvania	Manure application on fields	Livestock and manure management	Dairy	Modelling using IFSM on synthetic data set	Profitability	N balance; P balance	Postive: Reduction of mineral fertilizers costs and increment in crop yields	Reduction of nitrogen surplus and phosphorus surplus
O'Connor et al. (2020)	Ireland	Anaerobic digester	Livestock and manure management	Dairy	Ex-ante NPV combined woth LCA	NPV	GHG emissions	Positive: Time horizon of 14 years to be profitable thanks to energy production	GHG emissions reduction
Brečko & Žgajnar (2022)	Slovenia	Optimize herd	Livestock and manure management	Mixed	Modelling with Quadratic Risk Programming using synthetic data set	Expected gross margin (EGM)	N balance; P balance; K balance; GHG emissions	Maintain of EGM: Substitution of cattle with laying hens and pigs	GHG emissions reduction
Ouellet et al. (2021)	Canada, southwestern and eastern Quebec	Increase feed use efficiency	Livestock and manure management	Dairy	Modelling using N-CyCLES al with representative data	Net income	GHG emissions	Positive: Reduction of feed costs and more farmland available for alternative productions	GHG emissions reduction
Sintori et al. (2019)	Greece	Herd optimization	Livestock and manure management	Goat	Modelling using synthetic data	Gross margin	GHG emissions	Negative: Lower production due to herd and reduction of feed	Reduction of GHG emissions
Lehmann et al. (2019)	Denmark	Changing lactation	Livestock and manure management	Dairy	Modelling using SimHerd with synthetic data,	Marginal abatement costs	GHG emissions	Negative: Reduction of milk yield	Reduction of milk footprint
Flack et al. (2022)	UK, southeast England	Afforestation	Agroforestry	Timber production and C sequestration	Modelling using InVEST model estimating ex-ante NPV due to land use change on different land types	NPV; EAV	C sequestration; GHG emissions	Negative: Afforestation is always a loss with the lowest when converting pasture land while higher for arable due to higher production value	Max sequestration on afforested arable land due to trade-offs with arable production
Thamo et al. (2019)	Australia, West	Afforestation	Agroforestry	Changing land use of a dairy farmland for C sequestration	Modelling using MIDAS and APSIM model on representative farm	Farm net return	C sequestration	Negative: Without carbon policies unprofitable, need of a support of at least 40$/tCO2-e	Sequestration of carbon also when implemented on marginal land
Ryan & O'Donoghue (2021)	Ireland	Afforestation	Agroforestry	Changing land use of a dairy farmland	Modelling using ForBES and synthetic data on production and C income	NPV; EAV	C sequestration	Negative: lower private return, increasing only if increasing Carbon value and only with 100 €/ha becomes profitable for most of the farms	Reduction of twice the emission produced by animals per hectare
Monge et al., (2016)	New Zealand	Afforestation	Agroforestry	Comparing milk production and	Ex-post cost benefit analysis and analysis of the stochastic dominances accounting for prices variabilities	NPV; Stochastic dominance	N balance; C sequestration	Dairy farming in sure condition is profitable, but with ES payments forestry	n.a.

				afforestation				becomes appealing to risk avoiders	
O'Donoghue et al. (2024)	Ireland	Afforestation	Agroforestry	Stika Pruce cultivation	Modelling using ForBES synthetic data set	NPV; AEV	C sequestration	Economic and environmental Trade-off: maximising economic return in shorter rotations	Maximizing carbon sequestration requires time
García de Jalón et al. (2018)	UK	Afforestation, silvoarable	Agroforestry	n.a.	Ex-ante cost benefit analysis using and synthetic data between arable, silvoarable and forestry systems	NPV; EAV	GHG emissions; erosion; P balance; N balance	The performance of silvoarable systems similar to arable, while forestry the worse option in economic terms	Higher C sequestration in silvoarable while forestry best at nutrient balance
Kay et al. (2019)	Europe	High value trees systems, silvopasture	Agroforestry	n.a.	Modelling using synthetic data to understand if ES payments be comparable to usual ones	Net profits and benefits (valuing ES)	Nutrient losses; C sequestration; soil loss	<u>Negative:</u> The evaluation of ES in force make most of landscapes still unaffordable but high value ones, as the mediterranean, are exempted	Low costs of ES allow for high impact on soil loss, C sequestration and nutrient loss
Greene et al. (2023)	USA, east	Silvopasture	Agroforestry	According to species considered : nuts, wood and C sequestration	Ex-ante Cost-benefit analysis with different demand on products for different combination of species	EBIT; NPV; IRR	C sequestration	<u>Depend on the species:</u> the faster they grow, the faster break even and the density of production	Reduction of cattle emission in favourable circumstance of 11%
