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.

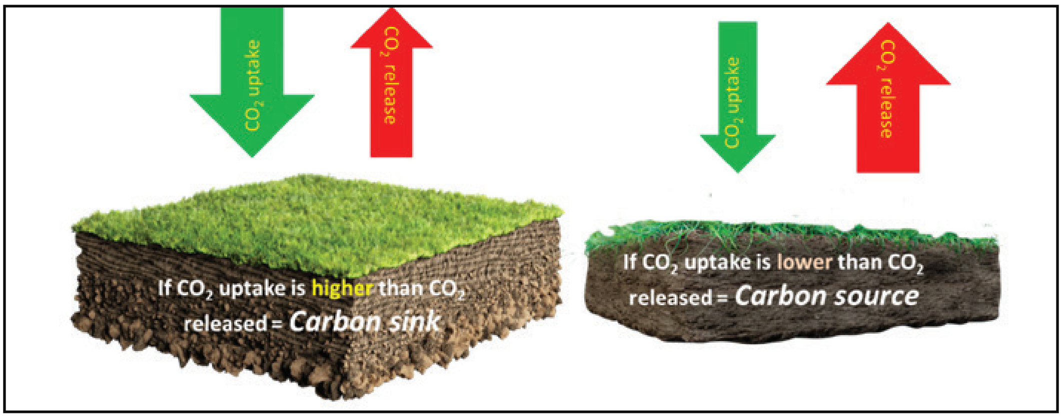

Figure 1: Schematic of soil acting as a C sink and a C source.

The typical carbon balance for an improved Irish grassland soil indicated the potential range in soil carbon sequestration ranges from 1.5 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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