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Report

Innovative carbon farming initiatives

An overview of recent and ongoing projects across the EU

Institute for European Environmental Policy

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EXECUTIVE SUMMARY

As the European Union steadily strengthens its climate ambition, with stricter emission reduction targets integrated into a raft of new and updated regulations, it is evident that a stronger commitment is needed from all sectors to ensure adequate progress towards those objectives.

Against the background of a limited contribution made by the agricultural sector to the climate mitigation effort to date, 'carbon farming' is emerging as one of the potential solutions. Carbon farming involves the management of carbon pools, flows, and greenhouse gas fluxes at the farm level to mitigate climate change, encompassing various land management techniques and technological solutions.

There are a number of factors hindering the widespread adoption of carbon farming in the EU, including financial uncertainty for farmers, monitoring challenges, and insufficiently tailored training and advisory services. The EU aims to address some of these challenges through research and innovation, with the Horizon Europe program as a key initiative facilitating this effort.

This report presents an overview of ongoing and recently completed EU projects that promote innovation in carbon farming, focusing on initiatives funded by Horizon Europe and a smaller selection of programs financed through other sources of public funding and private sector initiatives. These projects have been compiled into an accompanying project inventory, available at https://carbonfarminginventory.ieep.eu/. Through an analysis of a sample of over 50 projects, this report offers insight into the efforts being made to accelerate the adoption of more sustainable agricultural practices across the EU.

In the analysed sample, several key themes and trends emerge, with projects encompassing a range of innovative approaches, including decision support systems, innovative monitoring and reporting solutions, technological advancements, novel contract designs, and innovative agronomic techniques.

Decision Support Tools (DSTs) assist various stakeholders in making informed decisions related to agricultural land use and land management. While many of these DSTs are designed for farmers and agricultural advisors, some also cater to spatial planners, policymakers, and local authorities. The tools cover a wide range of areas, with a significant emphasis on crop production and soil health improvement, as well as reducing greenhouse gas emissions and enhancing climate resilience.

Innovative monitoring, reporting, and verification (MRV) solutions enable more accurate data collection, facilitate decision-making, and support result-based payments for ecosystem services and compliance verification. The analysed projects show advancements in the use of monitoring technologies, such as remote sensing, satellite imagery, and sensor networks, as well as citizen participation and improved carbon accounting methods.

Technological innovation is a central theme in many of the projects, with a focus on developing and commercialising novel technologies to enhance resource efficiency, reduce environmental impact, and lower greenhouse gas emissions. These innovations cover various aspects, including crop production equipment, methane abatement technologies, or the use of microalgae in agriculture.

Innovative contractual solutions are explored in several projects, both in the public and private sectors. These initiatives aim to incentivise sustainable practices within the agricultural sector while maintaining economic viability. They include programmes developed by large private sector entities to promote sustainable practices among their suppliers, including the co-design of financial products to support the transition to regenerative agriculture.

Despite significant research efforts to facilitate the uptake of carbon farming practices through innovation, challenges remain. Considering the key role of income variability as a decision factor for farmers, more sophisticated tools that consider economic factors and yield variability may be needed to communicate costs and benefits effectively. Only a limited number of DSTs allowed users to interact with the databases and upload local data to refine existing analyses and recommendations provided by the tool. Additionally, ensuring equitable access to these resources and overcoming barriers associated with disparities in the levels of digital literacy and internet access are ongoing challenges.

While agroforestry and peatland rewetting hold significant potential for climate mitigation and other positive environmental outcomes, there have been relatively few Horizon Europe projects focused on these practices. Certain types of agricultural activities, such as paludiculture, remain relatively unexplored – while initiatives are currently emerging in some Member States to address this gap, there continues to be a scarcity of cross-national research in this area. More concerted efforts are needed to promote innovation in these areas, particularly given the specific challenges and market dynamics associated with their adoption.

Even among projects that span multiple countries, there remains an imbalance in focus between Member States, with Western European countries leading and hosting more initiatives. This regional bias in terms of where decision support systems and agronomic techniques are field-tested is likely to impact the quantity and sophistication of data available with regards to the appropriate types of measures and their effects depending on the local context.

Overall, the analysed projects represent a significant effort to promote sustainable agriculture and carbon farming in the EU. They address various aspects of the agricultural sector, from technology and innovation to policy development and contract design. However, ongoing challenges related to access, regional disparities, farmer behaviour and adequate incentives need to be addressed to ensure the widespread adoption of sustainable practices in European agriculture.

1. BACKGROUND

With the adoption of the European Climate Law in 2021, the European Union has established a binding target of net greenhouse gas (GHG) emission reductions by 55% by 2030 and embarked on a program of realigning and strengthening its policy framework in line with the increased climate ambition. Under the 'Fit for 55' package, a set of policy proposals has been put forward to enable the achievement of the new target, while ensuring a just transition and competitiveness of the EU industry.

As the EU Commission's own impact assessments highlight, the importance of the land sector in the low-carbon transition is increasingly moving into focus given its role as both a significant source of emissions and a carbon sink, as well as its vulnerability to the impacts of climate change (European Commission 2020).

Shift to sustainable agricultural practice – is the pace of change quick enough?

According to the EEA (2022a), approximately 13.5%[1] of total GHG emissions of the EU-27 can be attributed to the agricultural sector. This estimate accounts for the key sources of emissions in the sector, such as enteric fermentation, manure management, N_2O emissions from managed soils (e.g. from fertilisers and crop residues), as well as CO_2 emissions from cropland and grassland use. Agricultural emissions are governed by two separate pieces of EU legislation: the Effort Sharing Regulation (ESR), covering CH_4 and N_2O emissions, as well as CO_2 emissions from energy use and liming, and the Land Use, Land-Use Change and Forestry Regulation (LULUCF) Regulation, which governs CO_2 emissions and removals from land use (croplands and grasslands).

The recently revised ESR sets an aggregate emissions reduction target of 40% by 2030 (compared to 2005), for a range of sectors including agriculture, as well as road and domestic maritime transport, buildings, waste and small industries. The LULUCF regulation sets an overall objective of 310 Mt CO_2 equivalent of net removals in the LULUCF sector for 2030.

To date, the contribution of agriculture to the progress against targets set in the ESR and LULUCF Regulations has been limited. Out of all sectors within the scope of the ESR, agriculture contributed the least to the achievement of the 2020

[1] Emissions from energy use in agricultural production are not included in this estimate, as inventory data is only available in aggregate for energy consumption in agriculture, forestry and fisheries (CRF category 1.A.4). These sources were together responsible for app. 2,2% of total EU-27 GHG emissions in 2020 (this excludes indirect energy emissions, e.g. from the highly energy-intensive production of fertilisers, pesticides and agricultural machinery).

reduction target of 20%, with GHG emissions from the sector remaining largely stagnant since 2005 (EEA 2022b). This is despite significant improvements in production efficiency, with the increase in production eliminating any potential benefits from the decline in emissions intensity (idem.). Based on a 2021 analysis, the national agricultural measures and policies in place across EU Member States were projected to deliver further reductions of only 1,5% by 2040 – an altogether insufficient decrease in light of the 2050 climate neutrality goal (ETC/CME 2021). In the land use, land use change, and forestry sector, cropland and grassland are also both sources of GHG emissions, with managed organic soils as a major contributor. While there has been a slight decrease in cropland emissions over the past decade, it is negligible when compared to the overall loss of carbon sink in the land sector (EEA 2022c).

