Teagasc Carbon Conference

"Counting Carbon: Science and Practice"

20th June 2024

Teagasc, Ashtown Research Centre, Dublin 15

Agriculture and Food Development Authority

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Carbon Conference

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Table of Contents

Programme

"Counting Carbon: Science and Practice"

10.00am **Welcome address**
Prof. Frank O'Mara, Director of Teagasc

10.10am **Opening address**
Charlie McConalogue, T.D., Minister for Agriculture, Food & the Marine

Keynote Speakers

10.20am **EU Carbon Farming Framework & Certification**
Christian Holzleitner, DG Clima, European Commission

10.40am **Carbon sequestration - A question of scale**
Giulia Bondi, Teagasc, Johnstown Castle

11.00am **Q&A**

Session 1:

"Counting Carbon - The Science"

Chaired by: *Karen Daly, Teagasc, Johnstown Castle*

11.15am **Counting carbon on mineral soils**
Rachael Murphy, Teagasc, Johnstown Castle

11.30am **Counting carbon on agricultural peat soils**
Dr Matthew Saunders, Trinity College Dublin

11.45am **Forestry carbon accounting**
Junliang Zou, Teagasc, Johnstown Castle

12.00pm **Farm carbon stocks monitoring, reporting and verification**
Stuart Green, Teagasc, Ashtown

12.15pm **Q&A**

12.45pm *Lunch & Poster Viewing*

Session 2:

"Counting Carbon - The Practice"

Chaired by: *Stan Lalor, Director of Knowledge Transfer, Teagasc*

1.30pm **Development of an Irish Carbon Farming Framework informed by stakeholder engagement**
Bernard Harris, Department of Agriculture Food and the Marine

1.45pm **Carbon farming and certification schemes – Lessons learned in France**
Anaïs L'Hôte, Institut de l'Elevage (idele) - French Livestock Institute

2.00pm **Pathways to climate neutral farming systems**
Jonathan Herron, Teagasc, Moorepark

2.15pm **Farming on peat soils – Experiences from FarmPEAT EIP**
Caroline Lalor & Bernard Duffy, Farm Peat EIP

2.30pm **Q&A**

2.50pm **Stakeholder Panel Discussion**

3.20pm **Closing Address**
Karl Richards, Teagasc, Virtual Climate Centre

Speaker Biographies

Anaïs L'Hôte – *Project Manager at Idele, French Livestock Institute*

Anaïs holds a Master's degree from AgroParisTech. After a final-year internship in the field of agricultural development in Armenia, she worked at the French grassland association and then she joined the environment department of the French Livestock Institute in 2021. Anaïs has managed the European LIFE Carbon Farming project for two years.

Bernard Harris – *Department of Agriculture, Food and the Marine (DAFM)*

Bernard Harris is an Agricultural Inspector in the Climate Change and Bioenergy Policy Division of DAFM working in the development of sustainable agricultural policy on climate change and bioenergy policy and supports the development of national, EU and International policies, strategies and programmes related to these issues. He has experience across several environmental policy areas including water and air quality. Bernard has collaborated across departments, agencies, external stakeholders and with EIT Climate KIC on the Deep Demonstration Project for Sustainable Food Systems in Ireland. Bernard holds a degree and masters in Agricultural Science both from University College Dublin.

Bernie Duffy – *Umeras Local FarmPEAT Officer*

Bernie farms 48 acres outside Monasterevin, Co Kildare. He has a background in computer programming, but currently has a farming system in fattening store lambs and hay production. On a small farm he has time for other work which included assisting the late Dr. Anne Behan to prepare Environmental Impact Studies. He is a member of Umeras Community Development who are working to turn part of Umeras Bog into a local amenity and a Blueway Tourist attraction. Bernie is a key member of the FarmPEAT Project Team acting as a local FarmPEAT Officer to help with the implementation of the project in Umeras and also contributing to the design of the overall project. Bernie has represented the FarmPEAT Project at many meetings and gave a presentation at a conference in Germany on Restoring the Fens and their Economic Potential to share the FarmPEAT approach.

Caroline Lalor, *BSc. MSc. MCIEEM*

Caroline is an ecologist with a strong interest and professional experience in Peatland Ecology. She has 19 years' experience working in nature conservation, impact assessment, ecological monitoring and ecological education. Based in Offaly, she has contributed to a variety of projects including habitat mapping projects, NPWS Monitoring Surveys, ecological surveys for existing and proposed Wind Farms and educational projects. Caroline was project lead on the UCC Pilot Biodiversity Survey 2014-2018 and she developed the first UCC Biodiversity Action Plan. She also worked with University College Cork as co-ordinator and lecturer on the Field Ecology Diploma course from 2011-2017. Caroline has a strong interest in agriculture in Ireland and how farmers interact with the landscape. Caroline has been working as Project Manager of the FarmPEAT Project since April 2021.

Christian Holzleitner

Christian Holzleitner is currently Head of Unit responsible for *Land economy and Carbon removals* at the European Commission's Directorate-General for Climate Action. Previously, he worked as Head of Unit for *Finance for Innovation and Land Use* and assistant to the Director-General for Climate Action covering all issues related to EU and international climate policy; and at the Directorate-General for Competition in the area of State aid for services of general economic interest in the postal, transport, and health sectors. Before joining the European Commission, Christian worked as senior manager with KPMG Germany on international transfer pricing. Christian is an economist and holds a PhD from the University of Linz (Austria).

Giulia Bondi – *Senior Research Officer, Teagasc*

Giulia Bondi is a Senior Researcher at Teagasc, specializing in soil carbon sequestration and dynamics. She leads the Soil Deep Sampling Campaign of the Signpost Programme, focusing on carbon sequestration monitoring across various climates, soil types, and agricultural practices in Ireland. Giulia has managed research activities and funds for national and European projects, including the EJP-Soil (European Union's Horizon 2020) project ICONICA. Over the years she has established an international network of collaborators and published extensively in top scientific journals. Currently, her research supports agricultural policies, and she actively disseminates her findings to multiple stakeholders.

Jonathan Herron – *Research Officer, Livestock Systems, Teagasc*

Jonathan Herron is a Researcher Officer in the Livestock Systems Department of Teagasc Moorepark. He is one the lead researchers in the development of the AgNav sustainability Platform in collaboration with ICBF and Bord Bia. He supervises a team of PhD students and post-doctoral researcher in the areas of life cycle assessment, bio economic modelling, and integrated farming systems. He has a number of publications in the area of life cycle assessment and has recently secured funding from the Department of Agriculture Food and the Marine for the continued development of the AgNav platform to expand the scope of the assessment to include all major agricultural systems and environmental impact categories.

Junliang Zou – *Teagasc Johnstown Castle Research Centre*

Junliang Zou is a Researcher Officer at Teagasc, focusing on estimating the impacts of afforestation and forest management, and climate change on carbon sequestration and greenhouse gas emissions. His work employs a variety of approaches, including model and broad-scale data synthesis, observational studies, and field experiments. In particular, his research has concentrated on ecosystem carbon cycling and the effects of climate change. He has worked on a rage of projects and published over 40 peer-reviewed papers on these topics.

Karl Richards – *Head of Climate Centre, Teagasc*

Karl Richards is a Senior Principal Researcher Officer at Teagasc. He leads the newly established virtual Teagasc Climate Centre. He led a team of researchers in the area of nitrogen cycling including the impact of management practices on reducing Nitrogen losses (nitrous oxide, nitrate leaching and ammonia). He has published extensively on measures to reduce nitrous oxide and nitrate emissions, including leading the protected urea research that commenced in 2012. Internationally, he has worked on a range of Internationally funded competitive research projects, was a member of the EU Nitrogen Expert panel, a national representative on the Global Research Alliance and has published over 180 scientific papers.

Matthew Saunders

Matthew Saunders is an Assistant Professor in Plant Ecophysiology, in the Trinity College Dublin, School of Natural Sciences, Botany Discipline. He specialises in the field of plant and environment physiology, in particular how plants respond to changes in their physical, chemical and biological environments and how this information can be used to assess the resilience and adaptive capacity of terrestrial ecosystems to global environmental change. This work utilises an integrated experimental and model-based approach to assess the physiological and environmental processes that regulate plant productivity, carbon sequestration, greenhouse gas dynamics, plant-water relations and energy budgets at the leaf, whole plant and ecosystem scale. Recent projects have focussed on the impacts of peatland restoration, afforestation and extreme climatic events on carbon, water and greenhouse gas dynamics in both temperate and tropical climates. This work has directly contributed to the development of policy relevant, sustainable land management tools that are centred on the role of terrestrial ecosystems in climate change adaptation and mitigation.

Rachael Murphy – *Research Officer in Measuring and Modelling Carbon Emissions and Sequestration*

Rachael Murphy is a research officer in Teagasc Johnstown Castle and the Teagasc Climate Centre. Her principal role involves over-seeing the management and data of the National Agricultural Soil Carbon Observatory (NASCO). Her research expertise is in measuring greenhouse gases on agricultural soils at different temporal and spatial scales with a specialization in using the eddy covariance technique.

Stuart Green – *Senior Research Officer, Teagasc*

Stuart is the remote sensing specialist in the spatial analysis department in Teagasc. His main research interest is in using terrestrial earth observation technologies to understand issues important to rural Ireland and Irish agriculture. He has produced many nationally important data sets around land cover maps, soil maps and new methods for estimating grass growth remotely. Stuart has extensive experience managing research projects and has collaborated with several third-level institutes. He established the Irish earth observation symposium in 2007 and it's now an annual event with over 150 attendees.

Foreword

Welcome to the Teagasc Carbon Conference.

Worldwide, Ireland is recognised for producing high quality food with a very low carbon footprint i.e. greenhouse gas (GHG) emissions per unit of product. Nevertheless, the industry is a major emitter, with the agriculture sector alone making up ~38% of our national GHG emissions. Currently, the sector is tackling the major challenge of staying within the sectoral emission ceilings established for it in the National Climate Action Plan.

The third iteration of the Teagasc marginal abatement cost curve (MACC), published in mid-2023, set out the most cost-effective pathways to reduce GHG emissions and enhance carbon removals in the agriculture, land use and bioenergy sectors. The Teagasc MACC 2023 shows that there is a pathway for the agriculture sector to meet its emission targets for 2030. However, it requires a very high adoption of currently available mitigation measures and emerging technologies. To accelerate adoption of these measures, carbon farming is increasingly being proposed as a possible solution.

Carbon farming has become more prominent within Irish and European policy in recent times and we are delighted to have three speakers on this topic. The concept of carbon farming is quite new in Ireland. In Europe, it is typically described as a green business model to reward farmers and land managers for limiting climate change through increasing carbon removals and cutting GHG emissions from soils. During this conference, our speakers will investigate innovative approaches to farming carbon. They will bridge the gap between theory and application in carbon counting by delving into the science and practice behind this important facet of sustainable agriculture.

The new Teagasc Virtual Climate Centre has put significant resources, in terms of staff and equipment, into the counting of carbon removals and emissions. With the support of the Department of Agriculture, Food and the Marine, cutting-edge technologies are now in place throughout the country to quantify carbon fluxes in real-time for various soil types and land use categories. We will learn about the progress that has already been made in measuring and mitigating carbon in our first session. We will also see how Teagasc is accelerating efforts to bring "almost ready" and "early stage" technologies to the deployment stage by co-ordinating research programmes across Teagasc, as well as with others institutes in Ireland and abroad.

Teagasc is translating much of this research into practice through the Signpost Programme. Signpost demonstration farmers are applying mitigation technologies and are calculating greenhouse gases with the new sustainability digital platform, AgNav. This platform is currently being built by Teagasc, Bord Bia and the Irish Cattle Breeding Federation (ICBF), and with the support of the Department of Agriculture of Food and the Marine. AgNav will facilitate robust whole farm sustainability assessments and in time contain measures to enhance carbon removals. It will provide advisors and farmers with decision support tools for improving carbon and address wider environmental goals to reduce ammonia emissions, improve water quality and increase biodiversity.

The Signpost Programme, AgNav and the Virtual Climate Centre will together provide reliable scientific solutions to lead the Irish agricultural and land use sectors towards climate neutrality by 2050. New technologies will emerge from ongoing research to meet this target. The penultimate paper of our conference looks at how new and existing technologies could be used to develop pathways to climate neutrality for common Irish farming systems.

Finally, I wish to thank all of the chairpersons and speakers who have contributed their time to make our conference what it is today. I express my gratitude to my Teagasc colleagues for their hard work in putting together and arranging this conference, which tackles very important issues and prospects facing Irish agriculture today. I hope after attending the conference you will have a better understanding of counting carbon on farms.

Professor Frank O'Mara, Director, Teagasc

Overview of the Teagasc Climate Centre

K. Richards
Head of the Teagasc Virtual Climate Centre

The Teagasc Climate Centre, established in December 2022, is a virtual centre to co-ordinate agricultural climate and biodiversity research and innovation across Teagasc. It will accelerate efforts to develop and implement technologies to reduce greenhouse gas emissions and enhance biodiversity. The Climate Centre will support and facilitate the Irish agriculture sector to meet its commitments in reducing greenhouse gas emissions and restoring biodiversity. The Climate Centre has expanded the research infrastructure and human capital in Teagasc to meet the increased demand for practical, effective and affordable solutions for farmers. The centre is working with national and international organisations and institutions to create effective and trusted partnerships.

In its first year, the Centre has produced a new Marginal Abatement Cost Curve (MACC) report for the agriculture, land-use and bioenergy sectors. This report identified a pathway for Agriculture and Land-use to achieve the sectoral targets set in the National Climate Action Plan. A roadmap for the implementation of the MACC is being considered by Government for the Agriculture and Land-use, Land-use change and Forestry sectors in the Climate Action Plan 2025.

Climate Centre Objectives

- Enhance Ireland's international reputation as a leader in sustainable agriculture research and innovation.
- Produce high quality research and innovation in the area of climate change and biodiversity to enable the Irish agriculture sector meet its commitments.
- Provide a central independent focal point in Ireland for the co-ordination and dissemination of agricultural climate change research and innovation.
- Inform policy makers with the required robust science and technology to be more responsive to the emerging needs associated with climate change.
- Collaborate with both national and international institutes in the area of climate change and biodiversity research and innovation.
- Build research infrastructure and human capital to support the agricultural sector meeting the National climate and biodiversity commitments.

Climate Centre Structure

The Climate Centre has eight Research Pillars surrounding the Signpost Programme focusing on Knowledge Transfer to increase mitigation measure adoption at farm level (Fig. 1). Each of these pillars focuses on reducing overall greenhouse gas emissions, enhancing carbon sinks and enhancing biodiversity on Irish farms.

Figure 1: The structure of the Teagasc Climate Centre.

There is considerable research underway within the Climate Centre on reducing carbon dioxide (CO_2) emissions and enhancing Carbon (C) sinks on Irish farms. The Centre has established four new national infrastructures to support the research programme.

1. The National Agricultural Sustainability Research and Innovation Centre based at Johnstown Castle (Fig. 2). This is a multi-million euro investment in state of the art research facilities to support the environmental and climate research programme across Teagasc.
2. The National Agricultural Soil Carbon Observatory: Network of 28 eddy covariance towers that are established across a wide range of soil types, land-uses and land management practices.
3. The SFI funded National Soil Greenhouse Gas Test Platform, which is a high resolution, automated infrastructure to examine the efficacy and derive emission factors for a range of fertilisers and additives to soils.
4. A large number of Green Feeds, across the organisation, for the quantification of enteric methane emissions from ruminants to evaluate the effect of feed type, feed additives, genetic variation and other management practices on emissions.

Figure 2: The New National Agricultural Sustainability Research and Innovation Centre currently under construction.

Researchers within the Climate Centre are currently conducting a wide range of research projects across Teagasc to reduce emissions, identify opportunities for diversification and increasing resilience to climate change, enhancing biodiversity and improving the sustainable circular food system. The centre works collaboratively with all Irish universities and an increasing number of universities and research institutes across the world. Working together and co-creating with farmers in collaborative multidisciplinary teams, increasing the development and adoption of measures and management practices to address the global climate and biodiversity emergency.

Further information available on **https://www.teagasc.ie/environment/climate-action/climate-centre/**

Carbon sequestration – a question of scale

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1. Introduction

Global warming is the long-term increase in the Earth's temperature due to the accumulation of greenhouse gases (GHGs) in the atmosphere, such as carbon dioxide (CO_2). Although the capacity for CO_2 to trap heat is less than that of nitrous oxide (N_2O) (global warming potential (GWP) of 265 over a 100 year timeframe relative to CO_2) and methane (CH_4) (GWP of 28 over 100 years or GWP of 86 over 20 years relative to CO_2), the production of CO_2 in the atmosphere is large. In 2022, emissions of CO_2 accounted for 60.6 % of the total national GHG emissions (excluding those from the Land-Use, Land use-Change and Forestry (LULUCF) sector), while CH_4 and N_2O accounted for 29.1 and 9.1 %, respectively (EPA, 2024). Carbon sequestration can help to reduce global warming by removing CO_2 from the atmosphere and in turn, offsetting the warming affect associated with high concentrations of CO_2 in the atmosphere. Soil carbon is important because it plays a crucial role in mitigating climate change, enhancing soil fertility, and supporting overall ecosystem health. Globally, soils contain approximately 1417 Gt of carbon, which is more than two times the amount of carbon in the atmosphere and about three times that stored in living plants. This makes soil the largest terrestrial carbon pool, highlighting its critical role in the global carbon cycle and its potential for sequestering atmospheric CO_2 (Lal, 2004). Grassland soils in Ireland store significant amounts of carbon, approximately 440 t CO_2/ha or an estimated 1,800 Mt CO_2 across all mineral soils (Paul et al., 2018). Managing soil carbon effectively can significantly reduce atmospheric CO_2 concentrations and improve agricultural productivity.