Laporta et al. (2021)	Portugal	Silvopasture	Agroforestry	Grazing under Montado landscapes	Ex-post Cost-benefit analysis accounting for different C pricing	NPV	C sequestration	<u>Negative:</u> Without financial incentive abandonment to be avoided with at least 103 €/h	In all the scenarios sequestration of carbon
Ovando et al. (2017)	Spain, Andalusia	Silvopasture	Agroforestry	ES provisioning	Modelling using environmental asset model and synthetic data set	NPV; economic asset value	C sequestration; water provisioning	The presence of silvopasture increase land prices, specie Q.Suber higher profit	Provisioning of ES depend on species, Pnus highest C sequestration capacity
Staton et al. (2022)	UK	Alley cropping management	Agroforestry	Apple production and wheat/barley	Modelling using experimental data	Gross nixed income; NPV; EAV	C sequestration; pollination	reduction of the arable yield but compensated by higher production and value of apples	Increment in the carbon sequestration and higher pollination capacity
Abdul-Salam et al. (2019)	UK, Scotland	Integrated management	Nutrient management	Arable crops	Modelling case study using experimental data on a representative farm	Farm profitability	GHG emissions	<u>Negative:</u> The reduction of fertilizers reduces significantly yields	GHG emissions reduction
Diacono et al. (2023)	USA, Southeast	Fertilization strategies, additional microorganisms	Nutrient management	Fennel crop	Modelling using experimental field level data applying different fertilizers ration with inoculum of new microorganisms	Costs	Soil carbon dynamics	<u>Positive:</u> the addition of the inoculum increases yields and reduce fertilizers costs	Inoculums improve the soil carbon dynamics on the field
Bos et al., (2017)	Netherlands	Rotations	SOC maintaining and enhancing practices	corn, sugar beet, winter wheat, yellow mustard	Modelling using NutMatch to develop trade-offs curve	Financial return	Soil organic carbon; N balance	The analysis shows negative trade-offs between financial returns and SOC	If SOC increment negative trade-offs with nitrogen balance
He et al. (2022)	Australia, Riverina region	Rotations, residue management	SOC maintaining and enhancing practices	Six arable crop rotations	Modelling using APSIM on experimental data simulating also different climatic and soil conditions	Gross margin	GHG emissions	<u>Positive:</u> Combination of practices increases yields also in different climate scenarios	Reduction of GHG emissions though increase of SOC but trade-off with N2O
Zhou et al., (2022)	USA, southern Mississippi river Basin	Rotations, not tillage	SOC maintaining and enhancing practices	Corn, cotton and soybean	Field experiment applied with partial budgeting techniques and analysis of variance	Net return	Soil organic carbon dynamics	<u>Positive:</u> Only when practices are combined, increasing the yields especially in the long run and reducing costs	In all cases improvement of SOC
Colombo et al. (2024)	Spain, Andalusia	Cover crops in woody crops, residues mulching in cover crops	SOC maintaining and enhancing practices	Olive groves	Modelling using GIS data and RothC model to build ex-post cost benefit analysis	NPV	Soil carbon balance; soil erosion	<u>Negative:</u> Increment of costs for new inputs purchases	Increase in SOC and reduction in erosion
De Leijster et al. (2020)	Spain, South east	No tillage in woody crops, green manure	SOC maintaining and enhancing practices	Almond orchards	Modelling using stochastic cash flow incorporating random variations	NPV; DPBT; IRR	Soil organic carbon; soil erosion	<u>Negative:</u> woody yield reduction that increases in time not compensated by	Reduction of soil erosion and improvement in nutrient balance

								lower machineries usage	
Martin-Gorriz et al. (2020)	Spain	Reduced tillage, reduced tillage with green manure	SOC maintaining and enhancing practices	Almond orchards	LCA of the entire management and partial budgeting	Profit	GHG emissions	Negative: crop yield reductions not compensated by lower machinery usage	GHG emissions reduction
Lorenzetti & Fiorini (2024)	Italy	No tillage with cover crops	SOC maintaining and enhancing practices	9 different Arable crops	Experimental data used on descriptive statistics and GLS regression	Gross margin	Soil organic carbon; C sequestration	Positive: Increase in yield fostered in time followed by lower cost	SOC increment with time
Flaten et al. (2019)	Norway	Organic	SOC maintaining and enhancing practices	Dairy	Modelling using FARM model on synthetic data	Profitability	GHG emissions; N balance	Neutral: Reduction of yield compensated by price premium keeping the same profitability	Reduction of nitrogen surplus and GHG emissions
Lambotte et al. (2023)	France	Organic	SOC maintaining and enhancing practices	Dairy	Using databases application of regressions adjusted propensity score and weighted regression, to see how easy the implementation of organic could be	Gross margin	GHG emissions	Neutral: Reduction of yield compensated by price premium keeping the same profitability	Reduction of GHG emissions