The environmental impacts of agriculture extend beyond high GHG emissions, with widespread land, water and ecosystem degradation resulting from intensive modes of agricultural production. The intensification of agriculture in Europe has been associated with chemical pollution, loss of landscape diversity, decline in soil health and fertility, and biodiversity loss, including pollinator decline (EEA 2019a; 2019b). In its review of the EU's efforts to achieve its 2020 biodiversity targets, the European Court of Auditors concluded that the Common Agricultural Policy had failed to address biodiversity loss driven by agricultural activity and the funding used towards that aim had been overestimated (ECA 2020).

In turn, the decline in biodiversity, impacts of climate change, soil degradation and other pressures affect agriculture's resilience and ability to maintain productivity (IPCC 2022; Midler 2022). The adverse effects of a changing climate are already being felt in Europe and will affect a growing number of regions with increasing severity over time. While the negative climatic impacts will manifest unevenly across the bloc, they could result in a substantial drop in farm income by 2050 in a high-emission scenario (EEA 2019c).

Carbon farming as a win-win solution for sustainable agriculture

Against the background of the limited progress on GHG emission reductions made by the agricultural sector, practices described collectively as 'carbon farming' have become an increasingly prominent part of the framing of the challenge and the solutions to it. Carbon farming refers to the "management of carbon pools, flows and greenhouse gas fluxes at farm level, with the purpose of mitigating climate change. This involves the management of both land and livestock, all pools of carbon in soils, materials and vegetation, plus fluxes of carbon dioxide (CO_2) and methane (CH_4), as well as nitrous oxide (N_2O)" (COWI, Ecologic Institute and IEEP 2021). In this sense, carbon farming encompasses all agricultural practices and land use changes that result in carbon sequestration, reduction or avoidance of emissions.[2]

McDonald et al. (2021) separate carbon farming into five main sub-categories of interventions: 1) peatland rewetting and restoration, 2) agroforestry system establishment and maintenance, 3) maintenance and enhancement of soil organic carbon (SOC) on mineral soils, 4) livestock and manure management, and 5) nutrient management on croplands and grasslands. Carbon farming can encompass a variety of agronomic practices, including land management techniques, such as e.g. improved crop rotations or peatland restoration, and technological solutions, such as e.g. feed additives or nitrification inhibitors (idem.).

The impacts of these practices can vary significantly in terms of resilience, agricultural output, mitigation potential, biodiversity, and other environmental aspects. The outcomes are frequently influenced by factors such as the pedoclimatic context, wider set of accompanying practices, crop species, and other variables. However, when carefully managed, carbon farming activities hold a significant potential to deliver a range of environmental co-benefits (Scheid et al. 2023). By increasing soil organic carbon levels, they can improve soil health, leading to better nutrient retention, reduced need for fertilizers, and improved pest and disease control. Practices like crop rotation, cover cropping, and agroforestry help reduce soil erosion and nutrient leaching, improving soil quality and fostering biodiversity above and below ground. Furthermore, carbon farming practices have the potential to enhance water management, reduce the impact of severe weather events like floods and droughts, and support climate adaptation by conserving water resources and reducing the risk of wildfires.

A review of scientific literature conducted by McDonald et al. (2021) identified a total mitigation potential of 101 – 444 Mt CO2e per year (equivalent to approximately 3-12% of the EU’s total annual GHG emissions.[3] Such results demonstrate the potential contribution of carbon farming in the EU towards its climate objectives.

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[2] The use of the term in this report is arguably broader than in the EU Commission’s Communication on Sustainable Carbon Cycles, where carbon farming is understood to specifically describe a green business model for farmers, with emphasis largely placed on rewarding land managers for carbon sequestration.

[3] These results however should be interpreted with caution given the differing approaches to defining potential (i.e. technical vs. feasible, with varying approaches to defining feasibility), the land competition and leakage effects, and the inherent uncertainties associated with existing MRV approaches (ibid.).

While many carbon farming practices will play an essential role in the transition to sustainable agriculture, it is important to note that several challenges and uncertainties remain (COWI, Ecologic Institute and IEEP 2021; McDonald et al. 2021; Paul et al. 2023). Key concerns around the implementation and incentivisation of carbon farming relate to the permanence of carbon removals, additionality in the design of certification schemes, potential negative outcomes for other environmental objectives, measurement and standardisation, and socio-economic impacts within the sector.

Upscaling carbon farming initiatives across the EU

The EU Commission's Communication on Sustainable Carbon Cycles identifies several barriers to a widespread uptake of carbon farming practices in the EU, including the related financial burden and uncertainty around revenue possibilities, concerns around certification in voluntary carbon markets, paucity of cost-effective and simple monitoring, reporting and verification (MRV) systems, and insufficiently tailored training and advisory services. The Communication lays out a set of measures for addressing these challenges, which includes the fostering of research and innovation. In the case of agriculture, the Communication **reinforces the central role of the Horizon Europe programme** as the main tool for stimulating innovation in this area. It commits to a strengthened focus on carbon farming for future Horizon Europe's programming periods, with emphasis on digital and data technologies for improved estimates of carbon emissions and removals. It also highlights the R&I European mission to promote soil health – "A Soil Deal for Europe" – which identifies carbon farming as a "hotspot" area and charts the related R&I activities, including the development of MRV and certification, management practices and technologies for soil health, and financial mechanisms for de-risking of carbon farming. The Communication also points to the assistance available through the European Innovation Council (EIC) and its "Technologies for 'Fit for 55'" Accelerator Challenge which supports the scale-up of sustainable agriculture.

2. CARBON FARMING – EU PROJECT INVENTORY

The purpose of the carbon farming project inventory is to provide a snapshot view of ongoing and recently completed projects within the EU that aim to foster innovation in the field of carbon farming. It focuses on initiatives prioritised for funding under Horizon Europe, as the EU's key funding programme for research and innovation, with a small selection of projects financed through other sources of public funding at the EU level and private sector initiatives. This report discusses the emerging themes and seeks to shed light on the efforts being made to accelerate the adoption of sustainable agricultural practices across the EU by offering insights into the activities undertaken as part of the projects included in the inventory.

In light of the definition of carbon farming discussed in section 1, we focus on projects which promote interventions aimed at facilitating good agricultural practices with positive impacts on climate mitigation and resilience. While the focus is primarily on on-farm measures, a small number of projects related to activities that create the necessary economic conditions for the implementation of carbon farming practices have also been included.

With this broad view in mind, we have compiled an inventory of carbon farming projects within the EU, selecting 52 projects from a pre-selection pool of over 200 initiatives. When compiling the shortlist, we prioritised projects that were likely to make a contribution to climate mitigation or resilience in the agricultural sector and did not exhibit a discernible potential to undermine other environmental objectives. While projects did not necessarily have to name carbon removals or GHG mitigation as their key objective, we included projects that were likely to yield such benefits based on the employed practices or could generate significant environmental advantages. In these cases, the selection was guided by the rationale that practices aimed at enhancing the overall system were more likely to yield robust climate mitigation outcomes. All selected projects are either ongoing or have been finalised within the last five years, with the oldest ones completed in 2018.

All projects mentioned in the text of this report can be found in the online inventory, which enables users to search carbon farming initiatives by the type of supported innovations, climate measures, participating Member States, and bioregions covered by each project. It should be noted that the list of projects included in the inventory is not exhaustive – we welcome further suggestions and contributions to enhance its completeness.

2.1 Most common types of innovations

In its guidelines on programming for innovation and the implementation of the European Innovation Partnership for Agricultural Productivity and Sustainability (EIP-AGRI), the European Commission provides a definition of innovation as **a successful implementation of a new idea in practice.** This idea can manifest in various forms, including new products, practices, services, production processes, or organizational approaches. Innovation can encompass technological, non-technological, organizational, or social aspects and can draw upon both new and traditional practices, adapted to suit new geographical or environmental contexts (EC 2014).