2. State of Knowledge

The Irish Scenario

The 2021 Climate Action and Low Carbon Development (Amendment) Act sets out in law Ireland's commitment to reduce overall greenhouse gas (GHG) emissions by 51% by 2030 and achieve climate neutrality by 2050. The sectoral emissions targets set by the Government in 2022 include a 25% reduction (5.75 Mt CO_2-eq) in emissions from the agricultural sector. In the Irish inventory, the second largest emissions source for the Land Use, Land-Use Change and Forestry (LULUCF) sector is grassland, which emitted 2.48 Mt CO_2-eq in 2022, consisting of 1.42 Mt CO_2/year sequestered on mineral soils and 3.90 Mt CO_2/year emitted from drained peat soils (EPA, 2024). The C dynamics in mineral and peat soils are presented in the conference papers by Murphy et al. (2024) and Saunders et al. (2024). Ireland currently uses an Intergovernmental Panel on Climate Change (IPCC) Tier 1 approach for calculating soil C sequestration on grassland on mineral soils. However, this Tier 1 approach does not fully represent Irish farming conditions or measured data, leading to uncertainty. To address this, Ireland needs measured CO_2 flux and C stock data across different soil types, management practices, and land uses. This would enable Ireland to develop Tier 2 approach that would enhance accuracy in the national inventory for land use and land management (Murphy et al., 2024).

A framework for climate-smart land management for Ireland incorporates a three-step approach to optimize carbon dynamics and mitigate climate change impacts (Schulte et al., 2016). Firstly, it focuses on maintaining existing C stocks, recognizing the crucial role of peatlands, which occupy approximately 20% of land but contain over 53% of carbon stocks, acting as hotspots for carbon sequestration. Secondly, the framework aims to prevent new emissions from emission-sensitive soils, thereby mitigating further atmospheric carbon release. This includes drained peats, or mineral soils moving from grasslands to arable, which can release significant amounts of stored carbon into the atmosphere. Thirdly, it emphasizes enhancing long-term carbon sequestration in grassland soils and through land use changes such as afforestation. This holistic approach not only prevents carbon losses but also actively promotes carbon accumulation, contributing to a more sustainable and climate-resilient land management system.

Understanding Carbon Sequestration and Carbon Stocks: Key Concepts for Climate Change Mitigation

There is often confusion between the concept of carbon sequestration and carbon stocks.

- Soil carbon stocks represent the total amount of C stored in an area, to a specific soil depth on a specific date. It is typically measured as tonnes of carbon per hectare (t C/ha).
- Carbon sequestration refers to the change in soil carbon stocks between one sampling date and another. It is the net change in soil C stock over time often referred to as carbon stock change.

Soil carbon sequestration is when carbon from the air is stored in the soil. Plants take in CO_2 during photosynthesis and store carbon in their leaves and stems. When plants die, this carbon goes into the soil. Soil microorganisms break down plant residues, releasing some carbon back into the air, but some remains in the soil (Fig. 1). Soil can reduce atmospheric CO_2 if it stores more carbon than it releases. The balance depends on land use, land management, soil type, and environmental conditions, and can shift quickly from storing to releasing carbon.

Figure 1: Schematic of soil acting as a C sink and a C source.

The typical carbon balance for an improved Irish grassland soil indicated the potential range in soil carbon sequestration ranges from 0.5 to 4 tonnes CO_2/ha per year. While Irish soils have substantial carbon stocks, the key question remains: Are we adding to or depleting these stocks? How permanent is soil C sequestration? Research shows that grasslands usually store carbon, but there is uncertainty about how much they store and how management and climate affect this.

The Challenge of Measuring C sequestration on soils

Carbon sequestration presents a significant measurement challenge due to the inherently small annual changes in carbon stocks. These annual variations are minute when compared to the vast total amount of carbon already stored in the soil. Measuring soil carbon sequestration goes beyond merely quantifying the total carbon content. Other critical factors need consideration for an efficient assessment.

- **Gold standard harmonised laboratory and field measurements:** Measuring carbon stocks is often expensive and time-consuming. Researchers are developing a standardized, efficient global method to make measurements more accurate and comparable. A gold standard method for accurate calculation of C stocks needs information on three elements, 1. depth of a soil layer, 2. a robust representative bulk density and 3. the organic carbon content of that layer (Fenton et al., 2024). An accurate measurement of soil bulk density is very important for C stock estimation. Inaccuracies can occur if bulk density is not adjusted for rock fragments or if soil core volume is not measured precisely, leading to carbon stock overestimations of up to 300% (Fenton et al., 2024).

- **Depth based approach for sampling:** Research has highlighted that substantial amount of carbon is stored in the deeper layers of soil (up to 40 t C/ha; Simo et al., 2019) with C stocks below 30 cm ranging from 18% to 30% of the overall profile C stocks (0-60 cm). Including this deep soil carbon in the monitoring schemes and disentangling these figures across soil types and management regimes, is crucial for providing a more accurate estimate. By accounting for these deep C stocks, we can integrate this value into the overall carbon budgets, ensuring that it is accurately reflected in national carbon inventories and better informs climate change mitigation strategies.
- **Carbon quality and persistence:** Soil carbon exists in different forms, each with varying stability and decomposition rates. These include: (1) Labile carbon: easily broken down by microbes, with a fast turnover of a few days to less than 5 years, (2) Physically protected carbon: encapsulated in soil aggregates, protected from microbes and (3) Biochemically protected carbon: organic compounds resistant to microbial breakdown, with a turnover of over 100 years, sometimes lasting thousands of years. The persistence of these carbon types affects how long carbon stays sequestered in the soil, which is important for understanding soil carbon sequestration and its role in mitigating climate change.
- **Soil type differences:** Soil type is important for carbon storage. Different soils can store different amounts of organic carbon, affecting their ability to act as carbon sinks. High clay content helps form and stabilize soil carbon within aggregates (Torres-Sallan et al., 2017). High clay content improves soil structure by causing soil particles to clump together, which protects organic matter from microbial breakdown. Clay particles tightly bind organic molecules, making them less accessible to microbes. Additionally, chemical bonds between clay minerals and organic matter help stabilize soil carbon. Soils with more clay often have greater potential to store carbon long-term.
- **Landscape distribution patterns:** Soil carbon content can vary significantly across different landscapes and even within the same field. Sampling schemes that do not account for this spatial variability may not provide accurate national estimates of C stocks. Furthermore, different studies may use varied methodologies for SOC content analysis, leading to inconsistencies in the data. Standardized methods are essential for obtaining accurate and comparable results.

A three pronged approach

Improving soil carbon sequestration and emissions estimates involves using a multiscale approach. This includes measuring fluxes at the field and farm levels, developing national soil carbon baselines, and using modelling techniques. This complex task requires observations across different scales and timeframes, using advanced tools and methods tailored to each scale. Initiatives like the National Soil Carbon Observatory (NASCO) and The Signpost Programme provide essential tools to enhance the accuracy of these measurements, focusing on critical elements for precise carbon stock estimates.

- **Field:** Eddy covariance towers measure gas exchange above soils, offering real-time data on carbon sequestration and release rates. Tracking these fluxes and combining with C removals helps researchers to understand how carbon is absorbed and released in fields over time.
- **National:** Accurate national baseline measurements of soil carbon and soil maps are essential. Monitoring carbon stock changes every 4 to 5 years across various land uses, landscapes, and soil types will reveal the factors influencing long-term carbon storage and stability. These baseline measurements will enhance the accuracy of flux measurements, which assess the long-term effects of changes in carbon exchange.
- **Modelling:** Computer modelling helps simulate carbon dynamics over time. Combining the outputs from flux measurements, soil carbon data, soil maps and activity data e.g. grazing dates, dry matter production etc. to provide a holistic view of the carbon budget. Models like DAYCENT, DNDC or RothC are commonly used for this purpose.

Integrating these approaches provides a more accurate and nuanced picture of how different land management practices and environmental conditions affect soil carbon sequestration and emissions over time. This comprehensive view is essential for accurate GHG inventories and understanding the overall role of soils in carbon cycling. Such detailed understanding is crucial to enhance the accuracy and precision of C estimates of Irish soils to improve the national inventory and to give farmers credit for actions on their farms (Murphy *et al.*, 2024).

3. Implications for Stakeholders

There is a need to improve the estimates of C emissions and sequestration on Irish farms that can be reflected in the national inventory. Accurate and regular measurement of soil carbon stocks, greenhouse gas emissions and activity data must occur regularly. This ongoing measurement is essential for Measurement, Reporting, and Verification (MRV) strategies, crucial for tracking progress of mitigation efforts, ensuring transparency, and verifying compliance with climate policies and agreements (Green et al., 2024). Implementing a standardized MRV system is needed to ensure reliability, consistency, and compliance with international or national guidelines. In Ireland, various soil sampling schemes are in place to monitor and estimate national soil carbon stocks. Along with field management data, these can be used to refine and validate soil carbon models, which in turn can be incorporated into an MRV system. Ultimately farmers will need a decision support system to assist them with enhancing C sequestration and protect soils with high carbon content on their farms. This system will provide tailored guidance and best practices for sustainable land management, integrating advanced data analytics, soil carbon monitoring, and climate models to offer actionable insights and recommendations.

4. Future Research Needs

Representative and accurate measurement and monitoring of changes in soil C stocks is essential for detecting trends and optimizing strategies for C sequestration. Research in the future should focus on integrating C datasets to further advance Tier 3 modelling for incorporation into the national inventory and decision support tools like AgNav. For this purpose developing more accurate soil carbon models that account for diverse soil types, agricultural practices, and climatic conditions is crucial. Improving the MRV system by incorporating remote sensing technologies and machine learning algorithms, for transparent and efficient carbon tracking and reporting is also essential. Ultimately, enhancing soil mapping capabilities through high-resolution spatial data and advanced geostatistical methods will provide more precise soil carbon assessments. Future research will more and more focus on the long-term impacts of climate change on soil carbon sequestration, including extreme weather events and shifting climatic patterns, which will inform adaptive management strategies. By addressing these research areas, we can enhance the effectiveness of the AgNav platform in promoting sustainable agriculture and sound advises to farmers.

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Counting carbon on mineral soils

R. Murphy[1,2], G. Lanigan[1,2], K. Richards[2] , J. Rambaud[1,2], T. O'Dwyer[1], G. Gleasure[1], G. Bondi[1,2]

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1. Introduction

Measuring carbon sequestration on mineral soils at national level represent a challenge. The annual changes in carbon stocks are subject to yearly variations, making it even more difficult to detect and quantify the exact amounts of carbon sequestered or lost each year from different farming systems. To address these issues and develop a coherent solution for carbon accounting at national level, in Ireland we have built a roadmap to measure carbon sequestration which takes into account different scales of approach and methodologies. This requires the use of advanced tools that can track both short-term carbon emissions and long-term carbon storage.

The National Agricultural Soil Carbon Observatory (NASCO) and the Signpost Programme are coherently combining knowledge, infrastructures and tools to establish Irish specific emission factors for soil carbon sequestration for inclusion in the national inventory. Through these projects Ireland is developing the largest infrastructure in Europe to measure and report emissions and calculate C stored in the soil and biomass. We are at the initial stages of combining these datasets, and this integration will be expanded in the future to explore scenarios of carbon sinks and sources in Irish agriculture, moving towards a Tier 2 and Tier 3 approach rather than the current Tier 1. Integrating the datasets developed will allows us to create a comprehensive carbon budget for Ireland that captures both dynamic fluxes and stable storage. The advanced techniques and tools used will improve our ability to quantify carbon sequestration, helping soils act as more effective carbon sinks and contributing to climate change mitigation.

NASCO comprises of a network of eddy covariance towers that directly measure the rate of CO_2 exchange between the atmosphere and terrestrial ecosystems, providing real-time data on the rates of carbon sequestration and release. This information is crucial for understanding the dynamic processes of carbon uptake and loss at the field level. The soil campaign from the Signpost Programme effectively addresses spatial variability with standardised and scientifically sound sampling techniques for a more detailed and accurate assessment of C stocks as national baseline of soil C in Irish farming systems (Figure 1).

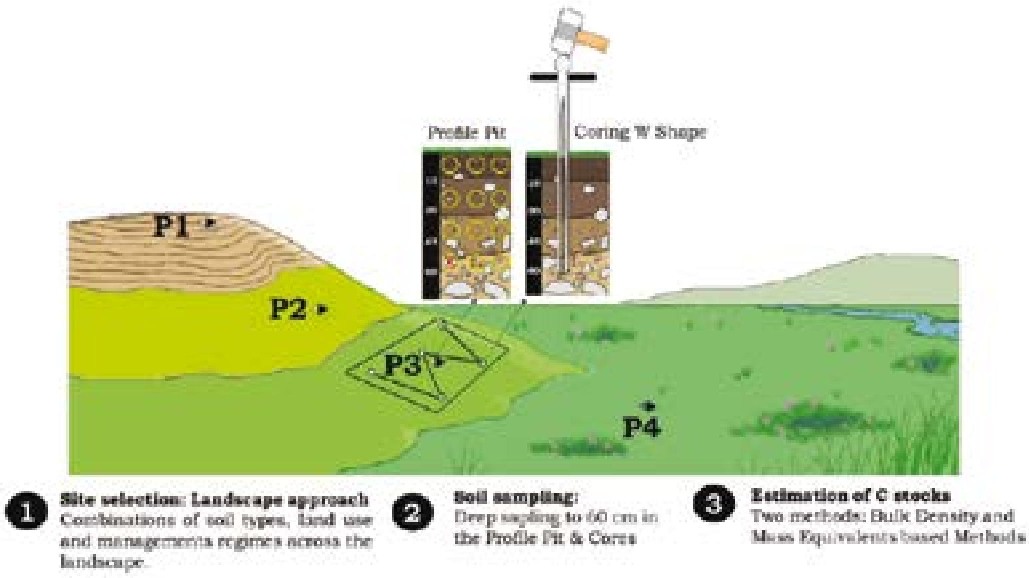

Figure 1: Method scheme for site selection and sampling within the Signpost Programme

2. Current Knowledge

Preliminary research from NASCO suggests that managed mineral soils are sequestering nearly 4.5 times more CO_2 than is reported in the NIR (Table 1), at a mean rate of 0.64 t C/ha per year or 2.34 t CO_2/ha per year. In order to validate these early research findings, long-term C flux measurements are required over different land-uses and management intensities, as is the overarching aim of NASCO and Signpost research.

Table 1: The IPCC Tier 1 emission factor (EF) for carbon sequestration on mineral soils and preliminary findings from the NASCO eddy covariance tower site at Johnstown Castle.

Units	Tier 1 EF	Measured Irish data
t C/ha per year	0.1	0.64
t CO_2/ha per year	0.38	2.34

However, it is important to note that managed pastures do not consistently act as a sink of C, and these systems are highly sensitive to management changes and extreme climatic events (Figure 2). For example, following conversion of grassland to forage crops at the Johnstown Castle site in 2005, the site shifted from a net sink of C to a net source in the following years, ranging from 1.9 to 6.9 t CO_2/ha per year. Similarly, during the 2018 heatwave, the Johnstown Castle grassland site transitioned from a net sink of C to a net source of C at a mean rate of 4.9 t CO_2/ha per year.

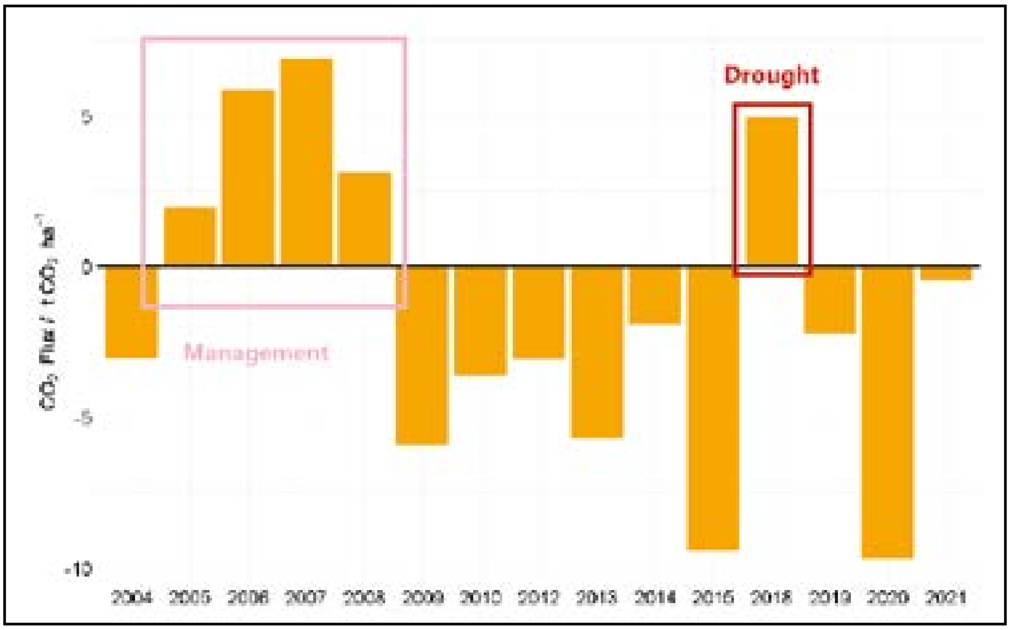

Figure 2: Preliminary findings from the Johnstown Castle NASCO site showing the long-term carbon balance in t CO_2/ha. Positive numbers represent net carbon that is emitted from the system to the atmosphere and negative numbers represent the net uptake of carbon from the atmosphere to soil and vegetation.