Plastina et al. (2024)	USA	No tillage, cover crops	SOC maintaining and enhancing practices	n.a.	Modelling of adoption of the practices with different C payments regime based on country level data	Net return	C sequestration	Negative: Reduction of crop yields not compensated by lower machinery costs	Reduction of GHG emissions
Wachter et al. (2019)	USA; eastern Washington State	Rotations, organic farming	SOC maintaining and enhancing practices	Grain production	Statistical analysis based on experimental data	Farm net return	Soil PH; SOC	Positive: Minimal reduction of yield compensated by price premium keeping the same profitability	Improvement of soil health
Liu et al. (2023)	Netherlands	Paludiculture, low intensity grassland	Petland management	Reed and sparghum	Environmental system analysis and modelling on six land use options	Net return	GHG emissions	Negative effect on profitability from status quo due to high establishment costs	GHG sequestration and maintenance of habitat
Deverel et al. (2017)	USA	Wetland management	Petland management	Rice	Modelling using SUBCALC model analysing for different land management scenario optimisation options	Farm profitability	GHG emissions	Positive effect on profit if area used partially for rice cultivation and flooded in richer SOC areas	GHG emission avoidance and SOC increment
Meier et al. (2017)	Australia	Rotations, fertilizer management, cover crops	Multiple	Grain production	Modelling using APSIM based synthetic data considering different climatic and soils	Gross margin	GHG emissions	Negative outcome since high abatement is correlated with negative gross margin, not compensated by policies	In all the practices considered reduction of GHG emissions
Bamière et al. (2023)	France	Cover crops, grassland introduction, agroforestry, hedges.	Multiple	n.a.	Modelling using BANCO based on regional data to show the cost per hectare of practices	Marginal abatement cost	SOC; GHG emissions	grass cover of vineyards, agroforestry, cover crops, and hedges are the most cost-efficient practices	Agroforestry has the highest abatement potential and SOC accumulation
Pellerin et al. (2017)	France	Reduction of fertilizers, rotations, no tillage, cover crops, grass buffer strips, agroforestry, hedges additive in ruminants' diets reduction protein in the diet of livestock, extend methanation, install flares, reduce fossil fuel use.	Multiple	n.a.	Comparison of the annual abatement potential and costs of 26 identified measures	Marginal abatement cost	GHG emissions	Practice that enables savings on inputs have a negative MAC, while the higher is the initial investment the lower the affordability	All submeasrue together may reduce 10% of emissions from the sector
Rubhara et al. (2024)	Ireland	Reduce chemical fertilizers, grazing management, manure management, use of native feeds, antimethane additives, reduce replacement rate, use renewable resources	Multiple	Dairy	Applying partial budgeting techniques and LCA analysis, with and without the practices, on a representative farm data with two scenarios: limited and full implementation	Net profit	GHG emissions	Full implementation larger profits thanks to savings of the technologies and full implementation brought also to higher yields	In the 2 scenarios reduction of 12% and 36% of emissions from baseline

Baccour et al. (2021)	Spain	Input optimization, manure fertilization, minimum tillage, cover crops, crop rotation, nitrification inhibitor, irrigation modernization, manure fertilization, protein diets, manure treatment plants, fat additives.	Multiple	n.a.	Modelling by applying the practices on the most suitable regional areas and estimating costs/benefits based on synthetic data	Margi nal abate ment cost	GHG emissions	N optimization, manure management, crop rotation, and protein diet have important win-win mitigation potential (increase also income)	The implication of all the measure interacting reduction by 75% GHG (interaction reduces of 10%), highest forest management
Alletto et al. (2022)	France	Crop diversification, nutrient management	Multiple	8 different arable cropping systems	Experiment codesigned with farmers and advisors assessed with economic, environmental and social indicators	Profit abilit y	Water wuality; climate mitigation	Reduction of costs and low effect on productivity led to some of the system to be profitable	Increment in the water and soil quality
Dumbrell et al. (2017)	Australia	Stubble management, optimizing fertilization rate, green manure legumes	Multiple	Grain	Modelling using APSIM on 3 different representative grain farms data	Farm profit s	SOC, N balance	Positive outcome on profits per hectar onlu in sandy soils and dry climates	Sandy soils and dry clamate bring farms reduce N2O emissions and increase SOC in all practices, while clay soils not

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