As proposed by Faure et al. (2019), the analysis of innovation can be supported by using different conceptual frameworks, such as the original 'agricultural knowledge and information system' (AKIS) concept (Röling, Wagemakers, 1998), the more recent 'agricultural knowledge and innovation system' version of the AKIS concept, or the 'agricultural innovation system' concept (World Bank, 2006; Touzard et al., 2015). These concepts share the understanding that innovation emerges as a complex, nonlinear process that encompasses social, institutional, and technical dimensions (Faure et al. 2019). A systems approach to innovation emphasizes the construction of knowledge and learning through social interaction, aligning with the Commission's description of interactive "system" innovation (EC 2014; Knierim et al. 2015).

Within this study, we maintain this comprehensive perspective of innovation. Based on our sample and for the purpose of this analysis, projects have been grouped under five main categories of innovation: decision support systems, MRV solutions, innovative agronomic techniques, technological innovation, and novel contract design, with several projects spanning multiple categories.

It should be noted that as several of the projects included here are ongoing, the planned outputs may undergo refinement and modifications.

2.1.1 Decision Support Systems

A decision support system (DSS) can be broadly defined as an interactive computer-based information system designed to aid decision-making (Sheng & Zhang 2009; Terribile et al. 2015). In the context of agriculture, it can be described more specifically as "a human-computer system which utilises data from various sources, aiming at providing farmers with a list of advice for supporting their decision-making under different circumstances" (Zhai et al. 2020).

Decision support systems have been gaining popularity in the agricultural sector due to their ability to utilise data analysis to aid farmers in addressing the complexities associated with food production. DSSs are recognized as an integral component of precision agriculture, as they support agricultural producers in key decision-making processes, farm management, and planning tasks. The fundamental process involves gathering data from various sources, including sensors, satellites, and in-field observations, which is then analysed using statistical models and the output of this analysis subsequently presented to the user to aid decision making.

Digital DSSs are computer-based systems that can be installed, accessed online or through mobile apps. Their level of sophistication can vary, with the most recent DSSs, commonly developed by agri-tech companies, incorporating remote sensing, GPS, the Internet of Things, and artificial intelligence into their design.

One key aspect of agricultural DSSs is their ability to integrate farm-specific characteristics and farmers' preferences. These systems are designed to account for the unique aspects of individual farms, such as pedo-climatic conditions, employed agronomic techniques, and agricultural equipment. The integration of context-specific features enhances the DSSs’ usability and relevance for end users. Additionally, DSSs strive to incorporate relevant general scientific knowledge, such as plant or animal physiological processes.

To ensure widespread adoption and effectiveness, the design of DSSs tends to prioritise accessibility and user-friendliness. Ensuring that a DSS effectively bridges the gap between complex data analysis and practical decision-making processes requires that farmers, who may have varying levels of technical expertise, are able to navigate and utilise the system with ease.

Decision Support Systems – overview of relevant inventory projects

The creation of decision support tools (DSTs) was a relatively common output across the projects in the analysed sample. 26 projects involved the development of such tools - although it should be noted that the creation of a DSS may not always be the primary focus of these projects. The DSTs exhibit varying levels of sophistication, reflecting the diverse needs and contexts they aim to address. While the majority of tools are designed for practitioners such as farmers and agricultural advisors, at least twelve projects include features that can assist spatial planners, policy-makers, or local authorities in their decision-making processes, expanding the reach and potential impact of DSTs beyond traditional agricultural stakeholders.

The majority of DSTs analysed were designed to support decision-making in relation to crop production, with 14 projects dedicated to this area. A smaller number of projects focused on general land use choices, specific mixed production systems like agroforestry, or the rewetting of peatlands. Livestock farming was addressed in only two projects specifically. Common focus areas included resource efficiency, GHG emissions reduction, soil health enhancing practices, cost-benefit analysis, and practices enhancing climate resilience. Multiple DSTs in the sample aimed to support decision-making in overlapping areas, for example, several DSTs focused on facilitating improved soil stewardship.

The tools in the analysed sample were largely designed to enable open-source online access, theoretically making them available to all interested stakeholders. A few projects in the sample involved the development of mobile apps which aimed to provide on-the-go access to relevant information and decision support functionalities. Furthermore, some tools focused on specific pedoclimatic zones, tailoring their functionalities to specific geographic regions.

Several projects in the sample were accompanied by knowledge sharing platforms that facilitated the exchange and distribution of agricultural knowledge relating to innovative practice. These platforms varied in their mediation levels, incorporating videos on agroecological practices, knowledge gathered directly from farmers, and social media platforms. Additionally, one project included the creation of a "serious game" as a DST, leveraging gamification techniques to facilitate participatory processes, knowledge sharing, and stakeholder engagement. However, only a limited number of DSTs allowed users to interact with the databases and upload local data to refine existing analyses and recommendations provided by the tool.

2.1.2 Innovative MRV solutions

The development of monitoring, reporting, and verification approaches in agriculture plays a crucial role in understanding and addressing GHG emissions, carbon storage, and other environmental impacts associated with agricultural practices.

Advanced monitoring technologies, such as remote sensing, satellite imagery, and sensor networks, can provide real-time data on crop growth, soil health, and greenhouse gas emissions. These technologies enable more precise and comprehensive monitoring of agricultural activities, allowing for better identification of emission hotspots and opportunities for carbon sequestration. By improving MRV capacity, innovation can enhance the accuracy of emissions inventories, inform policy-making processes, and guide the implementation of sustainable agricultural practices.

Innovation in MRV methods can also facilitate the development and adoption of result-based payment schemes which incentivize farmers to adopt climate-friendly practices. Innovative approaches, such as blockchain technology, can enhance the transparency, traceability, and integrity of data, ensuring the credibility and reliability of emissions reductions claims in market-based mechanisms.

In addition to supporting climate mitigation efforts, innovation in MRV capacity and methods can also contribute to sustainable land management and ecosystem preservation. By monitoring and assessing environmental impacts, such as soil erosion, water quality, and biodiversity loss, innovative MRV systems can guide farmers in implementing sustainable land-use practices that minimise negative effects on ecosystems and promote conservation.

MRV solutions – overview of relevant inventory projects

The development of improved MRV solutions to support more sustainable agriculture was the key focus of 14 projects in the analysed sample. At least eight of them leveraged Earth Observation (EO), and in particular Copernicus data, to provide improved MRV solutions. In some examples, this data was paired with wireless sensor networks or a range of in situ and open data sources. Some projects utilised advanced methodologies, such as automatic pixel, texture, and object-oriented change detection and classification methods, machine learning, and data fusion alongside EO technology. The generated maps and data could be integrated into existing tools or used for the development of new measurement methods.

Three projects specifically focus on the measurement, reporting and verification of soil organic carbon through innovative sampling methods and prototypes for a continuous monitoring of GHG fluxes. Their primary aim is to support carbon farming project developers, certification agencies, food companies, as well as provide input into decision support systems.

Two projects in the sample build upon the concept of a citizen observatory, involving the active participation of citizens in the generation and reporting of data on land, soil, and water resources. These projects test the potential for communities of citizens to validate remote sensing data and provide valuable information based on low-cost, easy to use instruments.

A handful of projects focused on developing or improving carbon accounting methods for certain types of land use and management practices, for example agroforestry or peatland rewetting. These initiatives aimed to provide accurate and standardized accounting methodologies to assess the carbon sequestration potential of certain practices and strengthen databases underlying decision support tools. While the majority of projects showed a tendency towards a standardisation of methodologies and approaches, some took more localised perspective, e.g. one project aimed to develop a GHG calculator customized to local needs.