The SOC to Clay ratio, developed by Johannes et al. (2017), is a recognized soil quality indicator for European soils and it provides an understanding of the carbon that is bound to finer minerals such as clay. This ratio was calculated for topsoil data across all Signpost farms to assess the quality status of different farming systems. Preliminary results indicate that 92% of Irish farms, mainly grassland farms, are in good status in terms of soil quality, 6% moderate status and <1% poor status with both land use and soil type affecting the quality of the topsoil. Intensive grasslands have the highest capacity for carbon sequestration, especially on Luvisols, reaching values of 121 t C/ha for the entire profile (Castellon Meyrat et al., 2024). Intensive farms also show higher carbon stocks associated to deeper soil layers. This suggests the importance of considering subsoil carbon beyond the IPCC depth of 30 cm. Teagasc research has flagged the presence of significant carbon amounts below this depth in Irish soils (up to 40 t C/ha; Simo et al., 2019). The sampling on the

Signpost programme has confirmed that C stocks below 30 cm ranged from 18% to 30% of the overall C stocks for 60 cm, and were influenced by soil type, climatic conditions and land use. While soil type, and in particular clay content, set the potential size of the sink, land use has an overriding effect on the permanence of C. Short term management help to switch to higher or lower factor rate of C sequestration.

3. Implications for stakeholders

Research is also investigating various measures to generate scientific data and provide knowledge for different stakeholders, which will significantly enhance the national greenhouse gas inventory. Emissions from the land-use, land-use change, and forestry sector must be reduced in line with all other sectors to help Ireland achieve its 51% greenhouse gas reduction target. As science advances in measuring carbon and refining emission factors, the identified measures will deliver immediate carbon savings. Many of these measures also improve incomes, agronomic yields, and offer benefits to biodiversity and water quality.

a. Farmers

Collaborative research projects between Teagasc and universities, state and private bodies will provide the farming community with a quantification of the carbon sequestered through specific management practices on particular land-uses and soil types that will support sustainable, low carbon farming. Reduced C footprint of agri-food is becoming a key consumer demand globally and Teagasc research aims to provide a scientific basis and pathway for the Irish agri-food sector to promote itself as sustainable with a low climate impact. Signpost will contribute to developing and implementing tailored management practices for increasing SOC stocks and robust carbon accounting frameworks for sustainable agricultural systems. This will benefit farmers, land managers, and society in effectively managing their soils and could be incorporated into carbon farming frameworks.

b. Policy makers

Accurate baseline measurements of SOC quantification in depth and estimates of SOC sequestration rates that are specific across various soil types, land use scenarios, and management regimes, are essential in order to enhance the accuracy and precision of carbon estimates of Irish soils from a Tier 1 to Tier 2 levels. Irish specific SOC sequestration factors across the main mineral soils will be produced that can be inputted into national inventories. This will provide the basis for inclusion of agricultural soils into carbon trading schemes and life-cycle assessments (LCA's), which will assist the sector in terms of carbon credits and a reduced carbon footprint on agricultural produce. Flux measurements of CO_2 incorporated with C imports (e.g. animal excreta) and C exports (e.g. biomass removals) enable the calculation of C balances from different agricultural systems will help inform and underpin DAFM climate policy. Field scale measurements of GHGs, soil carbon stocks and biomass in combination with machine learning approaches to predict how changes in management and climate will impact carbon stocks from agricultural soils in the future, will enable policy measures to be tested and assessed.

c. Industry

The implications of this research for the industry are significant, as it supports the development of carbon farming practices that not only enhance carbon sequestration but also provide economic incentives for farmers, leading to more sustainable and profitable agricultural systems. In addition, fostering collaboration between government agencies, research institutions, agricultural organizations, and farmers is key to ensure the successful implementation and scaling of Tier 2 and 3 approaches.

4. Future research needs

The ongoing research on mineral soils will support the development of a Tier 3 model that can be used to quantify carbon sequestration associated with changes in land-use, land management and climate change. The mapping of soil types across Ireland needs to be improved to provide the necessary data to constrain Tier 3 carbon models for individual farms. The development of a Tier 3 approach for carbon sequestration will facilitate the development of the national inventory and support carbon farming. This will include creating detailed, location-specific management practices, refining carbon sequestration techniques, and implementing advanced monitoring and modelling tools to maximise carbon storage in agricultural systems**.** To enhance current approaches to measure, report and verify (MRV) the net carbon sequestration potential of Irish managed agricultural soils, synergy and collaboration between parties working in this space, both public and private, is required. Ireland is a global leader in climate change research, evident from the extensive state of the art technology that is currently being utilized, and the multi-scaled approaches being implemented (soil sampling, ecosystem-scale flux measurement, remote sensing and earth observations of carbon uptake and complex empirical and process based modelling). Harmonizing individual efforts will strengthen Ireland's capacity to answer complex, whole system questions about the future state of soil carbon stocks in response to new management approaches to a changing climate.

Acknowledgements

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Counting carbon on agricultural peat soils

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1. Introduction

Peatlands represent an integral part of the Irish landscape, covering approximately 1.46 Mha nationally, which represents approximately 21% of the land surface (Figure 1a) (Connolly and Holden, 2009). Globally, these ecosystems are one of the most important terrestrial carbon (C) stores. They are made up of accumulated organic material that is partially decomposed and sequestered over long-time periods (thousands of years) when the soil is waterlogged, as low concentrations of oxygen in the substrate limits decomposition. In Ireland, peat soils store approximately 2.2 Gt of C, which constitutes 62–75% of the total soil C pool (Renou-Wilson et al., 2022). However, over 90% of the peatland area in Ireland has undergone land use change, through drainage and conversion to agriculture, forestry or either domestic or industrial extraction (Fluet-Chouinard et al., 2023; Habib and Connolly, 2023). The spatial extent of grasslands on drained organic soils is estimated to be 339,000 hectares (EPA, 2024), however there is still some uncertainty on the total extent of peat-based grasslands in Ireland. This figure may increase closer to 500,000 hectares when shallow peats and soils with high organic matter are included (Gilet et al., *resubmitted*). These grasslands all act as a net C source though, with reported emissions in the region of 3.9 million tonnes of carbon dioxide equivalents (CO_2-eq.) per year (Tuohy et al., 2023; EPA, 2024).

National and international climate mitigation policies recognise the role that organic soils can play in reducing emissions of carbon dioxide (CO_2), and a focus on hydrology and water-table management (WTM) can reduce decomposition rates. There is a significant opportunity to explore options within the Irish agricultural peatland area to reduce C losses while balancing agricultural productivity and their impact on key ecosystem services within the wider landscape.

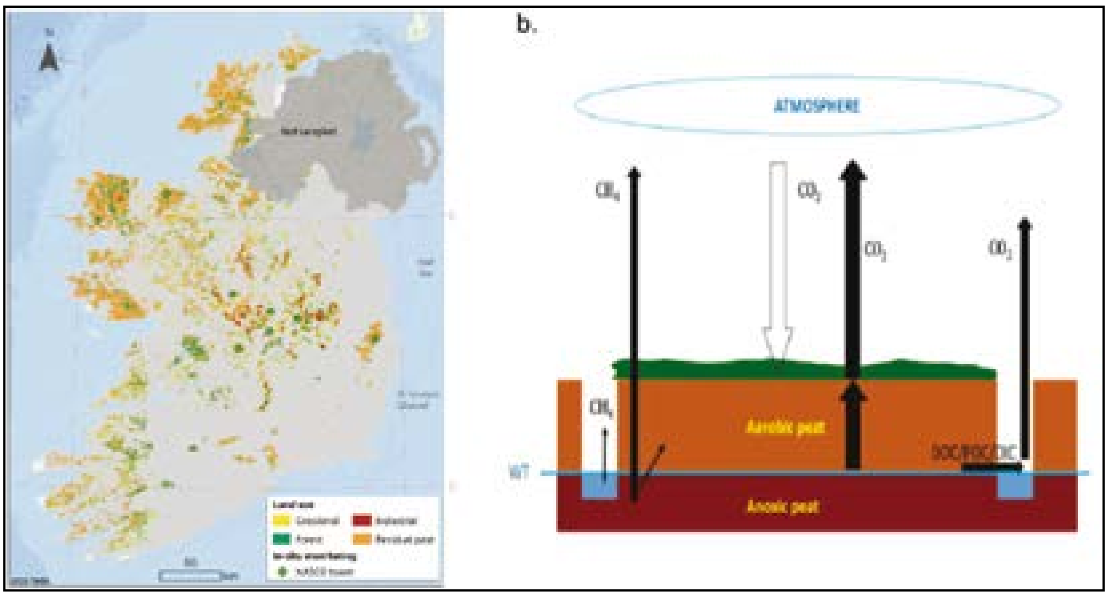

Figure 1a: Land use and the location of NASCO towers on peat soils (adapted from Habib and Connolly, 2023 by Louis Gilet, SmartBog and RePEAT projects). **Figure 1b:** An overview of the carbon (C) and greenhouse gas (GHG) dynamics of a drained peatland ecosystem under grassland management (Renou-Wilson et al., 2022).

2. State of Knowledge

An overview of the C and greenhouse gas (GHG) dynamics of drained peatland ecosystems under grassland is shown in Figure 1b. Carbon in the form of carbon dioxide (CO_2) is assimilated from the atmosphere through photosynthesis by the plants and is returned to the atmosphere via ecosystem respiration (R_{eco}), which is composed of two processes, autotrophic respiration (R_a, C released by the vegetation) and heterotrophic (R_{het}, C released by microbial decomposition of the substrate). When the water table is lowered, the depth of the aerobic layer increases and R_{het} tends to dominate the flux dynamics and a significant proportion of the C stored in the peat substrate is lost to atmosphere through microbial decomposition. In addition, the lower layers of the peat profile and the surrounding ditches are still wet and under anaerobic conditions can produce and emit methane (CH_4). Finally, additional C can be lost as dissolved and particulate C (DOC and POC) when water drains off the body of peat via open drainage ditches. These can also represent significant hot spots of CO_2 and CH_4 emissions (Peacock et al., 2021).

A comprehensive experimental assessment of C losses from drained organic soils under grassland in Ireland was undertaken by Renou-Wilson et al. (2015) as part of the CALISTO project. This work highlighted that nutrient status, extent of drainage, and variability in localised grassland management had the greatest impacts on the C and GHG dynamics of these systems. Nutrient poor sites, which represent a large proportion of the peat-based grassland area, under extensive grazing management with low rates of fertilisation tend to have low impacts on atmospheric warming. However, where the water table is increased and maintained 10 to 25 cm below the soil surface, sequestered C can be protected (Renou-Wilson et al. 2016). Modelling exercises have shown that emission reductions of 3 tonnes CO_2 per hectare can occur with each 10 cm increase in the height of the water table closer to the soil surface (Evans et al., 2021). Water table management becomes even more important at nutrient rich sites, which tend to be hotpots of both GHG emissions and losses of C through the fluvial pathway (Renou-Wilson et al., 2014). A review of peatland C and GHG fluxes from studies in Ireland compared default Tier 1 emission factors with country specific data and found that differences exist depending on land use and management/nutrient status (Aitova et al., 2023). Table 1 shows the Tier 1 and Irish estimated emission factors for both drained and re-wetted peat-based grasslands.

Peatland land use type	Nutrient status	CO_2 EF (t C/ha per year)		CH_4 EF (kg C/ha per year)		N_2O EF (kg N/ha per year)	
		Tier 1	Irish	Tier 1	Irish	Tier 1	Irish
Grassland	Nutrient poor	5.3 (3.7-6.9)	1.30 (0.04-2.6)	1.4 (0.5-2.1)	4.3 (2.6-15.02)	8.82 (1.9-6.8)	1.6
Grassland Nutrient rich	deep drained (5.0-7.3)	6.1 (3.7-6.6)	5.1 (1.8-21.8)	12 (-2.2-0.7)	-0.75 (4.9-11)	8.2	1.6
Rewetted grassland	Nutrient poor	-0.23 (-0.6-0.2)	0.85 (-1.6-3.3)	92 (3-445)	68.1 (20.9-115.2)	0	0

Table 1: Tier 1 and proposed emission factors for Ireland for CO_2, CH_4 and N_2O for agricultural grass-based peatlands. Data taken from Aitova et al. (2023). Values in brackets denotes the 95% confidence intervals.

The CO_2 emission factors for nutrient poor grasslands on peat from Irish studies are significantly lower than the default Tier 1 emissions, due to the lower intensity management in Ireland compared to the studies used to derive the Tier 1 emission factors, while emission factors for deep drained nutrient rich systems are similar to the Tier 1 emission factors. This difference, as well as a review of effective drainage of these grasslands (Tuohy et al., 2023) has had a significant impact in reducing the emissions reported in Ireland's National Inventory Report (NIR), as nutrient poor grasslands tend to be more widespread. The differences in the CH_4 emission factors for nutrient poor grasslands are due to the Tier 1 values being derived from deep drained sites with different climatic conditions, while Irish data are derived from shallow drained sites. The emission factors for N_2O are lower in the Irish context but lack certainty due to limited data.

Figure 1a shows the approximate location of the eddy covariance flux towers on peat soils in the National Agricultural Soil Carbon Observatory (NASCO). The flux towers will provide long-term estimates of the exchange of CO_2 and CH_4 between these ecosystems and the atmosphere. Some of the towers will also contribute to the EU-wide Integrated Carbon Observation System (ICOS). Further work is underway to enhance our understanding of the distribution of peat soils in Ireland in line with the Global Peatland Assessment (Gilet et al., *resubmitted*), their C and greenhouse gas dynamics and the impacts that WTM can have in reducing emissions and enhancing water quality.

Advances in the measurement of C and GHG fluxes and key environmental variables is crucial to provide data required to develop, validate and test model predictions of C dynamics. These models can be used as tools to understand the drivers of emissions and the impacts of land use/management scenarios at different temporal and spatial scales. This work and current activities, such as the CO2PEAT project will improve methodologies to report and verify C removals and emissions and will contribute to further refinement of higher IPCC (2014) tier reporting approaches.

Research into the hydrological dynamics and our ability to manage water tables in grass-based peats is currently under investigation in several projects (REWET, Carbosol, H2O, D-TECT, SMART CARBON FARMING) at various sites across the midlands and the west of Ireland. The REWET project will assess the availability and suitability of lands for rewetting, examine practical means of rewetting, assess the effects on hydrology, both at the designated sites and surrounding lands, and quantify associated impacts. The impacts of WTM on C and GHG dynamics are also being investigated on sites that represent a gradient of deep and shallow drainage and nutrient rich/poor status. Here, eddy covariance towers, part of NASCO, and state-of-the art automated chamber systems (Figure 2) combined with weekly manual chamber measurements are being used to address key knowledge gaps on the impacts of such interventions on components that dominate ecosystem C fluxes (R_a and R_{het}) and the application of various nutrient inputs on CO_2, CH_4 and N_2O emissions from agricultural peat soils. The refinement of water table control methodologies will allow for any implementation of such land use changes to yield maximal benefits on a per hectare basis and will inform strategies for the sustainable management of land resources, reduce the impact of GHG emissions, promote improved soil health and support sustainable habitats at all scales. Other projects will examine geospatial drainage status detection mapping of organic rich soils for NIR and policy support needs.

Figure 2: An eddy covariance tower and auto-chamber experiment investigating the impacts of water table management (WTM) on carbon (C) and greenhouse gas (GHG) dynamics on an agricultural peat-based grassland. Images provide by Ian Clancy.

3. Future Research Needs

There are still considerable uncertainties in the National Emission Inventory. It is important to further refine peat maps and country specific emission factors by assessing a greater range of sites, over the long-term, to better understand the impacts of peat depth, water table, management intensity, nutrient status and inter-annual climatic variability on the carbon and greenhouse gas dynamics of these systems. Further mapping and remote sensing of agricultural peatlands with particular focus on aligning GHG research on nutrient status and land use intensity to assess extensive, intensive and rough grazing would be beneficial to further disaggregate emissions and allow for the application of refined emission factors for these systems. Additional research is also needed on the development of models that will support higher IPCC (2014) tier reporting. The integration of modelling approaches, such as coupled and/or hybrid models and modelling platforms with integrated data-streams will allow us to effectively utilise the data, monitor and verify the observations, and refine the model predictions of C emissions from agricultural peat soils, under different management scenarios, and across different spatial and temporal scales.

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Forestry carbon accounting

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1. Introduction

Carbon sequestration is the process of capturing and storing atmospheric carbon dioxide (CO_2). This process is critical for mitigating climate change by reducing the concentration of CO_2, a major greenhouse gas (GHG), in the atmosphere. Forests play a very significant role in carbon sequestration. Trees absorb CO_2 from the atmosphere, convert it into organic matter through photosynthesis, and store it in their biomass (trunks, branches, leaves, and roots). Dead organic matter, such as deadwood, leaves and branches, decomposes and contributes to soil organic carbon. CO_2 is released through autotrophic and heterotrophic respiration.

Ireland has committed to reducing GHG emissions and enhancing carbon sequestration through a range of measures in the agricultural, land use, land use change and forestry sectors. The Climate Action Plan 2024 identifies enhanced delivery of afforestation, sustainable forest management and increased use of harvested wood products (HWP) as key measures in meeting the objectives. Ireland's National Forestry Strategy targets a major expansion of climate resilient and healthy forests to 18% of total land area. This paper aims to provide an overview of current knowledge and practices related to forestry carbon sequestration in Ireland, highlight the measurement techniques used and carbon accounting efforts, and discusses future research needs. The objective is to inform policy and industry stakeholders about the importance of measuring and increasing carbon sequestration through forestry.

2. Current Knowledge of Forestry Carbon Sequestration in Ireland

Forests store carbon in five primary pools on site: aboveground biomass, belowground biomass, litter, deadwood, and soil carbon. The amount of carbon stored in any one pool changes over time. An important and often overlooked carbon pool is wood products. Most of the carbon is retained when the harvested tree becomes a durable wood product (furniture, flooring, etc.). Ireland's National Inventory Report (EPA, 2024) indicates that the average carbon sequestration by forest land in Ireland between 1990 and 2022 was 2.45 Mt CO_2-eq per year. The average rate of sequestration by HWP was 0.83 Mt CO_2-eq per year. The Teagasc MACC Analysis to 2030 describes options for consideration aimed at increasing climate change mitigation contributions from forestry within the LULUCF sector. These include afforestation rates of 8,000 hectares per year; forest management by adjustment of the age of rotation on 21% to 31% of the area of commercial conifer forests on suitable sites avoiding deforestation and agroforestry creation. These four measures combined could deliver about 1.32 Mt CO_2-eq per year in 2030 (Lanigan et al., 2023).

Historical Planting in Ireland

Historically, Ireland has experienced various phases of afforestation, notably expanding forest cover from 1.5% in 1920 to 11.6% in 2022, with public planting dominant until the mid-1990s, and private planting significantly increasing from the early 1990s (DAFM, 2022). A key challenge is to enhance the capacity of our forests to be an effective carbon store, with due consideration to other future demands on our forests. Irelands Forest Strategy sets out the overriding objective to urgently expand the national forest estate on both public and private land in a manner that will deliver lasting benefits for climate change, biodiversity, water quality, wood production, economic development, employment and quality of life. Eligible planting sites for afforestation (based on soil type and site fertility) under Forestry Programme 2023-2027 are set out in the Land Types for Afforestation publication (DAFM, 2023). These include mineral soil, organo-mineral soil with peat depths of less than or equal to 30 cm or suitable modified fen and cutaway raised bogs. Environmental considerations incorporated into the planting approval process to safeguard the environment will have an impact on land availability for afforestation.

Carbon Measurement in Irish Forestry

Ireland employs several methods to measure forest carbon stocks including remote sensing, ground-based monitoring, and inventory modelling. Ground-based methods involve direct measurement of tree dimensions (e.g., diameter, height) and soil sampling, with new technologies like eddy covariance measurements being used in recent years. Remote sensing techniques utilize advanced satellite and aerial imaging to analyse forest cover, biomass, and changes over time to quantify carbon stocks. Inventory modelling employs sophisticated computer models that integrate remote sensing data, field data, and other inputs to project forest carbon dynamics at national and regional scales. As new measurement techniques become available and existing techniques are improved and refined, increasingly accurate estimates and more comprehensive assessment of carbon fluxes in forests can be achieved.

Carbon Sequestration for New Forestry Types

The Afforestation Scheme 2023-2027 (DAFM 2023) supports the creation of a wide range of forests with varying objectives. Landowners can plant a range of different forest types on the same holding depending on the management objectives chosen for the site. Each forest type will have specific carbon sequestration rates, reflecting factors such as tree species/species mixes, soil types, planting patterns, future management approaches and harvest products. Teagasc, in conjunction with DAFM and Forest Environmental Research and Services (FERS) Limited have developed an online Forest Carbon Tool. The tool uses the same modelling framework (CFS-CBM) as used in the national GHG inventory and for submissions to the EU. The tool provides indicative data for potential carbon sequestration associated with new forest enterprises which will shortly include current options under the DAFM Forestry Programme. It also provides indicative sequestration data for specific tree species/species groups. The Forest Carbon Tool takes user-defined descriptive information on the forest and combines it with existing growth models to estimate potential carbon storage over the lifetime of the forest.

There are two normalised values used to compare forests with different species, rotations ages and silvicultural management regimes: The average CO_2 cumulative removals/emissions is the CAP, which is a measure of the once-off maximum potential CO_2 sequestration. The average annual CO_2 sequestration rate over time until steady state is reached. This is a measure of the normalised rate of sequestration over successive rotations and allow comparison between silvicultural regimes with different rotation ages. Generally, forests with a high normalised sequestration rates will reach the CAP sooner than forests lower normalised sequestration rates. For example, afforestation with slow growing oak results in a higher CAP than Sitka spruce. However, Oak takes longer to reach the CAP because the normalised sequestration rate is lower than that of Sitka spruce. Figure 1 shows indicative carbon sequestration ranges and average CAP values derived from the Forest Carbon Tool (expressed in tonnes of CO_2 equivalents) for four different forest types (note the values for FT8 excludes emissions from livestock).

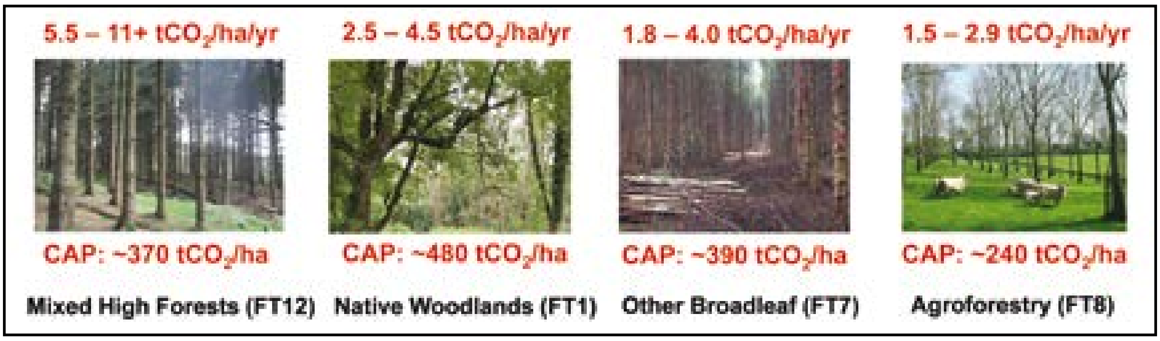

Figure 1: Carbon sequestration ranges and average CAP values for four forest types under the new afforestation scheme.

- **Mixed High Forests (FT12):** These forests are composed primarily of fast-growing conifer species with a 20% mixture of broadleaf species, resulting in high carbon sequestration rates. This type is designed to optimize both timber production and carbon storage. CAP time 60-100 years.
- **Native Woodlands (FT1):** These forests consist of species native to Ireland, providing significant biodiversity benefits and moderate carbon sequestration rates, but store carbon over long period of time. Native woodlands play a crucial role in conserving Ireland’s native flora and fauna and enhancing ecosystem services. CAP time 100 years.
- **Other Broadleaf (FT7):** This category includes fast-growing broadleaf species such as birch, alder, and sycamore. These species are chosen for their ability to rapidly establish and grow, timber, contributing to moderate carbon sequestration and offering diverse ecosystem benefits, including improved soil health and enhanced habitat for various wildlife species. CAP time 150-160 years.
- **Agroforestry (FT8):** This system combines agriculture and forestry, offering benefits of both systems. Agroforestry practices can improve soil fertility, enhance biodiversity, and provide additional income streams for farmers while sequestering carbon. By integrating trees with crops or livestock, they enhance land use efficiency and resilience against climate change. CAP time 120-150 years.

Forestry Inventory and Recent Changes

Ireland maintains a comprehensive forestry inventory to monitor carbon stocks. The DAFM National Forest Inventory (NFI) collects data on forest area, tree species composition, age structure, health, and carbon stock. Notably, 38% of forests are on deep peats (>40cm depth). Recent forest carbon inventory reporting incorporate a significantly adjusted emission factor for forested peat soils. Research in 2021 indicated that emissions from drained forest peat soils are in the order of 1.68 t C/ha per year, nearly three times the previously-used emission factor (Jovani-Sancho et al., 2021). This change in emission factors has significantly impacted forest carbon accounting, with forestland sequestration reduced by about 50% (EPA, 2022).

Ireland’s forests are transitioning to a source of emissions, and emissions reductions for this sector are set to become increasingly challenging, due to a number of combined factors including the decline in recent afforestation rates, continued emissions from organic soils, a projected increase in the level of harvest, deforestation and a reduction in landscape level sequestration potential due to age class structural shifts. Research work to further refine and validate emission factors on varying forest types and peat types is required and ongoing to strengthen knowledge and insights in this key area of forest sequestration accounting.

Higher timber yield is achieved on better forest site conditions, which largely determine the productivity and growth rates, ultimately influencing the carbon stocks in forests. Specific management practices, such as, ensuring optimum fertility status and appropriate thinning, can help optimise the carbon sequestration potential of forests. For example, selective thinning improves forest health and productivity by reducing competition for resources among trees, thereby enhancing the growth of the remaining trees. The continued inflow of wood from the harvest of successive rotations into the HWP avoids emissions by substituting energy-intensive products with wood and by replacing fossil fuel with bioenergy. Compared to unmanaged forests, high-production forests optimized for long-term HWP can potentially store double the amount of carbon at 100 years (FERS 2024).

3. Implications and Future Research Needs

Understanding and addressing social barriers to forestry acceptability is crucial. Engaging with communities, improving public perception, and providing incentives to landowners can promote afforestation. Outreach and education programs can highlight the benefits of forestry for carbon sequestration, biodiversity, and local economies. Collaborative approaches that involve stakeholders in the planning and implementation of afforestation projects can increase their acceptance and success. Enhancing the carbon sequestration capacity of Ireland’s forest resource is essential to helping achieve climate targets. A multi-faceted approach encompassing forest creation, appropriate management practices, and the utilisation of long-lived harvested wood products is paramount. However, to effectively implement such strategies, increased understanding of forest carbon dynamics is imperative.

One area requiring significant attention is the effects of different forest management practices on carbon sequestration. Currently, the impact of practices such as forest thinning, clear-cutting, deforestation for habitat restoration, adjusted rotations, second rotation dynamics and continuous cover forestry approaches, and on carbon dynamics remains incompletely understood. Research initiatives should prioritise assessing these practices to determine their efficacy in enhancing carbon sequestration while maintaining ecosystem integrity. In addition to management practices, improved quantification of emissions and mitigation measures for forestry on organic soils is crucial. Refining emissions data for varying species on a range of organic soils, which are significant carbon pools prone to GHG emissions when disturbed, is imperative. Collaborative efforts between researchers and forest stakeholders are essential to further enhance knowledge on emission factors and thereby inform policy decisions aimed at mitigating emissions from organic soil disturbances. Moreover, understanding species-specific carbon sequestration dynamics is vital for optimising carbon storage potential. Detailed studies on the carbon sequestration rates of different tree species and their interactions with soil carbon dynamics are needed.

Lastly, assessing the potential impacts of natural disturbances and climate change on forest carbon sequestration is another area that merits attention. Given the uncertain future climate scenarios, evaluating the vulnerability of forest ecosystems to climate change-induced stressors such as drought, wildfire, and pest outbreaks is essential. Collaborative research efforts should focus on developing adaptive management strategies that enhance forest resilience and mitigate the adverse effects of climate change on carbon dynamics. Through concerted research endeavours, Ireland can develop holistic approaches to optimize forest carbon sequestration and optimize the huge potential of our valuable forest resource, including climate change mitigation capacity.

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Farm carbon stocks monitoring, reporting and verification

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1. Introduction

Measurement, reporting and verification (MRV), are the tools that allow actions by farmers to reduce greenhouse gas (GHG) emissions and increase carbon (C) sequestration to be turned into trusted impacts. Without measurement, the size of the impact will not be known; without reporting, the source of the impact will be unrecognised and without verification the measured, reported impact will not be trusted. MRV can be done at national statistical scale for inventory reporting or it can be done at the farm level: scaling up for national inventory or staying at the farm gate for C farming or credits. MRV can come from data provided by the farmer or producer or they can acquired remotely using sensor technology. MRV approaches are particularly important with respect to C stocks on the farm – how much carbon is already stored in the soil and in hedgerows, value and credit will only flow from an increase in these stocks. The C stocks can increase due to actions being taken by the farmer (e.g. straw incorporation), and the measurement and verification of these actions is sufficient for reporting. This would be known as an action based approach to carbon farming. The second approach would be results based – demonstrating that a specified increase carbons stocks has been achieved. The MRV methods for results based schemes rely on measuring or modelling of carbon stocks before and after the period over which the scheme was to be run.

2. State of Knowledge

The suite of technologies and methods used in MRV have been explored and developed within the Teagasc research program looking at both action and results based approaches.

Within the Teagasc Signpost Programme, baselines of carbon stocks in soils and above ground carbon have been created. As part of the Signpost Programme, over 100 farms have been selected for comprehensive soil sampling and measurements of soil organic carbon sequestration. Signpost strategically chooses spatially distributed locations that comprise a variety of soil types, land uses, and management scenarios in order to measure SOC stocks, analyse distribution patterns, and identify factors influencing SOC stability. C fractionation measures are included at depth to identify the different carbon pools and understand the quality and persistence carbon present in soil. These measures are critical for understanding the potential for soils to sequester carbon. Changes in carbon stocks over the lifetime of the Signpost programme can be made, directly linking recommended actions with results on the farm. Combining these approaches improves quantification of soil carbon dynamics.

Cutting edge laser scanning technologies are used to give accurate estimates of above and below ground carbon stored in woody biomass. Teagasc has been researching the importance of hedgerows for carbon and habitat for many years and published the first national hedgerow map in 2010. A number of projects since then have developed methods to estimate volume and carbon of hedgerows from laser scanning, photogrammetry and satellites. Hedgerows are now mapped routinely by DAFM, Tailte Éireann and private companies. Teagasc developed the methodology to detect automatically hedgerow removal, in the BRIAR project and estimated approximately a net removal of hedgerows between 1995 and 2015 of between 0.16-0.3% pa. The FarmCarbon project created the first Irish allometric models to convert hedgerow volume to biomass C. The project found that hedgerows typically contain ~58 tC/ha and, if allowed to grow, increase this amount by 1-2 tC/ha/yr (Black et al, 2023). The project also found a net removal of hedgerows in Waterford/Wexford between 2015-2020 meaning that hedgerows were a source of GHG emission not a sink. Every farm in signpost will have full carbon inventories created, see figure 1, and a new PhD (in the AGNAv cluster) is developing methods of tracking change over time.

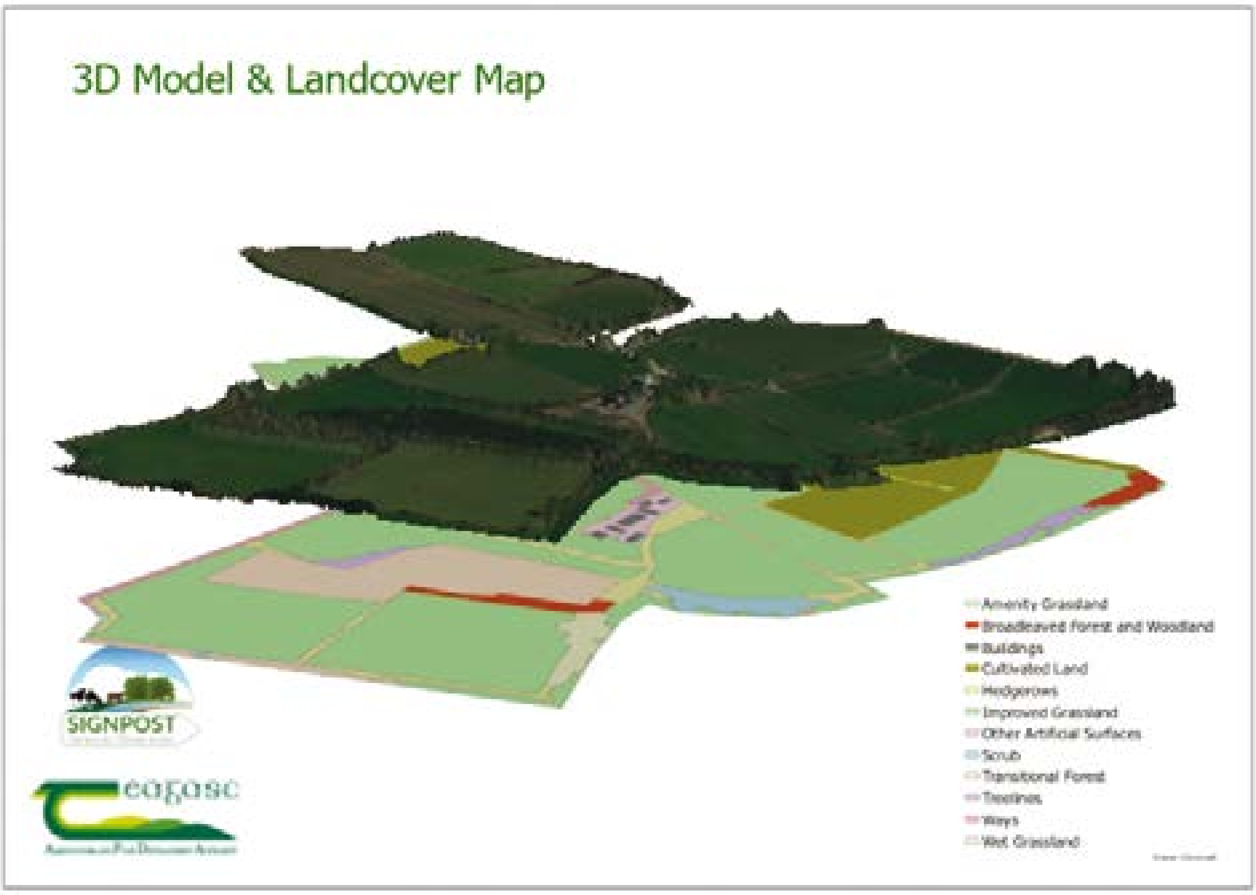

Figure 1: Laser Scanning of signpost farms allows us to very accurately estimate the C content of hedgerows, trees and forest and to create a biodiversity baseline map for the farms.