2.1.3 Novel forms of contract design

Innovative re-design of the forms of business and financial contracts in agriculture plays a crucial role in enabling a sustainable transition. Innovation in contract design is key to incentivizing the adoption of environmentally friendly practices, minimising risks, and rewarding the production of environmental public goods. Currently, many farmers face significant challenges in maintaining the economic viability of their operations, often encountering trade-offs between short-term profitability and sustainable production. To address these trade-offs, innovative contract-based approaches are necessary to enable farmers and land managers to balance the profitability of their farms with environmental objectives in a way that ensures positive outcomes for climate and the wider society.

Traditional agricultural contracts often focus solely on the delivery of products and economic aspects without giving sufficient consideration to sustainability performance. One key aspect of novel contract design will be incorporating environmental performance metrics into contractual agreements. By including specific targets and indicators related to GHG emissions reduction, carbon sequestration, and other environmental factors, contracts can provide clear incentives for farmers to adopt sustainable practices.

Innovation in this area is needed both in terms of financial compensation and exploring diverse forms of organization and involvement of different actors to ensure a holistic approach. Innovative contract designs can help foster long-term relationships between farmers and buyers, encouraging stable market demand for sustainably produced goods. By ensuring fair prices and long-term commitments, contracts can provide farmers with the confidence and security needed to make necessary investments in sustainable technologies, infrastructure, and practices.

Novel contract design – overview of relevant inventory projects

Five of the analysed projects have as their objective the development or implementation of novel contractual solutions to effectively incentivise sustainable practices and, by proxy, the provision of public goods by the agricultural sector. They aim to find solutions that effectively reconcile the need for an ecological transition with retaining economic viability at farm level.

Projects which fall into this category include both publicly funded research projects which aim to build a theoretical framework based on the study of existing contracts and stakeholder engagement, as well as innovative programmes implemented in the private sector. The former typically involve a synthesis of evidence, co-development of new, "dream" contract arrangements via a multi-actor process, and the testing of the proposed solutions through pilot cases. Initiatives in the private sector appear to be mostly implemented by large multinational companies, which enjoy a degree of leverage over the farmers in their supply chain. They are able to collect and manage granular data related to their suppliers' practices and effectively incentivise changes in practices in line with company strategy. One of the private initiatives included in the sample also shows potential for engagement between large agri-food businesses and financial companies to design new financial products to boost investment capacity and reduce risk associated with transition to regenerative agriculture. While the private schemes are practice-based and rely on contracts between actors within a value chain, other projects look at a variety of solutions, which may involve result-based payment schemes, land-tenure-based contracts including environmental clauses, or collaborative contracts.

Three of the analysed projects look at contract design in the general context of facilitating the delivery of environmental public goods by farmers, without focusing on any particular type of agricultural production. One publicly funded project involves the design of a results-based scheme for improved management of habitats on peat soils, while the two private initiatives in the sample are designed around dairy and vegetable supply chains.

Both private and publicly funded projects tend to bring together a range of actors that are relevant to the design and implementation of contracts such as farmer organisations, regional administrations, consultancy companies, research and financial institutions.

2.1.4 Technological innovation

While the significant resource efficiency improvements resulting from technological progress in the sector have not been translated into corresponding net environmental benefits in recent decades, technological innovation does have an important role to play in the transition to sustainable agriculture (Springmann et al. 2018; Bellon Maurel et al. 2022).

Technological innovation in modern agriculture encompasses a wide range of emerging technologies, including the Internet of Things (IoT), artificial intelligence (AI), machine learning, drones, advanced robotics and materials, genetic engineering and biotechnology. By integrating these innovations into agricultural practices, farmers can optimize resource utilization, reduce environmental impact, and enhance productivity.

Precision agriculture technologies can be expected to play a key role in the sustainable transformation of the sector. Through the use of automated observations from sensors and models, these technologies enable the monitoring of plant, animal and soil health, as well as the implementation of more complex cultivation processes on a large scale. By utilising precision agriculture solutions, farmers can gain valuable insights into the condition of their crops and livestock, enabling precise decision-making and optimizing resource allocation.

Automation and robotics are also an important aspect of technological innovation in modern agriculture. They enable the streamlining of agricultural processes leading to increased productivity and reduced labour-intensive activities. The implementation of robotics applications in agriculture has primarily concentrated on the indoor environment, specifically targeting livestock production (Bergerman et al. 2016), given the more complex challenges associated with deploying automated machinery in cropping operations, but it is increasingly explored across the spectrum of agricultural activity.

Technological innovation – overview of relevant inventory projects

Within the sample, there are at least eleven projects that showcase technological innovation and focus on the development or commercialisation of novel technologies with the potential to enhance resource efficiency, minimise environmental impacts, and reduce greenhouse gas emissions.

Two projects specifically centre around proposals for methane abatement technologies in livestock production. One project aims to enable plasma-based methane decomposition within meat cattle and dairy barns, while the other focuses on mitigating emissions from manure management through the application of slurry additives.

Most projects in this category concentrate on the development and improvement of agricultural equipment for crop production. One initiative involves the development and application of in-situ and real-time nutrient analysers, while testing a novel procedure for on-site production of biofertilisers from agricultural waste to promote a circular approach to nutrient management. Two further projects explore the use of new robotic vehicle technologies to reduce soil compaction, enable targeted tillage, and facilitate electric weeding. Another project incorporates technological innovation in hemp cultivation, where the participating farmers collaborate with an agricultural machinery company to design modified harvesting machines specifically adapted to the pressing of hemp straw.

Finally, the sample also includes a project which aims to demonstrate the viability of bioproducts made from microalgae in replacing chemical fertilisers and remediators in wine production. It will deliver a testing programme involving on-farm microalgae production and designed to facilitate the development of microalgae combinations which improve soil health and productivity, as well as resulting in climate mitigation benefits.

2.1.5 Innovative agronomic techniques

In the context of carbon farming, innovation does not solely refer to novel practices, as many carbon farming techniques, also known as regenerative, organic, agro-ecological, or climate-smart, have their origins in agricultural systems that were common before the rise of high-input, industrialized farming methods. While these practices have historical roots, their effectiveness on their adaptation to local conditions and a thorough understanding of the specific soil and climate characteristics of a given area.

In addition, while innovation often involves a return to traditional practices, it does leave room for the emergence of new strategies, with avenues for the development of novel approaches that incorporate new types of inputs and technological solutions. Traditional practices, such as cover cropping or crop rotations, can be augmented with modern crop varieties, the use of precision technologies or improved circular solutions.

Innovative agronomic techniques - overview of relevant inventory projects

A number of projects focusing on the development of new technologies, highlighted in the previous section, also entail the development of accompanying techniques in their application by farmers. Separately to those, the inventory contains four projects specifically targeting the implementation of innovative agronomic and livestock production techniques. These projects encompass different farming systems, such as crop production, livestock grazing, viticulture, and silvopastoral systems. Two of these projects aim to enhance the resilience of crop production against climate pressures while providing indirect climate mitigation benefits. One project focuses on the development of a cropping strategy incorporating new perennial grains and evolutionary cereal populations. This strategy enables the adoption of less soil-intensive practices and promotes higher levels of genetic diversity to enhance resilience. The second project examines the effectiveness of novel hydrogels in preserving soil water storage and reducing the need for nitrogen-based fertilisers.

Two additional projects centre on livestock systems and facilitate the implementation of practices with multiple environmental benefits. One project explores the utilization of multi-species swards and virtual fencing in grassland grazing management, focusing on their potential for reducing nitrogen fertiliser inputs and biodiversity benefits. The second project develops an innovative approach to reducing the life cycle environmental impact of mixed crop-livestock systems through the production of animal feed from waste from olive production and the release of digested biochar present in the feed back into the soil in olive groves.