Teagasc (funded by DAFM, the Agricultural Catchment Programme and SFI VistaMILK) recently established the National Agricultural Soil Carbon Observatory (NASCO) network to measure the greenhouse gas emissions from a 28 sites representing a range of land-uses and soil types across Ireland (Murphy and Bondi, 2024). These towers create vast amount of data but also need a lot of other support data on management activity, crop growth, weather and soil. The Maynooth University/Teagasc SFI/Microsoft funded TerrainAI project created a digital platform for the collation and analysis of all this data. Besides tower data, remote sensing data from drone surveys, aircraft flights and satellites were captured and analysed. This large array of data is being used on the platform to model emissions at farm and national scales and is being used to developed explicit MRV tools.

Ireland has implemented various soil sampling schemes to monitor and estimate soil C stocks at national level. While these schemes provide valuable insights, their accuracy can be further enhanced by considering additional factors such as the depth of sampling and precise measurements of soil organic carbon. The Signpost Programme serves as a valuable resource for informing national soil sampling schemes on strategies to enhance accuracy by addressing aspects crucial for precise C stock estimation. Teagasc research has shown that up to 40 t C/ha was found below 30cm (Simo et al. 2019) and different soil bulk density measurement can over estimate C stocks by up to 310% (Fenton et al., 2024). Thus robust soil MRV methods are needed and a gold standard method for accurate calculation of C stocks needs: 1. depth of a soil layer, 2. representative bulk density and 3. representative organic carbon. Soil carbon content can vary significantly across different landscapes and even within the same field. Sampling schemes that do not account for this spatial variability may not provide accurate national estimates of C stocks. Standardized methods are essential for obtaining accurate and comparable results. For the Tower sites in TerrainAI extensive soil sampling was carried out to provide a spatial assessment of the true small scale variation in soil properties across the tower footprints.

TerrainAI used satellites to map different types of grassland management and grassland productivity. These products act as verification of the adoption of grassland management as action to reduce emissions. Verification of grassland management is also verification of agricultural activity and the paddock detection tool has been adopted by DAFM as an input into its CAP payments system. In Tillage, the planting of winter green cover is an important measure for GHG mitigation and water quality; using Sentinel 1 satellites (that can see through cloud), Teagasc in TerrainAI has developed a method to detect green cover at field scale in November and December.

One of the significant measures for land-based mitigation could be controlling of the water table in agricultural peat soil settings. Significant research is underway nationally as summarised by Saunders et al.(2024) all of which will create new MRV tools for agricultural peat soils. These are being developed within the Teagasc D-TECT project.

Grassland and sward management can play a significant role in reducing greenhouse gas emissions and increasing soil carbon sequestration. Remote methods to detect use of clover or multi-species swards at farm scale have been developed within VistaMILK. Detection of growing and grazing season have also been explored within Teagasc.

Internationally tools for MRV in relation to forestry are significantly more advanced than those for agriculture. In Ireland, statistical knowledge of plantation and native forestry is good and remote sensing tools for detecting forest health and the impact of forest fires are being created. A number of flux towers are located on forestry to improve our knowledge of the impact of management on forest carbon sequestration or emission factors. Within Teagasc the role of farm forestry in achieving farm net reductions is that farm forestry contributes significantly to carbon sequestration, helping to offset emissions from agricultural activities. By planting trees on farms, farmers can sequester carbon in the biomass and soil, which helps in mitigating climate change.

3. Implications for Stakeholders

MRV as tool for the support of carbon farming and the possible development of carbon markets is quickly developing. There are yet no agreed standards in Ireland for the MRV of carbon credits and there are already a small number of firms attempting to offer different standards of MRV at farm scale. MRV for measures that impact the national inventory for agriculture have different accuracy and utility needs than those for reporting on farm scale actions.

There is a robust national hedgerow baseline and methods for measuring change at both farm and national scale. The automatic detection of hedgerow removal will soon become common place – farmers need to be aware that hedgerows and trees represent an important carbon store. Even if hedgerows are replanted it will take up 30 years for the new hedgerow just to absorb the carbon that was lost when the old hedgerow was removed. Farmers can be confident that any trees planted on the farm or within hedgerow will be accounted for both nationally and at farm scale.

For soil carbon, the data analysed within the NASCO project will massively improve the accuracy of national net estimates of carbon emission from agriculture. Within a carbon farming context action based approaches are easier to verify and some of the Teagasc research is allowing this to be done in areas such as grassland management, hedgerow management, winter green cover and the extent of agricultural peat lands.

MRV for results based carbon farming can be more difficult. Monitoring the establishment and growth of farm forestry is now routine- but also loss of biomass thought clearance, deforestation, natural disaster (forest fires, storms etc.) is also possible – results based markets could lead to loses for farmers if a forest is destroyed for example. MRV for changes in soil carbon is largely dependent on "before and after" soil sampling – but soil carbon accumulation occurs over decades.

The modeling tools developed around emission profiling of actual sites rather than generalised factors associated with particular soil/land use combinations can in fact be a cause of uncertainty for the land manager in results based schemes. Some sites may be a sink in some years and source of GHG in others due to seasonal weather impacts largely out the control of the farm manager. Financial support for farmers to adopt measures that are likely to improve net GHG budgets (action based approaches) do not suffer from this uncertainty.

4. Future Research Needs

The continued support of the NASCO network of towers is vital if specific factors for Irish land uses and soils in all seasons are to be created. Without these factors, international data will used in there stead, making in some cases poor approximations of the reality. Work will continue in the development of MRV tools that allow for actions by farmers to be translated into trusted national level statistics.

In Table 1 are selected measures from the Teagasc marginal abatement cost curve, MACC, advices. Measures such as hedgerow management have technical solutions to measuring, reporting and verification by remote systems and are ready to be included in national inventories. Some such as extended grazing need a small amount of research and technical development to be ready whilst options such as water table management are only now being researched in the context of MRV.

Table 1: MACC measures that are amenable to remote MRV - the table indicates whether the technology is ready for measuring, reporting or verification.

Measure	Measuring	Reporting	Verification
Grassland Management	Yes	Yes	Yes
Cover Crops	Yes	Yes	Yes
Prevent Deforestation	Yes	Yes	Yes
Afforestation	Yes	Yes	Yes
Hedgerow	Yes	Yes	Yes
Clover & Multispecies Swards	Yes	No	No
Extended Grazing	Yes	No	Yes
Soil Drainage	Yes	No	Yes
BIRCH (wetlands)	Yes	No	No
Agro-Forestry	Yes	No	No
LESS (low emission slurry spreading)	No	No	No
Mean Annual Increment (farm forestry)	No	No	No
Water Table	No	No	No
Straw incorporation	No	No	No

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Development of an Irish Carbon Farming Framework informed by stakeholder engagement

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1. Introduction

Carbon Farming is an important enabler for the agriculture and land use sectors to meet Ireland's climate targets (25% emission reduction in agriculture by 2030). As set out in the most recent Climate Action Plan (2024; gov - Climate Action Plan 2024 (www.gov.ie)), the Department of Agriculture, Food and the Marine (DAFM) is committed to the development of an enabling Carbon Farming Framework in 2024 to support the rewarding of farmers, foresters and landowners partaking in emission mitigating and carbon removal activities.

There is a need to establish a national carbon farming framework that compliments the environmental activity within for example the CAP Strategic Plan 2023-2027 (gov - The CAP Strategic Plan 2023 -2027 (www.gov.ie)) and that is cognisant of the trajectory and requirements at EU level, within a parallel process.

A well-functioning National Carbon Farming Framework that provides confidence, verification and certification is essential to generate a potential additional income source for landowners in the actions they take to remove and store carbon in Irelands soils, forests, grasslands, croplands, and hedgerows.

The development of the national framework is guided by a public consultation launched in September 2023 (gov - Carbon Farming Framework for Ireland (www.gov.ie)) and informed by an expert advisory group chaired by the DAFM and EIT Climate-KIC, the EU's leading climate innovation agency and community, as part of their international strategic partnership to accelerate climate-smart agriculture and sustainable food systems.

2. Public Consultation on a National Carbon Farming Framework

The objectives of the public consultation were as follows:

- Obtain feedback from stakeholders on the scope of a Carbon Farming Framework for Ireland.
- Reflect and gather insights on existing initiatives.
- Identify stakeholders who need to be involved.

3. Feedback from stakeholders

Strong farmer/forester engagement

DAFM received 457 responses to an online survey in late 2023, which asked stakeholders to provide input into the scope of a Carbon Farming Framework. The biggest response to the online survey (30.6%) came from farmers followed by farm advisers (24.9%) and then foresters (18.6%).

What should be included in the Framework?

There was broad agreement that a compensation mechanism to reward eco-systems services was needed. The responders strongly agreed that carbon removal, greenhouse gas (GHG) reductions and biodiversity measures needed to be included in the Carbon Farming Framework developed.

Governance

In terms of governance responsibility, 44% of the total replies indicated that independent body/ multistakeholder group should have governance responsibility. 33% of the responders indicated that DAFM should provide the over-arching governance responsibility.

Who should pay for these services?

A great majority of respondents saw the State or the EU responsible to pay for the services covered by a national framework. The payment for services was divided with the State being indicated as a key pillar however a clear group of those taking part in the consultations believe that the costs can be shared by consumers, processors, and food producers themselves.

Readiness to join the initiative

The facility to diversity farm income was viewed by 62% of responders as a positive opportunity. However, when asked if they were willing to join an initiative right now only 53% of the consultation participants answered "yes", but the rest would rather wait and admit that they do not know enough to be able to decide now. This is an important signal showing the scale of uncertainty and a lot of space to be developed through sensible consultation, deliberation, and information activities.

Acceptable time horizon for financing activities

It was clear from the survey that longer duration is considered more acceptable. Close to 50% of responders indicated funding of 20 years was preferred.

Principle of fairness

There was strong consensus that those who have adopted measures early must be recognised under fairness.

Forestry perspective

There was strong support for the idea that Ireland needs a Forestry Carbon Code (akin to the UK Woodland Carbon Code).

Feedback from an open Question

Feedback from the open question was robust, with plenty of constructive ideas and critique. Many people left contact details, which is very helpful from the perspective of building a community of users for the implementation phase of that framework. The consultation provided an invaluable resource of stakeholders to invite for more in-depth discussion.

The following organisations were consulted in subsequent meetings:

Irish Farmers Association, Irish Grain Growers Group, Irish Environmental Network, Irish Cattle and Sheep Association, Irish Organic Association, Environmental Protection Agency, Bord Bia, Meat Industry Ireland, Dairy Sustainability Ireland, IrBEA and Teagasc.

4. Consensus on the overall Objective and Purpose of the National Framework

The public consultation process and stakeholder engagements have shaped the overall objective of this framework, which will be to support and enable the adoption and scaling of management practices within primary production systems. This will enable Ireland achieve its climate, biodiversity and water quality targets by the end of 2030 and attract additional investment into the agri-food sector to potentially support primary producers (farmers, landowners and foresters) for the ecosystem services that they provide.

The purpose of the Framework will be to:

- Define the principles under which a National Framework for Carbon Farming to support ecosystems services will operate in Ireland. For example, governance, permanence, additionality.
- Set the rules for what ecosystem services will be measured and the protocols for measurement that must be followed in order to achieve certification, with the aim to harmonise multiple ongoing initiatives.

- Attract additional investment into the agri-food sector to pay primary producers (farmers, landowners, and foresters) for the ecosystem services that they provide.

Set out the next steps for development of Carbon Farming.

5. Future research needs

Funding Opportunities for research/pilot programmes (ongoing)

Throughout this process, extensive funding has been in place supporting activities on the ground through the Innovation Fund, the Common Agricultural Policy, the Regional Development Fund, the LIFE programme, the Climate Fund and the Horizon Europe programme (including the Mission 'A Soil Deal for Europe'). However, additional funding is needed to develop Carbon Farming further.

Communications and knowledge transfer

There is a significant knowledge gap amongst farmers, landowners, and agri-food stakeholders around the topic of carbon farming as it is a new and developing area. As a first step, it would be useful to develop a "knowledge transfer strategy" around the carbon farming demonstration. This could include specific actions identified around the launch of the DAFM carbon farming framework, delivery of the pilot phase, launch of the main phase and engagement with all stakeholders etc.

Acknowledgements

We wish to acknowledge the support of the Project delivery team in driving the process of developing the framework and designing pilots/demonstration to test the framework.

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Carbon farming and certification schemes – Lessons learned in France

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1. Introduction

Following the publication of the national low-carbon strategy in 2015 by the French government, the Ministry for Ecological Transition (2020) created the "Label Bas Carbone" in 2018. This certification framework is managed by the Ministry and its decentralised administration. The goal of the framework is to certify low-carbon projects in France, across sectors, and to attract funding toward these projects. Through this framework, the French Government wishes to encourage all sectors to reduce greenhouse gas (GHG) emissions, and/or to increase carbon sequestration, as in the case of forestry and agriculture. Then, the ambition is to scale-up by building a low carbon standard on a European scale through a pilot project. Consequently, the LIFE Carbon Farming project was launched in 2021, for seven years, and it involves six countries.

2. State of Knowledge

A Label Bas Carbone project is defined as a project with a limited lifetime that reduces emissions or stores carbon. The tons of carbon dioxide equivalent (CO_2-eq) 'avoided' (i.e. emission reduction or sequestration) is determined by comparing a situation where a low-carbon project is implemented with one where there is no change. The latter situation corresponds to a baseline scenario i.e. the position before the implementation of the project. The project must be additional, i.e. go beyond the regulation and would not have been implemented without the Label. Emissions of GHG and carbon sequestration must be verified by an external auditor. Additionally, other indicators must be followed to assess the impact of the project on other environmental aspects. Furthermore, the methodology needs to account for the risk of non-permanence of the carbon sequestration practices.

The first method validated by the Ministry for Ecological Transition was the Carbon Agri method (IDELE et al., 2019), which involves beef, dairy and tillage farms. In the frame of the LIFE Carbon Farming project, the European partners agreed to develop a harmonised MRV (Monitoring, Reporting, Verification) process, based on the Carbon Agri method, with slight adaptations (adding of new low carbon practices for instance). In this method, the overall farm is considered to assess the tons of CO_2-eq avoided, through Life Cycle Analysis (LCA), including the production and the transport of inputs to the farm. The analysis ends at the farm gate (i.e. activities beyond the farm gate, such as product processing, are excluded), and the functional unit used is the kg CO_2-eq/kg of product.

The baseline scenario is determined from an initial carbon audit of the farm, which is carried out by an advisor. Once the baseline is determined, the farmer and the advisor build a mitigation action plan by choosing the most appropriate low carbon practices from a list of available options. These practices cover all aspects relating to the 'technical' working of the farm, including inputs, fuel and electricity consumption, crop management, fertiliser application, herd management, feed and manure management, in order to reduce GHG emissions, and land management to increase carbon sequestration. The project lifetime is five years. During this time, implementation of the mitigation practices on-farm is supervised by the advisor, with a mid-term visit to assess if the farmer is on-target and if he or she continues with the low-carbon project or not.

At the end of the project, a final carbon audit is carried out by the advisor to determine the amount of carbon avoided (i.e. reduction and removal of emissions). This calculation is expressed per production unit. It takes into account the year of implementation of the low-carbon practices. Indeed, the earlier a practice is put in place, the greater an impact it has to reduce GHG emissions. Furthermore, other indicators are monitored in the project: biodiversity, ammonia emissions, water quality, renewable energy production, soya consumption, irrigation, surfaces with plant cover, and quantity of products sold through direct distribution.

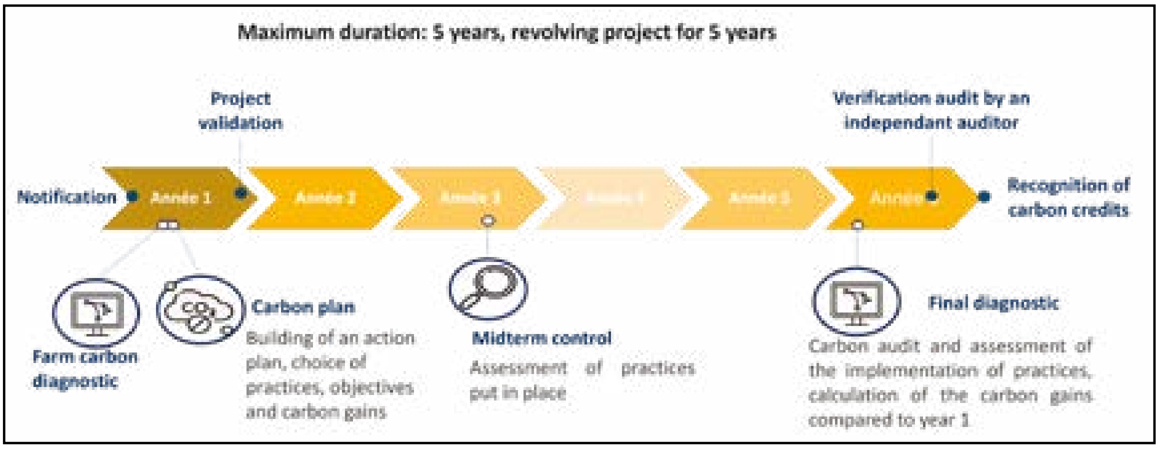

Figure 1: The stages (Anneé) of a low carbon project in France

According to the simulations carried out in the LIFE Carbon Farming project, farmers decide to put in place around 4 and 5 practices. For instance, one of the LIFE Carbon Farming farms located in France could avoid 435 t CO_2-eq by implementing the following mitigation action plan:

- Direct seeding on 155 ha
- Seeding of legumes on 5 ha
- Increasing grazing length to 75 days per year
- Improvement of the equipment to spread slurry.
- Biogas plant

This farmer has 69 dairy cows and 203 ha, of which 164 ha is tillage and 10 ha is permanent grassland. The initial carbon footprint of the milk is 0.86 kg CO_2-eq/L and should be reduced to 0.78 kg CO_2-eq/L. On average, French farms in the LIFE Carbon Farming project should avoid 600 t CO_2-eq during the 5 years of their projects. Applying this LIFE project’s goal of avoiding 15% of emissions in 5 years to average Irish beef and dairy farms, we obtain the following results:

Table 1: Projected avoided emissions and carbon income for typical Irish farms in a 5-year low carbon project

Enterprise	**Suckler Beef**	**Dairy**
Farm size, ha	34	40
Stocking rate, LU/ha	1.6	2.1
GHG emission, t CO2 eq/ha	6.2	11
GHG emission, t CO2-eq/farm	210	428
Carbon price, euro/t CO2 equiv.	32	32
LIFE carbon farming targets	15	15
Emissions avoided, %	15	15
Emissions avoided, t CO2 equiv./farm	31	64
Carbon income, euro/farm	992	2048
National targets		
Emissions avoided, %	25	25
Emissions avoided, t CO2 equiv./farm	53	107
Carbon income, euro/farm	1696	3424

3. Implications for stakeholders

a. Farmers

Through several European, national and regional programs, farmers have been involved in low-carbon projects. In France, most of the time, the recruitment and the follow-up of these farmers is carried out by local organisations such as regional Chambers of Agriculture, breeders' associations, cooperatives and advisory companies. To qualify for low-carbon projects, French farmers must commit to do the following activities:

Two carbon assessments with an advisor at the beginning and at the end of the project, meaning that several data and documents must be made available to fill in carbon audit tools.

Building of a carbon action plan listing the practices to be put in place and the objectives to be reached.

Implementation of low carbon practices on farms. The action plan can be changed at any time by adding new practices or on the contrary withdrawing planned ones.

Formalise their involvement with a contracting procedure.

Comply with the external audit at the end of the project.

The certification process aims at rewarding farmers for their results. If the initial targets are not reached, there will be no consequence for the farmer, except that the payment will be lower than expected.

b. Policy makers

In France, policy makers took the lead and created the Label Bas Carbone certification framework, enabling the submission of sectoral methods by experts and stakeholders. These methods are verified and approved by the Ministry. Its role is then to validate the files received from project developers and therefore to certify these low carbon projects. At the end of the projects, once the external audit has been carried out by an independent auditor and the tons of CO_2-eq avoided verified, the Ministry finally recognises the emissions reductions. The Ministry is also constantly exchanging with the developers of methodologies to clarify if needed the implementation of the methods on field, and to discuss about the changes to bring to the methods.

c. Industry

The Label Bas Carbone certifies emissions reductions. These certificates are sold on the voluntary carbon market. In order to avoid double-counting, once the certificates have been purchased by a company, they are not transferable to another one, and the identity of the funder is published on a register of the Ministry. The companies buying these certificates are from a wide variety of sectors, including agri-food industries, but also banks, luxury companies etc., and have diverse low-carbon strategies. Some of them aim to reduce the GHG emissions on all of their value chain, including scope 1, scope 2, and scope 3. For example, Lidl France chose to pay its beef suppliers to implement low-carbon projects on their farms. Other companies buy these Label Bas Carbone certificates to voluntarily offset their residual emissions or to contribute to the low-carbon transition.

Finally, following a recent law approved by the parliament, coal-fired power plants have the obligation to offset their emissions. The price defined in French law specifically addressing these types of emissions is €50/tonne of CO_2-eq, and it is mandatory to fund French low-carbon projects, such as Label Bas Carbone projects.

d. Aggregator

The aggregator is the organisation whose role is to make the link between the farmers, the advisory companies, the Ministry for Ecological Transition and the companies buying carbon credits. In France, breeders' associations decided to create France Carbon Agri (FCAA, 2021) to endorse this role of aggregator. The missions of the FCAA are:

- Act as a representative for the farmers. This means that it carries out the administrative process to propose farmers' files to the Ministry to get the labelling.

- Make the link with the external auditor.
- Propose low-carbon projects to companies wishing to contribute to the low-carbon transition by funding the farmers.

To formalize these partnerships, FCAA draws up contracting procedures specifying the obligations of the farmer, the advisor and the buyer, including the price of the carbon credit sold by FCAA. Today it is at €40/tonne of CO_2-eq including €32 for the farmer, €5 for the advisory company and €3 for the FCAA. It represents around €19,000 for a farm avoiding 600 t CO_2-eq, corresponding to an income of €115/ha.

4. Future research needs

In 2022, the European Commission published its proposal for a Union certification framework for carbon removals (European Commission, 2022). This framework would work with a panel of experts validating the methods submitted and verification by an external auditor. Furthermore, it would take into account general indicators of sustainability, not only those related to GHG, and it would deal with the issues of additionality and long-term storage. According to trilogue negotiations, this framework would only certify carbon sequestration and soils emissions reductions. However, the commission will be in charge of a report to assess the feasibility of including livestock emissions reductions, by July 2026. In the meantime, first methodologies are expected to be published by the end of 2024. Moreover, a Union-wide registry will be created to identify certified carbon removal units.

Simultaneously, the European Commission is also investigating the possibility to include the agricultural sector in an emissions trading system. To that extent, it raises the question of what part of the value chain should bear this pricing of emissions. Three options have been analysed at the moment: on-farm ETS (for all GHG or livestock or peatlands emissions), upstream ETS (fertiliser producers and importers), and downstream ETS (meat and dairy processors).

5. Conclusion

Funding the transition towards a low-carbon agriculture is an integral part of the European strategy to become the first climate neutral continent by 2050. The Label Bas Carbone created by the French Ministry for Ecological Transition is one of the ways to earmark funds towards low-carbon projects in France. It also ensures the quality of these projects by verifying the emissions reductions and monitoring other environmental indicators. To upscale this French initiative, it has been expanded to five other countries in Europe with a pilot project, the LIFE Carbon Farming project. On a larger scale, the European Commission decided to create a certification framework too, that should be published at the end of 2024. Furthermore, alongside the increase of low-carbon projects, rules must be clarified regarding funding opportunities, and how they are considered between offsetting, contribution or emissions reduction.

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Pathways to climate neutral farming systems

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1. Introduction

The EU's sustainable growth policy, the Green Deal, aims to curb climate change by cutting greenhouse gas (GHG) emissions and enhancing carbon removals. Ireland is supporting the EU Green Deal through implementing the Climate Action Plan mandated in the Climate Action and Low Carbon Development Bill 2021. The Bill legally commits the nation to a 51% reduction in GHG emissions by 2030 relative to 2018 levels, and requires the state to reach climate neutrality by 2050. Climate neutrality in an Irish context means a sustainable economy where GHG emissions are balanced or exceeded by the removal of GHGs.

Achieving the ambitious national targets requires concerted action from all sectors of the economy, including agriculture. In contrast to most European nations, agriculture accounts for a major share (35%-40%) of Ireland's GHG emissions (Duffy et al., 2023). This is in part because Irish agriculture is comprised mainly of pasture-based ruminant livestock systems i.e. beef, dairy and sheep farms. It is also caused by the lack of heavy industries in Ireland, which tend to dilute agriculture related emissions in industrialised nations. Last year, Teagasc re-examined the capacity to mitigate agricultural GHG emissions using a marginal abatement potential curve (MACC). The third version of the Teagasc GHG MACC showed the sector can meet the 2030 climate commitments by widely adopting existing mitigation practices, and by developing and implementing new technologies e.g., feed additives (Lanigan et al., 2023). Post 2030, Irish farmers will need additional emission reduction and removal technologies to become climate neutral. This study seeks to develop pathways to climate neutrality for some of the Teagasc Signpost demonstration farms, namely beef, dairy, sheep and tillage farms. For these farms, climate neutrality was evaluated on a territorial basis with the Intergovernmental Panel on Climate Change (IPCC) methodology.

2. Pathways to farm neutrality

Before plotting a pathway to neutrality, it is important to establish the starting point to assess the size of the task across different farm systems. The Teagasc National Farm Survey (NFS) is a nationally representative sample of approximately 850 farms from across Ireland. Data from the Teagasc NFS represent the Irish component of the European Union's Farm Accountancy Data Network (FADN) dataset. However, the data collected in the Teagasc NFS surpasses the requirements of FADN, giving the Teagasc NFS dataset much more capacity to measure and track developments in agricultural sustainability. Teagasc publishes an annual sustainability report, which outlines the economic, environmental and social position across a number of farm systems. This report included GHG emission at farm scale across dairy, cattle, sheep and tillage farms using the national GHG inventory report methodology for agricultural and energy sectors. The GHG emissions profile of these farm system types is presented below in Table 1 (Buckley & Donnellan, 2023).

Table 1: Farm and Emissions profile by farm system type, in 2022, using Teagasc National Farm Survey

Farm Type	Dairy	Cattle	Sheep	Tillage - Average	Tillage - No Livestock
Sample No.	262	333	106	73	27
Population Represented	15,323	48,227	13,979	6,246	2,393
UAA[1] (ha)	64.8	34.8	45.0	63.9	78.4
Total LU[2]	134.3	42.7	50.2	32.1	0.0
Gross GHG emissions (t CO_2-eq/ha)	9.6	4.6	3.5	2.1	0.8

[1] Utilised agricultural area, [2] Livestock unit

The objective of the Teagasc MACC is to identify the most cost-effective mitigation pathway to reduce GHG emissions and enhance carbon sequestration in the Agricultural, Land-Use, Land-Use Change, Forestry and Bioenergy sectors. This is achieved by assessing the abatement potential of GHG mitigation measures and the associated costs of adoption. The Teagasc MACC is an important report for the agricultural industry as it assists stakeholders in making informed decisions on achieving targets such as climate neutrality, by providing insight into the cost effectiveness and abatement potential of mitigation measures. While the MACC report is at a sectoral level, farm level plans can be created by identifying mitigation measure appropriate for individual farms. To demonstrate how the MACC can be applied at farm level to achieve neutrality, four Teagasc Signpost demonstration farms, each representing a beef, dairy, sheep and tillage farm, were modelled from the sample of farms. The farms selected were; 1) a highly stocked progressive dairy system, 2) a suckler-to-weanling/store beef system, 3) tillage systems with and without livestock and a 4) highly stocked sheep system with high ewe prolificacy.

To determine the starting point for each system, enterprise specific life cycle assessment models developed by Teagasc (Foley et al., 2011; Farrell et al 2022; Herron et al. 2022) were populated with farm activity data collected as part of the Teagasc Signpost programme. This establishes the "Baseline", or starting point for each system. To achieve neutrality, the farms first must adopt available and emerging measures outlined in the Teagasc MACC. To establish the "Target" system, these measures were applied to the relevant system:

- **Ruminant systems**: fertiliser measures (quantity, type), feed measures (quantity, quality, source, additives), manure measures (timing, additives), and production measures (EBI, age of finishing, age at lambing).
- **Tillage systems:** straw incorporation and cover crops.

Consistent with the Teagasc NFS sustainability report and the national climate targets, the scope of this study includes emissions from the agricultural and energy sector. Emissions are presented on a per hectare basis as a proxy for total farm GHG emissions. Three GHG emissions scenarios were simulated:

1. Gross – Baseline systems simulated, and Target systems simulated with a high adoption rate for available and emerging mitigation measures. The measures adopted are tailored to the type of farming system.
2. Net - The Target systems with the inclusion of C sequestration in soils and hedgerows. All farms are on mineral soils, an average sequestration rate of 0.64 t C/ha was used (Murphy et al. 2024). Carbon sequestration rates for hedgerow were calculated using LiDar measurement of hedgerow length and the new hedgerow model (Black et al., 2023).
3. Split – Building on the Net scenario but treating short and long-life greenhouse gases separately: Biogenic methane meeting Methane Pledge (IEA, 2022) commitment (10% reduction) and long-life gases (CO_2, N_2O) balanced by removals to achieve neutrality.

Table 2: Greenhouse gas emissions (tonne CO_2-eq/ha) from selected dairy, beef, sheep and tillage farms participating in the Teagasc Signpost programme

	System	Dairy	Cattle	Sheep	Tillage - Average	Tillage - No Livestock
Gross emissions	Baseline	12.0	5.3	8.7	1.0	0.6
	Target	9.6	4.3	7.0	0.9	0.5
Net emissions	Target	7.8	2.5	5.2	-0.1	-0.5
Split emissions	Target	0.4	-0.6	0.0	NE[1]	NE

[1] Not estimated

The farming systems, most notably the ruminant systems, had higher GHG emissions/ha in comparison to their respective averages in the NFS (Table 1). This was due to the selected farms having higher stocking rates and production per ha in comparison to NFS average. Being part of the Teagasc Signpost programme, all four farming systems had already adopted a number of the mitigation strategies outlined in the Teagasc MACC. However, as evident when comparing Baseline with Target scenarios further mitigation can be achieved.

Transitioning towards the Target system reduced gross GHG emissions from the dairy, beef, and sheep systems by 2.5, 1.0, and 1.7 t CO_2-eq/ha, respectively. However, gross GHG emissions alone do not capture the true flux of GHG emissions from agricultural systems.

When C sequestration by practices such as cover crop and straw incorporation were included in the Net scenario for the tillage system, climate neutrality was achieved. In contrast, no ruminant system achieved climate neutrality in the Net scenario despite the adoption of the current MACC mitigation measures and the addition of C sequestration through appropriate management of mineral soils and hedgerows. The removal of C on the selected Signpost farms was not sufficient to balance GHG emissions, in particular enteric methane emissions. The NFS average farms had lower gross GHG emissions per ha than the Signpost farms, and thus would have lower Net GHG emissions per ha if the same C sequestration rate was applied. However, while all Signpost farms in this analysis are managed on mineral soils, the nationally representative sample of NFS farms operate on a range of soil types, including organo-mineral or peat soils, which have been noted as source of C emissions rather than removal.

A key criticism of the IPCC’s Global Warming Potential is its inability to distinguish the behaviour of short- and long-lived greenhouse gases in the atmosphere, with calls to adopt a “split” gas approach when creating GHG reduction targets (Lynch et al., 2020). In the “Split” scenario, biogenic methane emissions were reduced in line with the Global Methane Pledge, with residual long life GHG (CO_2 and N_2O) emissions needing to be balanced by carbon removal to achieve climate neutrality. By taking a split gas approach, the beef and sheep systems achieved climate neutrality. The dairy system was still a net emitter of GHG emissions albeit 0.4 t CO_2-eq/ha. The dairy system fell short as emissions driven by stocking rate exceeded the farm C removals implemented.

3. Future research needs

Improvement in the efficacy of existing mitigation measures and the development of new measures is urgently needed to reduce emissions of CH_4, N_2O and CO_2 from agricultural sources, in particular:

- Development of methane reducing feed and slurry additives for incorporation into grazed grassland systems.
- Further breeding and selection of low emitting ruminants to enhance methane abatement potential.
- Research and demonstration to increase the integration of trees with agricultural systems to enhance carbon capture and other ecosystem services such as biodiversity and water quality.

The adoption rates assumed in this analysis and under Pathway 2 within the latest Teagasc MACC analysis are very ambitious. Historically change happens slowly or incrementally and not uniformly across the farming population. Additional research to elucidate what drives change around adoption across different cohorts of farms as a one size fits all policy approach is not likely to produce the desired level of adoption of mitigation measures, this will establish the barriers and enable policymakers to tailor a mix of instruments (e.g. incentives, regulation, education & extension) to enhance the uptake of mitigation measures.

Data collection will be needed to measure and verify management change at farm level on its journey to climate neutrality. Data integration will be central in this process. AgNav, a digital sustainability platform, developed by Teagasc, ICBF, and Bord Bia with the support of the Department of Agriculture Food and the Marine will provide farmers with accurate and verifiable information to support decision making on farm to help meet agriculture’s climate targets (Herron et al., 2023). To achieve this, data integration is at the core of AgNav. A selection of the GHG mitigation measures in the Teagasc MACC have already been incorporated into AgNav. Over time, AgNav will have more of the mitigation measures in the Teagasc MACC, including carbon removal practices. This should better reflect the overall GHG balance at farm level and provide a tool to support carbon farming.

This analysis used an average soil C sequestration rate, however it is important to note that large uncertainties exist, with grassland soils on the dairy farm in Johnstown Castle ranging from a sink of 2.65t C/ha per year to a source of 1.88 t C/ha per year. Due to the drought in 2018, Johnstown Castle soils were observed to emit rather than sequester C, thus highlighting volatility and the need for long-term measurement. Furthermore, the farms in this analysis were all managed on mineral soils. If farms were managed or partly managed on organo-mineral or peat soils, achieving climate neutrality would be even more difficult, if not impossible, as such soils are viewed as a major source of GHG emissions under the Land-use, Land-use change and Forestry sector in the National GHG inventory.