2.2 Project responses to the challenges and opportunities of agricultural systems – case studies

This chapter provides an overview of the unique challenges and opportunities associated with climate mitigation in various farming systems. It presents 10 case studies that showcase inventory projects designed to address these challenges and offer innovative solutions. By exploring the diverse range of agricultural systems, this chapter aims to shed light on the specific obstacles faced by farmers and the context-specific strategies employed to mitigate climate-related impacts.

2.2.1 Crop production

Crop production is a significant contributor to greenhouse gas emissions, primarily through the release of nitrous oxide (N_2O) from soils and the loss of soil organic carbon (SOC). N_2O emissions from agricultural soils in the EU amounted to approximately 156 $MtCO_2e$ in 2020 (EEA 2022a). They are mainly associated with the use of synthetic fertilisers and can be decreased by optimizing fertilization practices, through a precise selection of the fertiliser doses and direct land application methods. These measures can result in emission reductions by between 13% (Smith et al 2013) and 20% (Roe et al 2021).

Regenerative agricultural practices offer multiple options for mitigating emissions in crop production. The use of legume crops or pastures in rotation instead of nitrogen fertilisers promotes slow release and efficient utilization of organic nitrogen by growing plants. Minimum tillage practices can also minimise organic matter breakdown and N_2O release. Technological options, such as nitrification inhibitors, are also available and can reduce nitrate leaching and N_2O production. Roe et al. (2021) estimate the cost-effective mitigation potential from improved nutrient management in the EU to be around 19 Mt CO_2e/yr.

In addition to N_2O emissions, crop production results in CO_2 emissions from mineral and organic soils. Emissions from histosols constitute the bulk of EU's cropland CO_2 emissions and are discussed in section 2.2.4. The loss of SOC from mineral soils is responsible for the emissions of approximately 10,2 Mt CO_2e (EEA 2023), with about 45% of mineral soils in Europe estimated to have low to very low organic carbon content due to intensive management practices. Several carbon farming practices, such as cover cropping, improved crop rotations, conversion from arable land to grassland and organic farming, have the potential to maintain and improve SOC levels (McDonald et al., 2021). Estimates for additional SOC sequestration in EU croplands range from 9 Mt CO_2eq/year (Frank et al., 2015) to 70 Mt CO_2eq/year (Roe et al., 2021).

It should be noted that, compared to other carbon farming practices, the mitigation potential of SOC sequestration in croplands and grasslands is more limited and uncertain, and feasible mitigation potential may be more constrained (Batjes, 2019). In addition, the monitoring, reporting and verification of carbon removals in soils remains a challenge given the dependence of sequestration potential on local context (including water and nutrient availability, soil type, climate and management conditions), and uncertainties relating to the limited understanding of factors that influence SOC quantity and stability (COWI, Ecologic Institute & IEEP 2021).

Three carbon farming inventory projects presented below showcase innovative efforts to enhance the sustainability of crop production. They encompass advancements such as electric agroecological robots, digital technologies for optimized resource use, innovative decision support tools, and enabling value chain solutions.

Box 1: SWARM - Cultivating crops with a fleet of electric agroecological robots that preserve the soils

The **SWARM** project aims to bring to market the first collaborative electric agroecological equipment, providing an alternative to heavy thermal tractors that are responsible for soil compaction and significant CO_2 emissions.

SABI AGRI, supported by the European Innovation Council Accelerator programme, is a French designer and manufacturer of agroecological equipment. With the use of the project grant, SABI AGRI is developing a new generation of multipurpose robots for field crops and vineyards.

SWARM consists of a fleet of lightweight vehicles where one ALPO Electric Tractor and up to four ZILUS robots work together to perform all agricultural tasks. When operating the tractor, the farmer performs all crop-related tasks and controls the robots, which carry out the same or complementary tasks. SWARM allows to multiply work capacity and alleviate the ground pressure up to 15 times compared to thermal tractors.

By combining lightweight electric vehicles and the use of best agricultural practices (e.g. shallow soil cultivation, permanent cover) the project facilitates the agroecological transition and supports ecosystem services such as soil preservation and fertility, climate change mitigation, preservation of field biodiversity and others.

SABI AGRI will scale-up the agroecological collaborative robotic technology and industrialize the SWARM before market uptake in the EU and the US.

Box 2: PestNu - Field-testing and demonstration of digital and space-based technologies with agro-ecological and organic practices in systemic innovation

The **PestNu** project aims to field-test and demonstrate digital and space-based technologies and agro-ecological and organic practices (AOP), under a systemic approach to reduce the pesticides and fertilisers use, and loss of nutrients. It will develop real-time nutrient analysers and use Copernicus data to map soil and plant nutrients and pests, interconnecting the technology to a user-centred cloud agricultural management system.

Novel digital and space-based technologies brought by the consortium include: AI robotic traps for real time pest monitoring, autonomous mobile robots for pesticide monitoring and 3D spot spraying; Earth Observation missions with robust Agroradar AI algorithms to map soil/plant nutrients and pest plant inputs using Copernicus data/services, and in-situ and real-time nutrient analysers. All these technologies will be interconnected to a user-centric cloud-based Farm Management System, which features a robust Decision Support System integrated with a blockchain based system for DST data evidence, integrity and AI models verification and with a cybersecurity platform.

The agro-ecological and organic practices that will be tested include: on-site production of biofertilisers from agricultural waste-waters via an innovative enzymatic hydrolysis procedure, a novel foliar biopesticide formulated by circular bioeconomy operations, targeting fungal diseases with biostimulant effect, and advanced nutritional programmes for organic farming.

The solutions will be demonstrated and tested in aquaponic and hydroponic greenhouse and open-field vegetable cultivation in Greece and Spain.

Box 3: ReMIX - Redesigning European cropping systems based on species MIXtures

The aim of the **ReMIX** project was to analyse and optimize the functioning of species mixtures, also called intercrops, in order to help design sustainable and diversified cropping systems for both conventional and organic agriculture. The studied species mixtures were mainly cereals and grain legumes. Eleven multi-actor platforms were set up in ten countries in order to demonstrate potential performance of species mixtures, taking into consideration the local conditions and the social and economic context in which farmers operate.

Several knowledge syntheses, new experimental and modelling studies have been carried out to determine how plant traits (e.g. root architecture and canopy morphology), cropping practices (e.g. plant density), and environment (availability of N, P and water, light quality) influence the performances of species mixtures as compared to sole crops for the capture of abiotic resources and the control of animal pests, diseases and weeds. Novel ideas and specific concepts were developed in order to support breeding for intercropping. To the extent possible, the project aimed to convert scientific results into practical tools and synthetic information disseminated not only to farmers, advisors, and other farming sector stakeholders, but also to policy makers.

Based on the findings and results of the project, a practical toolbox for achieving best practices in intercropping was assembled by the project team. It includes, for example, specific guidance on the proper settings for using combined harvesters during intercropping, an array of decision support tools, educational materials, an ecosystem services assessment tool, and an interactive intercropping game.

Box 4: Operational Group HANFANBAUER WERRA-MEIßNER

The **OG Hanfanbauer Werra-Meißner** project aims to establish a complete regional value chain to support hemp cultivation. Hemp has been receiving an increasing amount of attention, given its possible application in environmentally friendly industrial products such as bio-concrete, bio-composite, paper, textile as well as its carbon sequestration and water conserving properties (Faiz Ahmed et al. 2021).

However, there are several obstacles faced by farmers interested in hemp cultivation given the relatively undeveloped value chains. In Germany, few suitable hemp varieties are available, and high transport costs and long transport routes impair the economic viability of hemp cultivation. In addition, various requirements must be met in terms of conveyor technology, drying and storage, and the technology adapted for the already established varieties requires retrofitting.