Further research is required to improve our understanding of the factors influencing GHG emission from agricultural systems. Examples of such research are presented by Murphy et al. (2024) and Saunders et al. (2024) who highlighted the considerable research effort across Teagasc and the Universities to reduce uncertainties through the refinement of GHG emission factors and carbon sequestration rates for mineral and organic soils. This research will provide soil type specific land-use, land management and climate emission factors that can be coupled with high resolution soil maps. There is a need to provide farmers with field and farm specific soil maps that build on the existing national soil maps available for Ireland. The soil information system has mapped Irish soils at a scale of 1:250,000, but this is insufficient for field and farm specific soil mapping to underpin carbon farming. New soil maps are required, utilising more recent soil sampling and geophysical surveys of Irish soils to create a derived soil map to support carbon farming and soil health monitoring.

4. Conclusion

The rapid adoption of existing mitigation measures and the development of new emerging technologies is urgent to ensure the Irish agricultural sector achieves sector targets set out in the National Climate Action Plan. Accounting for C removals can partially balance agricultural GHG emissions with residual GHG emissions occurring in ruminant systems. To achieve climate neutrality further C removal will be required. When separate targets are set for biogenic methane and long life GHG emissions, nearly all systems achieved climate neutrality. Further research into soil types and factors influencing soil C sequestration is required to reduce uncertainties.

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Farming on peat soils – Experiences from FarmPEAT EIP

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1.Introduction

The FarmPEAT Project EIP is a pilot project funded by the EU Recovery Instrument Funding under the Rural Development Programme 2014-2022. This pilot was set up in 2021 in order to design and trial a results-based agri-environmental scheme with farmers who farm on peat soils around raised bogs in the midlands of Ireland. Another main objective of the project was to increase awareness of the importance of peat soils in terms of climate, water quality and biodiversity both within the local farming community and the wider local communities.

The FarmPEAT Project worked with 36 pilot farmers in Year 1 and this has increased to 49 farmers to date. These farmers have helped design the pilot agri-environmental scheme and their input and engagement has been vital to the success of the project. There is no obligation on any famer to undertake any specific actions on their farm as part of the FarmPEAT Project. The only obligation that is asked of them is to allow their farm to be assessed by the FarmPEAT Team, to engage with the Team and to attend one training day a year.

One of our main focus areas is farming on peat soils and how this can be best done to reduce greenhouse gas emissions from drained peat, while also benefitting biodiversity, water quality and the farmers. Some farmers (5) have undertaken drain management actions to rewet some of their peat soils and an additional two farmers are planning to follow suit. In other words 14% of farmers are committed to undertaking, or have undertaken, drain management actions to rewet peat soils. We are interested in exploring why some farmers are willing to do this and others are not.

Increasing awareness of the importance of appropriate management of peat soils among farmers, local school children and the wider local community is an important part of the project. We believe that sharing the latest knowledge and up-to-date science with farmers is an important factor in influencing decisions on farm management and educating local school children is a way of influencing future decision makers, landowners, farmers and policy-makers. However, we also felt that it was important to have the support and understanding of the local communities and so we have reached out to local community groups at our project sites to share knowledge and ideas.

2. The Results-Based Approach

Results-based agri-environment schemes are where farmers are paid to deliver a specific result or outcome. They differ from the more traditional approach to agri-environment schemes which were typically action-based schemes where farmers are paid to complete an action irrespective of the quality of the intended outcome. However, in a results-based (RB) scheme, farmers are paid depending on the quality of specific results delivered on their farm (generally environmental quality of the land). In a way, RB schemes create a market for ecological goods and services of the land.

The FarmPEAT Project's main focus in the results-based agri-environment scheme was to design a scheme that would pay farmers for managing farmed peat soils in a way that was beneficial, or more beneficial, for climate, water quality and biodiversity. However, we decided to take a whole-farm approach and so the scheme also pays farmers for managing peatlands, semi-natural grasslands, woodlands, hedgerows and treelines on their farms, irrespective of soil type.

Table 1: Payment rates for plots in the FarmPEAT scheme

Plot Score	Payment rate (€/ha)
0	0
1	25
2	50
3	75
4	150
5	200
6	250
7	300
8	350
9	400
10	450

Most results-based agri-environment schemes use a scoring system in order to assess the quality of the desired ecological result and have a payment rate associated with each possible score. In FarmPEAT, we used scorecards from existing, well-established and successful RB schemes in Ireland as a foundation to design our own scorecard – schemes such as The Burren Project, the Pearl Mussel Project, the Hen Harrier Project and others. The scorecard is designed to be relatively simple and straightforward to use, but the importance of proper consideration to its design cannot be overstated. If the scorecard is designed correctly and the farmers understand it, it serves as a good communication tool to the farmers who can see clearly what the desired outcomes are and they can modify their farming practices to maximise their score/payment if they wish. As the scorecard is essentially the method of incentivising change or of maintaining certain management practices, it is crucial that it is designed correctly to ensure that appropriate actions/results are incentivised.

The results-based payment issued to each farmer is based on the score of each plot. Each plot receives a score between 0 and 10 with 0 reflecting low ecological value (and probably high agricultural value) and 10 indicating very high ecological value (and probably a low agricultural value). A plot that achieves the highest score of 10, will receive a payment of €450/ha. Payment rates for plots are shown in Table 1. Based on this payment system, the average annual payment in the FarmPEAT Project over three years is €2,442 per farmer. These payments are not for carbon credits, but they do incentivise carbon emission reduction and maintenance and enhancement of existing carbon stocks on farms.

3. Farms and Case Study

There is a variation in terms of farmers' willingness to undertake 'carbon farming' or drain management actions on their peaty soils. We have found that there are a variety of factors that will influence this – factors such as if are they full-time or part-time farmers, the type of farm enterprise, the make-up of their farmland, in what condition their peat soils are and their succession status. A big factor is the strength of the desire to 'do the right thing' for future generations and what they believe this to look like. Farmers need absolute certainty from the scientific community that actions that go against all previous professional advice, which supported increased farm productivity and government schemes, are beyond contradiction and are the correct actions to follow for the best climate outcome. Financial compensation on its own may not be enough to sway some farmers who would see some of the actions that are asked of them as undoing their lives' hard work.

Table 2: Summary of farm types in the FarmPEAT Project and of those farms that are committed to drain management on peat soils

	Number of farmers in FarmPEAT	% breakdown of categories of farmers in FarmPEAT	% (number in brackets) breakdown of farmers who have undertaken, or committed to, drain management actions on their peat soils
Predominantly Dairy	4	8%	0% (0)
Predominantly Tillage	1	2%	0% (0)
Sheep/Beef	45	88%	86% (6)
Other	1	2%	14% (1)
Total	**51**	**100%**	**100% (7)**

Within the FarmPEAT Project farmers, average farm size is 27 ha. The peat soils on the farms cover an average of 41% of the farm with a range from 4% to 89%. A summary of the types of farms that are within the FarmPEAT Project and those that have undertaken or are committed to undertaking, drain management actions on peat soils, is given below in Table 2 above.

Case Study A

Farmer	Full-Time, Sheep/Beef
Farm Size (within Project Area)	34 ha
% Peat Soils	35%
Length of drain impacted by raising the watertable	140 m
Approx. area of peat soil with raised water-table	1.2 ha
No. of dams installed	6
Type of dams:	Peat (4), Peat/Soil mix (1) and Plastic (1)
Installed by	Contractor

Adjustable pipe in peat dam gives flexibility and control with farmer – can adjust height of water in drain. Plastic notch can be made lower or wider. This flexibility is key.

Plastic dam being installed on Case Study Farm A on 7th Feb 2023

Drain one week after installation of dams

Drain one week after installation of dams

4. What's the Future of Farming on Peat?

The FarmPEAT EIP is due to end in December 2024 and the farmers are keen to continue to receive financial rewards for farming their peaty soils in a carbon-friendly manner that also benefits biodiversity and water-quality. They are currently left with questions such as: Are carbon-credits the way that we will get funding for this in the future? How will the carbon be quantified and verified? Can a results-based approach be used as part of a carbon-farming system?

The FarmPEAT Project Team share these queries and below are some thoughts we have on the subject developed over the last couple of years working with these farmers.

- What is the baseline? Will farmers who have undertaken peat soil restoration measures as part of EIPs or other projects be able to access further financial support?
- Price of carbon units needs to be high enough to attract farmers and reward adequately but not so high as to attract large companies to buy up large tracts of land in rural Ireland
- Carbon credit should be linked strongly to biodiversity and water-quality, i.e. the accumulation of carbon or reduction of GHG emissions should not occur at the expense of water quality or biodiversity. We would see a carefully designed results-based approach as being a potential way to provide this balance.
- Verification for carbon/biodiversity needs to be thorough and of a very high standard

If a results-based approach is going to be used, FarmPEAT believes that further work is needed to:

- Develop and refine a suitable scorecard for carbon-farming (to include water-quality and biodiversity)
- Develop robust training for scorecard users to ensure consistence across time and space
- Conduct research into the distance from drains where water-table impacts are seen as a result of drain management actions
- Conduct research to determine the magnitude of the impact on watertable from drain management actions

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Poster Abstracts

Heterogeneity in the effect of GHG mitigation strategies on Irish dairy farms

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The agricultural sector is increasingly under pressure to participate in the greenhouse gas (GHG) emission reduction effort and reach carbon targets. Significant improvements can be achieved through the adoption of new farm technologies, as suggested by the Teagasc Marginal Abatement Cost Curves and the AgClimatise strategy of the Department of Agriculture, Food and the Marine (DAFM). However, it is unclear whether and how the effect of promoted technologies varies across farms. There can be delays in achieving desired policy outcomes if technologies are not adopted as quickly as first assumed and if they do not deliver the expected result. In this context, the objective of this study is to assess how the effect of GHG mitigation strategies varies along the distribution of Irish dairy farms. Specifically, we explore differential effects for lower- vs higher-emitting farms.

We use a 2016-2020 unbalanced panel dataset from the Teagasc National Farm Survey (NFS). The data is combined with information from the Irish Cattle Breeding Federation (ICBF) database. We focus on a subsample of 678 observations that account for 159 dairy specialised farms, remaining on average 4.3 years in the panel. Farm GHG emissions are modelled with a life cycle assessment (LCA) model. We consider two separate outcome variables; GHG intensity measured as dairy GHG emissions per unit of product (g of carbon dioxide equivalent (CO_2e) per kg of fat-protein-corrected-milk (GHG)), and absolute GHG measured as dairy GHG emissions per land area allocated to dairy animals (kg CO_2e per hectare). The effects of various technologies are estimated with two-way fixed effects (FE) unconditional quantile regression models (Q) along the distribution of both GHG outcome variables. In this way, we compare the effects on lower- and higher-emitting farms. Model results are also compared to mean-estimated effects that are obtained through a two-way FE linear regression model (ordinary least squares (OLS)). The technologies under study are those currently promoted through AgClimatise. They include nitrogen use efficiency (NUE), length of grazing season, the share of homegrown feed in dairy cow diet, average calving interval, optimal age at calving, and bulk tank somatic cell count (BTSCC).

The results reveal that only 23.6% of farms achieve the same performance in terms of both GHG intensity and absolute GHG. In line with this, we find that technologies that reduce absolute GHG do not necessarily improve GHG intensity (e.g., homegrown diet, calving interval), and vice versa. Moreover, the estimation results show that all studied technologies show some GHG-reducing effect, but this can vary by percentile of the GHG distributions. Specifically, some technologies have an insignificant effect in certain parts of the GHG distributions (e.g., NUE). In the case of grazing season, we also find that the effect is positive for lower-emitting farms, while it is negative for higher-emitting farms. Overall, estimations at the mean do not provide the full picture. Finally, our findings reveal that higher-emitting farms have more mitigation potential than lower-emitting farms. This is because technology effects tend to be larger for higher-emitting farms. These farms also exhibit lower levels of technology implementation. The effect of GHG mitigation technologies is heterogeneous across farms. Consequently, estimations at the mean can be misleading and mitigation measures should be farm specific. Thus, our study demonstrates the importance of tailoring extension advice and policy to mitigate emissions effectively.

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Farmer awareness & preferences for GHG mitigation measures

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In the Republic of Ireland, the agricultural sector accounted for 38.4% of total greenhouse gas (GHG) in 2022. A climate action law was enacted in Ireland that set down a binding 25% reduction target for GHG emissions from the agricultural sector by 2030 (from a 2018 base) and movement towards climate neutrality by 2050. Teagasc published a strategy document based on marginal abatement cost curve analysis in 2023, which sets down the most cost-effective pathways to reduce GHG emissions at farm level across Ireland. Previous iterations of this strategy were published in 2012 and 2018 yet uptake of proposed mitigation measures by farmers has been mixed. This analysis explores the awareness and willingness of farmers to adopt a suite of mitigation measures that could reduce farm level GHG emissions as proposed under the Teagasc 2023 MACC report.

Based on a survey of 400 farms contained within the Teagasc National Farm Survey (NFS) the awareness and willingness of farmers to adopt a range of mitigation measures was elicited. Technologies examined include feed additives, slurry additives, low emission slurry spreading, sexed semen based artificial insemination, protected urea fertiliser, clover and multispecies swards as well as more established practices like forestry and hedgerow planting, organic farming, liming and reduced livestock numbers. The awareness of these as mitigation measures and there likely future uptake by farmers was assessed via Likert scale type questions, where farmers were asked how aware they were of the measure (1=unaware & 5=very aware) and how likely they were to adopt in the future under certain conditions (1=very unlikely & 5=very likely).

Preliminary analysis indicates a higher level of awareness among farmers of the mitigation potential of more traditional practices such as liming, clover, LESS and hedgerows (mean awareness score of circa 4 and above). There was however a lower level of awareness of more emerging technologies such as slurry and feed additives. In terms of likely adoption, measures such as covering slurry stores, LESS, liming and sowing cover crops were the most likely to be adopted, followed interestingly by the emerging technologies (slurry and feed additives). The bottom 3 measures in terms of likely adoption revolved around reductions in agricultural activity namely reducing livestock numbers, converting agricultural land to forestry and re-wetting soils. However, results vary by farm system type and farmer profile and additional analysis is required to explore this in detail.

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Carbon dynamics of Irish forest types - promoting resilient sustainable carbon sinks

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Climate change poses a significant threat to the carbon (C) sequestration capacity of Irish forests, exacerbated by heightened risks from escalating climate extremes such as intense rainfall and drought. ADAPTForRes is a project dedicated to assessing forest management options and identifying enhanced climate-smart mitigation strategies. The research presented here is aimed towards identifying adaptive forest management strategies to promote resilient sustainable carbon sinks in the face of escalating climate extremes.

In this project, we utilise the Eddy Covariance (EC) technique to investigate the C flux dynamics of three distinct forest types: commercial Sitka spruce coniferous forest on mineral soil, broadleaf-dominated native woodland on mineral soil, and a mixed species (Norway spruce and Birch) forest on peat soil. Inter-annual variability of Net Ecosystem Exchange (NEE) is assessed to improve understanding of how exceptional climate events (intense rainfall, increasing temperatures) impact Irish forests ability to uptake carbon and mitigate climate change.

Advanced footprint analyses have been employed to address the heterogeneous nature of the native Irish forest studied here – acknowledging challenges posed by dynamic forest management practices, diversity in vegetative distribution and complex terrain. This approach provides additional insight into the flux dynamics from the forest compartments and encompasses management practices (thinning, clearfelling, underplanting), phenology (budburst, leaf expansion, senescence), inventory (species, ages, height), and disease outbreak information. The additional parameters generated from this analysis enhances data richness, allowing for a greater understanding of ecosystem C dynamics and intra-annual variability of NEE.

Initial results suggest that the Sitka spruce forest nearing the end of its first rotation assimilates the most C of the three study sites. Winter carbon uptake rates remain high, which may be linked to a delay in growth cessation induced by higher mean temperatures in winter periods. The native deciduous broadleaved forest shows near C neutrality due to the age/maturity of the stand and high quantities of decaying biomass on the forest floor. A year of exceptionally high NEE was measured, potentially associated with climate anomalies (such as high levels of summer precipitation), ash dieback and understory vegetation dynamics. The C dynamics of the Norway spruce/Silver birch mixed forest were dominated by high levels of ecosystem respiration driven by the high organic content of the soil and low water table heights in summer.

Climate, management and underlying soil type significantly impact the carbon uptake and release rates of the forests examined here. High levels of inter-annual variability in NEE was observed at the mature broadleaf forest, partially driven by anomalous climate events and disease outbreak. Further data collection is necessary to determine (i) the feasibility of afforesting drained peatlands and (ii) carbon losses associated with clearfell events. Results should inform adaptive forest management decisions that consider future climates and the impact on both forest health and ability to uptake carbon.

Farm-level decision support tool to enhance economic and environmental performance in an Irish context

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Amidst the significant sustainability challenges faced by global agriculture, including the degradation of the environment and uncertain economic implications, integrated farming systems emerge as a potential solution. In the context of Ireland, where the majority of emissions stem from enteric fermentation, greater integration of crop and livestock systems could provide a desirable balance of emission reduction and economic performance.

One of the most practical and effective optimisation techniques used in farm planning is mathematical modelling. This tool enables advisors and farmers to simulate various scenarios and assess the outcomes before making decisions. By considering factors such as crop rotations, input usage, market prices, and environmental considerations, these models provide a comprehensive view of the farm's operations. Through mathematical optimisation, farmers can determine the most efficient allocation of resources, such as land, labour, and capital, to achieve their production goals while upholding sustainability.

Firstly, the approach explores system-level integration. HOLOS-IE, an established Life Cycle Assessment tool intertwined with enterprise budgeting methodology, is utilised by developing the economic component of a systems-based framework. Production inputs are combined circularly, considering synergies between production enterprises. HOLOS-IE encompasses a variety of crop and livestock enterprises, allowing for the evaluation of mixed farming systems. Secondly, a more detailed focus on the dairy farming system and the potential to optimise profit while meeting greenhouse gas (GHG) emission goals is provided through an IBM CPLEX software system. Preliminary results illustrate potential synergies between production resources that impact revenues, costs, and GHG emissions.