The project include a range of activities which aim to respond to these challenges, including: field trials on optimal site conditions for hemp seed and straw, development of capacities for the pre-processing of hemp straw to reduce transport costs to the processing partner, modification of harvesting machines adapted to the pressing of hemp straw in cooperation with an agricultural machinery company, development of hemp seed processing methods for specific uses (seeds, animal feed, baked goods, insulation materials), and development of own sales structures for the marketing of hemp products.

Notably, the project responds to the key challenge associated with high transport costs by minimizing the transport volume of the hemp straw to such an extent that an economic benefit can be achieved for the hemp growers. This is done by pre-processing the hemp fibres after harvest by separating shives from the fibre, resulting in a reduction in transport volume by 80%.

The success of the project is a result of farmer collaboration, with machinery rings and workshops as well as the regional advisory centres contributing their expertise and facilities.

2.2.2 Livestock production

Livestock production has a significant climate impact, primarily due to enteric fermentation occurring in the digestive systems of ruminant animals, which is the largest source of emissions from agriculture. In 2020, methane emissions from enteric fermentation reached 181 Mt CO_2e (EEA 2022a). Manure management constitutes another large source of agricultural emissions, estimated to have contributed to the emissions of approximately 63 Mt CO_2e in the EU in 2020 (idem.). Methane emissions represent around two-thirds of emissions from manure management, with 52% coming from cattle; 47% from pigs, and 1.4% from sheep (idem.). Emissions of nitrous oxide are responsible for the remaining one-third of emissions from manure management.

The guidance provided to Member States for updating the 2021-2030 National Energy and Climate Plans (NECPs) suggests specific measures to decrease methane emissions stemming from enteric fermentation. This guidance emphasizes the implementation of breeding incentives that enhance animal health and fertility, effective feed management, and the use of feed additives. Furthermore, the NECPs guidance advises the promotion of various manure storage techniques to minimise emissions related to manure management, such as cooling slurry, acidification of slurry, covering manure and slurry stores, implementing emission limit values, and imposing monitoring requirements. In addition, the adoption of anaerobic digestion with biogas recovery as a means to mitigate methane emissions from manure management is recommended.

Research suggests that carbon farming practices on livestock farms could reduce their emissions by 12-30% by 2030 (COWI, Ecologic Institute, and IEEP 2021), corresponding to an annual potential mitigation of 26-66 $MtCO_2e$. Mitigation potential differs widely across different livestock farm types and locations, with confined and high-intensity systems better suited to implementing feeding regimes including additives or manure management options, and smaller farms better positioned to draw mitigation benefits from efficiency and carbon sequestration measures (Jia et al. 2019).

In the context of extensive livestock production, grassland management and grazing practices have implications for the maintenance of SOC in mineral soils. Practices with the highest mitigation potential include maintaining grassland without ploughing up and the management of grazing land and grassland e.g. by optimising stocking densities or grassland renovation. It is estimated that grasslands in the EU could feasibly sequester 27 $MtCO_2e$ per year at a cost of less than USD100/t (Roe et al. 2021). It should be noted that transitioning between extensive and intensive livestock production methods does not offer straightforward solutions given the trade-offs between higher carbon intensities and broader environmental impacts.

Considering the significant climate impacts of livestock production, it is important to note that achieving the necessary emissions reductions requires not only the implementation of innovative technologies, but also a reduction in livestock populations, particularly cattle (Smith et al. 2021). Importantly, the livestock sector should avoid a trajectory whereby the promotion of innovations allowing for incremental reductions in emissions leads to socio-technical lock-in, hampering the broader transition that is required in terms of production and business models, as well as consumption patterns.

Two projects highlighted below provide examples of innovation relating to livestock farming, including technological solutions for methane abatement, novel contractual arrangements, and circular solutions for improved carbon sequestration and sustainability of livestock systems.

Box 5: CANMILK

The EU-funded **CANMILK** project aims to develop simple-to-use, low maintenance technology for methane abatement with the use of non-thermal plasma. The project's goal is to deliver dedicated equipment for dairy and meat cattle barns that can convert methane captured from barn air into carbon dioxide.

CANMILK aims to utilise non-thermal (cold) plasma, otherwise commonly used in e.g. fluorescent lamps and ozone generators, in a novel application to support methane emissions conversion to carbon dioxide with an estimated efficiency of 90%. The resulting conversion of methane is predicted to reduce the climate impacts of milk production by an estimated 30–40%. The work is focused on methane activation by plasma-derived oxygen or hydrogen species, which enable methane decomposition with the help of catalysts in mild conditions. The project team expects to develop: 1) simple and efficient equipment for methane abatement in dairy and meat cattle barns, 2) a good view of the socio-economic and environmental feasibility of plasma-based methane abatement, and 3) increased public, scientific and industrial awareness of feasible solutions available for GHG abatement in agriculture.

The project aims to develop a technology with a high potential for commercialisation and affordable for farmers, with expected cost of EUR 80 per tonne of CO_2eq.

Box 6: Arla Foods' Sustainability Incentive model

Arla is a farmer-owned cooperative comprising over 8,900 farmers from Belgium, Denmark, Germany, Luxembourg, Sweden, the Netherlands and the United Kingdom, with ownership of over 1.5 million dairy cattle.

In 2020, the company began annual data collection under its Climate Check initiative, which features over 200 questions on subjects such as feed, energy use and manure management, and allows for the calculation of the carbon footprint of milk production on Arla farms. Participation in the scheme is voluntary for conventional producers and mandatory for organic producers, with farmer owners paid an incentive on their milk price to complete the Climate Check survey.

Building on the Climate Check tool, Arla has introduced a point-based Sustainability Incentive model to help fund and motivate actions required to hit its 30% emissions reduction target by 2030 against a 2015 baseline. Under this model, farmers can collect points based on their environmental sustainability activities under 19 different levers. Levers with the biggest potential to reduce a farm’s carbon footprint (including e.g. feed efficiency, fertiliser use, land use, protein efficiency, sustainable feed) are associated with a higher total amount of points available. Not all levers have a direct influence on the farm's carbon footprint.

The model currently allows farmers to score of maximum 80 points, but more options for sustainable actions will be built into the scheme over time, with a maximum of 100 points to be made available in the future. Farmers will receive 1 eurocent per kilo milk for submitting climate check data, which is the prerequisite for receiving the sustainability incentive, and, in addition, they will receive 0.03 eurocent per kilo milk per point awarded in the sustainability incentive model. In the first full year, at least 270 million euro is expected to be distributed through the monthly milk price with an estimated average of 39 points scored.

Box 7: SURFOLY - Sustainable ruminants feed with olive pomace and polyphenols enriched charred olive stone

SURFOLY aims to demonstrate and promote an innovative circular business development model for the production of animal feed for small ruminants (sheep and goats) while supporting mixed crop-livestock systems and the olive industry in the Mediterranean area.

The new feed formula contains olive oil by-products (pomace, stone and polyphenols from wastewaters) utilised in an innovative way to improve product quality and reduce the life cycle environmental impact of the system (olive mill - feed manufacturer – farm). Pomace from olive mills is either centrifuged (three-phase process) or dried (two-phase process). Olive stones and dried pomace are then pyrolyzed in a regenerative rotary kiln to obtain biochar which is used to reduce the COD (Chemical Oxygen Demand) of olive mill wastewaters by absorbing polyphenols, hence reducing significantly the polluting impact of their use as a fertiliser or disposal. The polyphenol enriched char has antioxidant potential and can reduce methane emissions from ruminants – it is added to dried pomace to produce a nutrient mix which is subsequently pelletised and used as ingredient in the new formula for sheep and goats. Where small ruminants fed with the developed formula are allowed to graze in olive orchards, digested biochar is released back into the fields, improving carbon sequestration.