In conclusion, by using a whole-farm bio-economic model to calculate GHG emissions and economic performance, we can effectively assess integrated systems and create financial and emission plans at farm level. These tools facilitate farmers' decision-making, aid authorities in policy planning, and contribute to restructuring the agricultural sector to enhance environmental and economic sustainability.

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Quantifying baseline soil organic carbon in depth to assess the impact of land use systems on carbon in agricultural lands of Ireland

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Soil organic carbon (SOC) stocks mediate several ecosystem services relevant to food production, such as nutrient cycling, water supply, biodiversity, carbon sequestration, and climate regulation. But at the same time, SOC stocks in agricultural systems tend to decrease. However, the impact of different agroecosystems and land management practices is not fully understood, especially for carbon stored below 30 cm depth. We postulate intensive systems and management practices affect SOC stocks beyond 30 cm depth. The goals of our study were: a) Build an accurate baseline of SOC stocks at depth to improve the carbon accounting framework in agricultural lands; b) assess the impact of different agroecosystems on SOC dynamics; and c) expand our understanding of the carbon to develop sustainable systems.

Under the Signpost Programme, Teagasc leads a multiannual soil sampling campaign. During 2023, our team sampled 37 farms, covering 148 soil profiles, and collected about 592 soil samples. In each farm, we selected four sampling sites at different landscape positions trying to capture multiple combinations between soil types, agricultural systems, and land management practices combinations. We sampled at four depths (0-15, 15-30, 30-45, 45-60 cm) using three methods; single samples from pits, bulk density rings, and composite samples using soil cores, following a “W” shape in an area of 30 x 30 m around the pit. The samples from the pit became the reference values of carbon, whereas the composite sample helped to estimate the natural variability of the carbon stocks within the same field. The carbon content was estimated in the lab, by combustion of samples at 950 °C. Bulk density and stoniness were used to calculate the carbon stocks.

Our results suggest that tillage farms had the lowest SOC stock, presenting an average of 81 t/ha for 0-60 cm profile. The topsoil of tillage farms registered low values (34 t/ha) due to the constant tillage and harvesting activities. In permanent grassland, carbon stocks were 90 to 94 t/ha for the entire profile, containing 42 to 48 t SOC/ha in the first 15 cm, 23%-41% more than croplands. This increase is partly explained by the permanent cover on the surface that reduces exposure of carbon to the atmosphere. Improved grassland had the highest SOC, especially on Luvisols, reaching values of 121 t/ha for the entire profile. The first 15 cm had 40 t SOC/ha, exhibiting a general increase in the whole profile. These high values are associated with the high clay content in the soil that protects carbon against microbial activity. In addition, they receive inputs of organic manure and farmers implemented full inversion tillage during reseeding. This practice relocated carbon in the subsoil. Soil organic carbon stocks were determined by the combination of soil types, agricultural systems, and management practices. Furthermore, an adequate combination of management practices can boost carbon sequestration. Finally, SOC from 30-60 cm depth should be considered when reporting stocks as it’s affected by management practices.

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MIR and NIR spectroscopy combined with chemometrics can predict soil carbon and other attributes

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Determining total organic carbon (TOC), bulk density and clay content is essential for understanding soil health, fertility, and its role in the global carbon cycle. Traditional methods for soil analysis often involve labour-intensive and time-consuming laboratory procedures. However, advancements in spectroscopy, specifically Mid-Infrared (MIR) and Near-Infrared (NIR) spectroscopy, offer efficient and non-destructive alternatives for soil analysis. These techniques leverage the unique absorption characteristics of soil components in the infrared region, allowing for rapid and accurate estimation of soil properties. MIR spectroscopy (4000 to 650 cm^{-1}), is particularly sensitive to the fundamental vibrational modes of soil organic matter and clay minerals. This makes it highly effective for detecting and quantifying soil carbon content and mineral composition. NIR spectroscopy (10,000 to 4000 cm^{-1} or 1000 to 2500 nm), is less sensitive than MIR, benefits from faster measurement times, being less affected by water and the ability to penetrate deeper into soil samples, showing potential for field analysis.

A systematic approach using MIR and NIR spectroscopy was augmented by including spectral control charts to identify unrepresentative spectra in the prediction of unknown samples. This step increased the confidence in the predicted results by identifying samples with spectral signatures outside the range contained in the calibration set. Samples classified as unrepresentative by the spectral control chart cannot be predicted by spectral models and must be analysed using the reference method. About 1,000 samples from a spectral library of 10,000 samples (Peat = 3145, Non-Peat = 6855), representing an area of approximately 35,716 km^2, were selected for laboratory analysis using classical wet chemistry methods. The MIR and NIR spectra of these samples, combined with their clay, TOC, and clay reference values were used to build spectral regression models using chemometrics algorithms. To predict TOC, clay and bulk density from the other 5,855 non-peat soils, a spectral control chart was used to identify unrepresentative samples. Samples classified as under control were predicted, and the soil properties maps were built.

For clay content, the proposed methodology was used to predict clay values from 5855 soil samples; of these samples, 5254 samples were classified as under control (~ 90%), and the remaining (n = 601) were classified as "out of control" i.e. not predicted by the spectroscopy model. From these 5254 samples predicted, we selected ~2% (n=280) to be sent to the laboratory for classical chemistry analysis to validate the methodology. For the TOC and bulk density validation, ~3000 and 200 samples, respectively, were used as an external validation set. The accuracy obtained for external validation was the same as that obtained initially by the spectroscopy models for clay, TOC, and bulk density. This shows that the proposed methodology could predict TOC, bulk density and clay content in an accurate way.

MIR and NIR Spectroscopy can predict soil particle size, bulk density, and carbon, among other parameters in Irish soils. To guarantee the accuracy of soil analysis, spectral control charts are necessary. This saves time and costs when building regional and national-scale soil maps.

AgNav: A digital sustainability platform for Irish agriculture

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Building on years of collaboration, Teagasc, the Irish Cattle Breeders Federation (ICBF), and Bord Bia with the support of the Department of Agriculture Food and the Marine are developing AgNav, a digital sustainability platform that will provide farmers and advisors with information to support decision making on farm to help meet agriculture’s climate targets. AgNav aims to present the environmental performance of commercial farms and will provide the user with a live decision support tool that communicates the benefits of best practice adoption. This platform will be used to develop bespoke farm sustainability plans. The three core elements of AgNav are – Assess, Analyse and Act.

The ‘Assess’ feature AgNav establishes a baseline for a given farm. Through data integration and farmer consent, AgNav collates farm data residing in existing databases to build a picture of each unique farming system. The Bord Bia Quality Assurance Scheme captures data such as fertiliser use, concentrates and manure management. The ICBF data provides animal identification, inventory, movement, and production data. Integration of this data allows a Life Cycle Assessment (LCA) of the farm can be completed. The underpinning LCA models have been developed through years of Teagasc research to calculate GHG emissions, ammonia emissions and other environmental indicators of the farming system. This will then be used to provide a “starting point” as to where the farm is in terms of GHG emissions.

The second element – ‘Analyse’ – is a live decision support tool, which allows the AgNav user to assess the effect of different mitigation strategies, at different adoption rates, on a given farm GHG and ammonia emissions on total farm and product basis. Following analysis, the final step is the Action Planner, through which the farmer and the advisor develops a farm-specific action plan to identify the practices that will make a difference on their farm in terms of sustainable performance. AgNav (www.agnav.ie) will be available to all Irish livestock farmers, regardless of their affiliation with the platform’s partners once the pilot phase has been completed.

Prediction of soil bulk density in agricultural soils using mid-infrared spectroscopy

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Soil carbon is recognised as a natural carbon sequestration measure to enhance CO_2 removal beyond greenhouse gas (GHG) cutting measures for climate change remediation. Hence, soil carbon stock baseline assessment and soil monitoring in carbon farming programmes are urgently needed. Soil bulk density (BD) is a key physical parameter in soil quality control and in the calculation from soil organic carbon (SOC) mass (g/kg) content to area stock (kg/ha). However, BD laboratory analysis is time-consuming, labour intensive and expensive, especially for a national-scale soil assessment. Hence, how to fill the omissions of BD values for records in soil databases is widely discussed.

This study employed different chemometric and machine learning algorithms to estimate BD in Irish soil from 671 horizon-based samples from Mid-Infrared (MIR) spectral libraries by partial least square regression (PLSR), random forest, cubist and support vector machine (SVM). The results were compared on different horizon types, specific depth categories, and overall performance with published pedo-transfer functions (PTFs) to assess if the spectral soil BD model could be a potential new methodology for filling BD missing in national soil carbon stocks and sequestration projects.

The best performance was observed in the SVM model with higher RPIQ (3.61) and R^2 (0.81) values and lower prediction error (RMSEP = 0.132 g/cm^3). With relationship analysis, soil BD was identified to be highly correlated with soil organic matter (SOM). This was proved in principal component analysis (PCA) on pre-processed MIR spectra and variable importance analysis in PLSR and Cubist models, in which SOM-related wavenumber bands were used in model establishment with higher importance. Moreover, the results show that the spectral soil BD model obtained significantly better results than traditional PTFs on overall, with RMSEP equalling 0.132 g/cm^3 and 0.196 g/cm^3 receptively. The spectral soil BD model shows a similar accuracy on the A horizon with a slight decrease of RMSEP compared to traditional PTFs, but considerable improvements were found on other horizon types. As for different depth categories, there is no accuracy difference between shallow (A-Samples: 5-20 cm) and deep (S-Samples: 35-50 cm) topsoil for the spectral soil BD model, which is the opposite for traditional PTFs. In terms of the model performance on topsoil and subsoil, even though sharp decreases of accuracy were observed between above-50cm-samples and below-50cm-samples, both on spectral soil BD model and traditional PTFs, considering the range of soil BD (0.22-1.97 g/cm^3) and its variance (0.33 g/cm^3), the accuracy of spectral SVM model on below-50cm-samples (RMSEP = 0.197 g/cm^3) was acceptable.

In conclusion, compared to traditional PTFs, the spectral soil BD model combined with chemometrics and machine learning algorithms shows several benefits, such as high accuracy and the homogeneity of performance on different depth layers above 50 cm. These characteristics can be noteworthy strengths of spectral modelling techniques when carrying out national soil surveys and large-scale carbon stock assessments. However, it still should be warned that the accuracy of the spectral soil BD model might be distorted by samples with extreme BD values caused by compaction, which should be investigated in detail in future research.

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Assessing the Cost and Benefits of Carbon-Sequestration Measures – The CarboSeq Project

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Carbon sequestration in soils is a negative emission technology that can contribute to mitigation of climate change. However, for European soils, a comprehensive assessment is missing on how much soil organic carbon (SOC) can be sequestered with different management options using also national data on agricultural management. In 2022, the EU Commission introduced "fit for 55" legislation that requires all the member states to remove approximately 310 million tonnes of CO_2 emissions in the land use, land use change and forestry (LULUCF) sector. The aim of CarboSeq is thus to estimate the feasible SOC sequestration potential taking into account technical and socio-economic constraints.

One major constraint for the implementation of SOC sequestration measures among others arises from quantification of the related cost and sequestration potential. Under CarboSeq, the cost and effectiveness of a range of mitigation measures will be assessed using marginal abatement curve methodology. The study adopts the use of Eurostat amongst other national macro and farm-level datasets to assess the carbon sequestration potentials, costs, cost-effectiveness and cost-benefit analysis of measures to include 1. Tillage operations 2. Planting of cover crops 3. Crop rotation 4. Land-use change from pasture to silvopasture 5. The practice of alley cropping 6. Hedgerow planting 7. Crop residue management 8. Biochar 9. Irrigation. These measures are assessed under different implementation scenarios. The measures are assessed at a farm-level (hectare) and aggregate-level (country-level). The bottom-up approach to MACC was used.

Preliminary results obtained from farm-level analysis for the Republic of Ireland showed that the planting of cover crops where crops are harvested and the replacement of inversion tillage with zero tillage are cost-beneficial. In addition, the use of cover crops when harvested also reported a cost-beneficial scenario. However, other measures such as legumes in crop rotation, land use change from cropland to grassland, land use change from grassland to agroforestry, the practice of alley cropping and the use of irrigation facilities among others are ranked as being cost-effective to cost-prohibitive measures. The study also intends to further explore how the ranking of these measures varies across EU member states.

Most of the abatement measures considered in this study are essential for sequestering carbon, reducing GHG emissions, and mitigating climate change. The analysis conducted at both the farm and aggregate levels will aid various stakeholders and guide policy formulation while also allowing for farm-level decision-making.

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Evaluation of DayCent performance to simulate C fluxes in Irish grassland ecosystem

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The Climate Action Plan envisages a 51% reduction in national greenhouse gas (GHG) emissions by 2030, with agriculture set the goal of achieving climate neutrality by 2050 (CAP, 2024). The Teagasc Marginal Abatement Cost Curve (MACC) 2023 outlines various measures that can significantly enhance carbon (C) sinks; however, wider adoption of the mitigation strategies requires evaluation of their potential across a range of soil and climatic conditions. Ecosystem process-based models that are capable of capturing complex dynamics in soil-crop-atmosphere systems provide effective and robust tools to understand and quantify soil GHG emission responses to changes in management. The aim of this study is to evaluate the performance of DayCent model to simulate C fluxes in grazed and fertilized grassland ecosystem using data from the long-term experiment in Johnstown Castle.

Field data (2009-2020) collected from the Johnstown Castle experiment was used in model calibration and evaluation, paddock 11 and 10, respectively. The site is managed for silage production and livestock grazing (3.2 LU/ha) and receives mineral fertilisers (20-80 kg N/ha). DayCent is an ecosystem model of an intermediate complexity used to simulate the daily flows of C and nutrients. To establish the initial distribution of soil C pools, a long-term simulation (1650 years) was performed with the model until equilibrium ('spin-up run') assuming native deciduous forest. Following deforestation, the simulation of land use history assumed these changes in the land use and land management: a) 1653-1900-occasional grazing b) From 1901 low fertilisation, grazing and silage production. Both (spin up and experiment-specific) simulations were driven by site-specific weather data from Met Eireann. The model was calibrated to improve performance in simulating daily soil water content (2019-2020), seasonal grass silage yield (2009-2020), daily NEE (2019-2020), in this order following the calibration protocol. The model performance was evaluated against independent data from paddock 10, with a slightly different management during the experimental period. Evaluation involved statistical criteria: root mean square error (RMSE), relative root mean square error (rRMSE) and modelling efficiency (ME).

Model performance to simulate seasonal grass silage yield, daily NEE, daily GPP, daily ecosystem respiration, daily soil temperature was improved compared to the default simulation i.e., all these observations were reproduced by the calibrated model with lower rRMSE and higher ME except for NEE. The greatest improvement was observed in simulating the seasonal grass silage yield where rRMSE was reduced by 81% and model efficiency went from -9.46 to 0.66. Daily ecosystem respiration as well as daily GPP was underestimated by 10.4% and 8.6%, respectively. Despite satisfactory overall performance, DayCent failed to produce the magnitude of the peaks of NEE. Based on the performance in simulating C fluxes in the long-term grazed grassland experiment, DayCent has potential to be further tested at different sites under different management conditions.

DayCent model calibration to assess the long-term impact of animal slurry application on grassland in Ireland: Performance, sensitivities and scope for improvement

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Measurement of changes in soil organic carbon (C) under various management practices at the field scale poses significant challenges due to inherent spatial and temporal variability. Ecosystem and biogeochemical models offer a robust framework for simulating nutrient cycling, soil C and greenhouse gas emissions. They can be used to identify and evaluate long-term effects and strengths of climate change mitigation strategies. DayCent is a coupled soil-plant dynamic model that has been widely used to simulate long-term ecosystem responses to changes in soil management and climate in the US. Its application to agricultural systems in Ireland requires calibration and evaluation for common management practices across a range of pedo-climatic conditions. The objectives of this study were a) to calibrate the DayCent model with several types of field data and to evaluate its performance in simulating soil C and soil N_2O emissions, and b) to explore relationships between model parameters and types of field data. We aimed to simulate the effects of a long-term application of dairy, pig and mineral fertilizers on grass yields, soil organic C and nitrogen stocks and soil N_2O fluxes in a long-term permanent grassland at Hillsborough.

In order to improve model performance under Irish conditions, the control and high-rate pig slurry application treatment data from 1970 to 2022 were used to calibrate parameter values. This was to ensure an equal contribution of different data types to the overall model error at the beginning of the calibration process driven both manually and by the PEST parameter estimation software. PEST was further used to conduct sensitivity analysis. All remaining treatments, differing in the rate and type of fertilizer and animal slurry application, were used in the independent model evaluation. The performance of calibrated model was substantially improved for grass yield (rRMSE=0.19, r^2=0.75, d=0.93) compared to the default model (rRMSE=1.08, r^2=0.03, d=0.48) across all validation treatments. Similarly, an improvement has been observed for annual soil C stock from the validation treatments (rRMSE=0.08, r^2=0.80, d=0.93) compared to the default model (rRMSE=0.29, r^2=0.46, d=0.50). Daily soil N_2O fluxes are not simulated well potentially due to the missing peaks during the discontinuous measurements.

DayCent successfully simulated the long-term dynamics of soil C and nitrogen stocks, annual N_2O emissions, grass yields, soil water content, and soil temperature across varying nutrient application rates and therefore might become a robust tool for optimizing nutrient management strategies under Irish conditions.

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