The project will produce experimental data, currently not available in the literature, on various aspects such as biochar quality, efficiency in the removal of polyphenols from wastewaters, the energy and economic sustainability of the pyrolysis process of solid mill residues. There is also potential for positive economic impacts from the uptake of the developed processes by farmers given the competitiveness of biochar production.

2.2.3 Agroforestry

Agroforestry systems, which involve the integration of woody vegetation with crop and/or animal systems, play a vital role in carbon storage both above-ground and in soils. These systems cover approximately 8.8% of the EU's agricultural area, with a concentration in the Mediterranean and southeast Europe (Burgess et al., 2018). In the EU, silvopastoral agroforestry systems, which integrate animal grazing or fodder production with trees or woody perennials, are more widespread compared to silvoarable agroforestry systems, which involve combining arable or horticultural crops with trees.

A wider shift to agroforestry in the EU offers high climate mitigation potential, estimated by Kay et al. (2019) to be in the range of 7.7 – 234.8 $MtCO_2$/yr. The total sequestration potential is likely to be higher, as this estimate does not include below-ground soil organic carbon (SOC), the stocks of which have been shown to be larger under agroforestry systems compared to conventional arable land (Upson and Burgess 2013). Agroforestry can also contribute to reducing nitrogen-related emissions and increasing resilience against climate impacts by improving microclimate and enhancing drought resistance (Aertsens et al. 2013).

The adoption and expansion of agroforestry face various constraints, including the permanent nature of the change, legal and economic implications, uncertainties for farmers, and the need for specific knowledge and skills. Consequently, the uptake of agroforestry measures under the 2014-2020 Common Agricultural Policy has been limited.

The monitoring, reporting and verification of carbon benefits of agroforestry projects is also particularly challenging. Assessing carbon storage in above-ground biomass can be relatively cost-effective using methods employed in afforestation projects based on observable characteristics (Bey et al., 2021). However, measuring soil carbon in agroforestry is challenging and costly due to the heterogeneity of soil organic carbon stocks, particularly at small scales within a single land parcel. Protocols for calculating soil organic carbon are not yet robust enough for implementation in result-based schemes for agroforestry (COWI, Ecologic Institute & IEEP 2021). The wide variability of carbon sequestration outcomes across different geographies and vegetation types, as well as the challenges in capturing changes beyond natural variability, further contribute to significant uncertainties in establishing a credible MRV system for agroforestry (ibid.). Additionally, there is a need to accurately account for the GHG emissions resulting from soil disturbance associated with the introduction of agroforestry.

Below, we present an example of a project which aims to address some of the challenges associated with agroforestry GHG-related MRV, while devising possible climate finance solutions to support a more widespread adoption of agroforestry.

Box 8: TREES4CLIMA - Enabling carbon accounting of trees on farms for agroforestry-based climate action

The EU-funded **TREES4CLIMA** project will develop and test cost-effective methods to detect and classify agroforestry systems, facilitate carbon accounting, and enable innovative environments for climate finance.

The aim of this project is to develop and field-test robust, cost-effective approaches to account for carbon in agroforestry systems and create innovative mechanisms for climate finance in this area. Three working packages will contribute to filling the existing gaps: WP1) Accessible detection, classification, and representation of agroforestry systems; WP2) Development of methods for rapid, non-destructive quantification of carbon in agroforestry; WP3) Enablement of novel environments for agroforestry-based climate finance. The combination of accessible tools and robust methods to facilitate carbon accounting in agroforestry with climate finance mechanisms will provide for a strong multidisciplinary approach to catalyse agroforestry-based climate action.

2.2.4 Peatland management

Peatlands are a hugely important carbon sink, estimated to store four to five times as much carbon as trees in the EU (Swindles et al. 2019). The ongoing drainage of peatlands for agricultural use in the EU releases significant amounts of CO_2 and N_2O, reaching approximately 220 Mt CO_2e per year (Greifswald Mire Centre et al., 2019). Climate mitigation measures to reverse this trend can include preserving existing peatlands to avoid emissions (including through paludiculture), by rewetting and restoring drained peatlands, or by adapting the management of drained peatlands where they cannot be rewetted.

Peatland rewetting is a highly effective climate mitigation measure on a per hectare basis, estimated to contribute to avoided emissions in the range of 3.5-24 t CO_2/ha annually, depending on previous land use and final state (McDonald et al. 2021). Overall, the mitigation potential associated with retiring and rewetting of peatlands in the EU has been estimated to range between 51.7 Mt CO_2e (Perez Dominguez et al. 2020) and 54 Mt CO_2e per year (Roe et al. 2021). Despite the fact that rewetting can result in a temporary rise in methane emissions, the overall benefits in terms of CO_2 savings outweigh this effect and can be mitigated through proper management practices, such as mowing and removing biomass before elevating the water table (Günther et al., 2020). Peatland restoration also results in multiple other benefits, including improved water filtration, climate resilience, erosion prevention and increased biodiversity.

The monitoring of peatland emissions is considered challenging due to the variety of peatland habitats and the numerous parameters (such as weather, vegetation, soil, and species) that influence emissions on a seasonal and annual basis. While direct measurements of carbon storage and GHG emissions at the site can yield accurate data, the associated costs can be prohibitively high (McDonald et al., 2021). In addition, peatland rewetting present challenges associated with land ownership and need to raise the water table potentially impacting several landowners.

Two examples of projects highlighted below showcase efforts to develop results-based agri-environmental schemes for improving the management of habitats on peat soils and decision support systems for peatland re-wetting.

Box 9: FarmPEAT - Farm Payments for Ecological and Agricultural Transitions

The **FarmPEAT** Programme is a locally-led pilot initiative for farmers who manage lands that surround some of Ireland's remaining raised bogs. The project trials an agri-environmental scheme across eight project sites centered on raised bogs or former raised bog areas in the Irish midland counties of Roscommon, Offaly, Kildare and Westmeath. It rewards farmers for improved management of habitats on peat soils along with other important landscape features such as eskers, field boundaries and watercourses. The programme is results-based – farmers are paid depending on the scores they achieve, with higher scores, indicating higher environmental quality, receiving higher payments.

On joining the programme, a participating farm is scored, with a corresponding payment made to the farmer. If the score increases (indicating that the habitat and environmental quality has increased) the following year, a higher payment is issued. Result indicators include terrestrial farmland habitats, watercourses and drainage features, and transitional bog habitats. Results are assessed on a scale of 0 to 10 using habitat scorecards adapted to the target habitats and features.

If a farmer wishes to undertake measures to improve the farm score, the FarmPEAT Project Team provides advice and guidance on appropriate measures that can be taken to achieve this. In addition, the Project Team can offer financial assistance to complete these actions in the form of a Supporting Actions Payment. Neighbouring landowners who are not participant famers can take part in an Affiliate Member programme, allowing rewetting actions impacting their land to occur.

Over a period of two years, the Project Team has worked with 51 farmers, with over EUR 250,000 disbursed in results-based payments and Annual Work Plans agreed with 26 farmers to support actions to improve their environmental score. The FarmPEAT Wet Grassland Scorecard is being used by the Irish Department of Agriculture, Forestry and the Marine in the new national agri-environmental scheme, ACRES.

Box 10: Care-Peat

The main goal of **Care-Peat** is to set up and demonstrate innovative technologies for new restoration and carbon measurement techniques and involve local and regional stakeholders.

As part of the project, nature protection organisations, together with local landowners, restore peatlands at seven pilot sites ranging from 1 to 250 hectares, and demonstrate the associated carbon savings. For each pilot site different restoration techniques are used - from manual management to growing additional peat moss. Throughout the project the organisations are supported by the knowledge institutes that work together to develop and test new equipment, methods and models to predict carbon flows (e.g. by the use of drones and satellites to guide restoration and provide input into carbon models). Care-Peat also works with innovative companies in the field of restoration and develops partnerships with local and regional stakeholders to increase the impact of pilots and maximise socio-economic benefits.

The outputs of Care-Peat include the publication of a management and decision support tool and a set of socio-economic models concerning the best options for peatland restoration in regard to carbon storage. These outputs should enable the transfer of results and replication by users across North-West Europe.

As part of a 2021 extension of the project, a unified methodology for assessing GHG emissions from peatlands, applicable across different peatland types and regions in North-West Europe, is being developed to increase the impact of the decision support tool.

2.3 Discussion

Carbon farming has gained significant attention as a strategy to mitigate climate change while promoting sustainable agricultural practices. By looking at a selection of recent and ongoing projects facilitating the roll-out of carbon farming within the EU context, we discuss the innovative solutions, areas of focus, and challenges associated with this area. As the EU strives to meet its climate targets and promote more sustainable agriculture, understanding the dynamics and outcomes of these carbon farming initiatives becomes an important piece of the puzzle.

In the context of carbon farming, innovation does not solely refer to novel practices; rather, it can often involve a return to techniques employed before high-input, industrial methods came to dominate in the modern food production system. Carbon farming often draws from traditional practices, that may be described as regenerative, organic, agro-ecological or climate-smart (Muhie 2022). While many of these practices are considered to be well-established, adaptation to local conditions and a comprehensive understanding of the pedo-climatic contexts are essential for successful implementation. The prevalence of projects which include the delivery of decision support systems reflects the importance of testing and developing context-specific solutions and ensuring appropriate knowledge transfer.

The scarcity of practical, on-the-ground information to guide farmers in adopting carbon farming practices remains a challenge and the need for decision-support tools is clear. These tools should consider the differences within regions, between types of soil, the local climate, the way farms are structured, and how much it costs farmers to adopt carbon farming practices. Within most projects that aim to develop decision support systems there is a clear recognition of this need and a deliberate effort to meet this demand. However, only a limited number of DSTs allowed users to interact with the databases and upload local data to refine existing analyses and recommendations provided by the tool. There also appears to be room for enhanced coordination and more concerted efforts across the EU.

An imbalance persists in terms of the focus directed towards specific Member States, resulting in a greater emphasis on certain biogeographical regions, influencing the amount and sophistication of information available with regards to the appropriate types of measures and their effects. There remains largely a focus on Western European states, with Spain, Italy, France, and Germany each hosting ten or more projects that field-tested decision support systems. They were followed by Czechia and the Netherlands with nine projects each. In Romania and Hungary, which have the highest contribution of agriculture to their GDP among all EU Member States and some of the largest utilised agricultural area, there were four and six projects respectively.

The equitable access and use of these resources could be further impeded by the prevailing disparities in terms of internet accessibility, digital literacy, and familiarity among farmers across regions and Member States. Although all the analysed DSTs were structured for open-source online access, theoretically catering to all stakeholders interested, most were exclusively available in English, possibly constraining their accessibility for non-English-speaking users. Also, the extent to which the developed decision support systems are embraced and incorporated by a substantial number of practitioners beyond the lifetime of the project remains uncertain.

With many of the examined tools designed to facilitate similar decisions, such as optimizing soil management, the complementarity or the individual value add of these tools is not always immediately clear. To select the most appropriate tools that align with their specific needs, farmers would likely need to conduct own, more in-depth online research or seek recommendations from project developers or experts.

Notably, decision support systems designed to facilitate the uptake of more sustainable agricultural practices may compete with advice that farmers most frequently receive from advisors or sales representatives of agro-chemical companies. Advice from independent extension services, non-governmental organisations, and scientists may not reach farmers as readily as it is not always a well-resourced core part of their business (Kleijn et al. 2019). It is not always clear if the independently developed decision support tools are sufficiently competitive to support farmers who are used to relying on agricultural input providers and other commercial advisors.

The majority of projects that facilitated the development of decision support systems included an economic evaluation aspect, often integrated directly into the DSS. However, the extent and level of detail concerning the parameters impacting farm profitability varied. Yield and income variability is a major concern for farmers, which must be taken into account in the promotion and development of a scientific evidence base for carbon farming practices and their benefits. Despite the relatively large number of decision support systems being developed, there remains room for more sophisticated tools with the capacity to communicate both direct and opportunity costs, as well as the environmental effectiveness and yield variables associated with different practices and scenarios.

The analysed sample of projects indicates that a variety of promising technologies are currently in different phases of development, holding the potential to drive resource efficiency and enhance sustainability of both crop and livestock production. To guarantee sustainability outcomes, complementary measures are essential to prevent the potential gains being offset by increased production volumes in farming systems that exert the greatest negative impacts on climate and biodiversity. Smallholder and other farmers with limited financial resources may also have a much more limited access to advanced equipment and technologies, creating potential equity challenges. It is important that the cost of accessing new technological developments is not prohibitive to smaller and less affluent businesses and does not effectively result in the widening of inequalities within the sector across the EU.

Overall, while considerable efforts are dedicated to innovation promoting more sustainable crop production and less GHG-intensive livestock management, agroforestry and peatland management have received relatively less attention to date. Despite the significant mitigation potential and a wide range of other environmental benefits associated with agroforestry and peatland rewetting, there have been relatively few projects developed with a primary focus on those practices. However, they are receiving an increasing amount of attention, with a few more recent Horizon Europe projects that are yet to be completed holding promise for the development of financing, policy and MRV mechanisms, particularly in support of a more widespread roll out of agroforestry in the EU. These projects tend to be quite comprehensive in their outlook, considering a range of challenges and looking to support both policymakers and practitioners. However, some areas, such as paludiculture, remain relatively unexplored – while initiatives are currently emerging in some Member States to address this gap, there continues to be a scarcity of cross-national research in this area. A more concerted effort would be needed to promote innovation in agriculture on organic soils, taking into account the particular challenges of collective rewetting, opportunity costs of more sustainable peatland management, and the market for paludiculture products.

A key obstacle to the widespread adoption of carbon farming practices is the associated financial uncertainty and the perceived risk to farms' bottom line. Research into farmer behaviour has consistently shown that short-term economic benefits enhance the adoption of more sustainable agricultural practices (Liebman et al. 2016, van der Horst 2011) This suggests a need for improved incentives, facilitated through enhanced contract models and tailored financial instruments. There are examples of publicly funded initiatives that delve into this issue and offer innovative solutions, ranging from specific approaches tailored to local conditions to more high-level efforts to refine contractual frameworks for delivering public environmental benefits. Notably, large private sector entities are increasingly developing their own initiatives aimed at their supplier base, seeking to lend credibility to their corporate commitments. Ultimately, the influence of these initiatives remains uncertain, as does the extent to which they bring about significant reductions in emissions. However, the fact that multinational companies (including those beyond the scope of the analysed sample) are actively gathering detailed data on farmer suppliers may indicate that there is scope for policy development based on more ambitious reporting requirements, drawing on private sector frameworks and experiences.

The analysed initiatives include efforts to bring innovation into play to better support policy development for carbon farming. Most of the decision support systems developed as part of the analysed projects are designed in a way that enables policymakers to draw benefits from them. Among those, some specifically target policy and other decision makers. They focus on easily understandable land management strategies and the trade-offs between different approaches in this context. Alternatively, they may take a broader view, considering value-chain dynamics and perspectives related to the food system, for instance, in the examination of legume supply chains and the supply-demand transformation needed for more sustainable modes of agricultural production.

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