LAND USE for NET ZERO HUB

14 Things We Learned About the Science of Soil Carbon Sequestration with Helaina Black and Pete Smith

TALKING HEADS

This conversation is the ninth instalment in a series of Talking Heads interviews with the LUNZ Soil Health and Carbon Dynamics TAG community. Throughout this series we will explore the key themes that the community will be working on throughout the LUNZ project lifecycle.

In this instalment, TAG lead Ellen Fay (Sustainable Soils Alliance) speaks to soil carbon expert and TAG co-lead Professor Pete Smith (University of Aberdeen), and Helaina Black, Honorary Associate with the James Hutton Institute and chief scientist at Agricarbon, a company that looks at direct measurement to support soil carbon projects.

The article below provides a summary of the key takeaways from the interview. The full interview can be viewed on the LUNZ YouTube channel.

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1. Evaluating Soil Carbon Claims: A scientific Checklist

When assessing soil carbon studies in the media, Helaina highlights the devil is always in the detail. It is important to look beyond headlines and ask: Is there sufficient methodological information that could enable a repeat of this study? Are the statistical techniques robust? Does the headline accurately reflect what the original authors actually said? Miscommunication between research and media reporting is unfortunately common. It can also be useful to consider the credibility of the research team, the length of the study, and examine funding sources for potential vested interests that might influence how results are communicated. A study should also acknowledge its limits and areas requiring further research, as no study is ever complete.

Key takeaway

Scientific rigour is paramount. To validate soil carbon claims, scrutinise the study's methodology, statistics, and funding transparency, not just the headline.

2. The Methane-Carbon Compensation Myth

Pete explained that when soil carbon increases, it removes carbon dioxide from the atmosphere, which is positive for climate mitigation. In theory, greenhouse gases can be compared based on their warming effects over a 100-year timescale, allowing carbon dioxide sequestration to be weighed against methane or nitrous oxide emissions. However, this approach is contested because methane behaves differently—it has a much shorter lifespan in the atmosphere (around 12 years) but is far more potent during that time.

Because of this, methane reductions are seen as an urgent and highly effective way to slow warming in the near term, acting as an "emergency brake." Soil carbon sequestration, while beneficial, happens slowly and cannot fully offset ongoing methane emissions. This is not an "either-or" situation—both strategies are needed. In many grassland systems, the focus may be less on increasing soil carbon dramatically (since levels are already relatively high) and more on maintaining existing stores. Ultimately, reducing methane emissions remains critical, alongside efforts to build and preserve soil carbon, to achieve climate goals.

Key takeaway

Methane and soil carbon are separate challenges. Reducing short-lived, potent methane is an "emergency brake" we can use to slow temperature rise quickly, while sequestering carbon in soils is a slow, long-term necessity—both are required for climate goals.

3. Sequestration vs Removal: Precision in Terminology

Terminology and definitions concerning carbon sequestration vary and create confusion. Helaina recommends using the IPCC definitions which provide clarity in this confused landscape:

- **Carbon sequestration:** A broad, scientific term describing the natural process by which carbon moves into and is stored in soils, typically through plants. This process happens regardless of human involvement—it's essentially the biogeochemical mechanism of carbon being locked into soils.
- **Carbon removal:** Specifically refers to deliberate human actions and interventions designed to take carbon dioxide out of the atmosphere and store it, often in soils. This distinction is important because removals are actively managed and are also used in corporate and policy reporting, in parallel to reporting GHG reductions.

Adopting clearer definitions—like those from the IPCC—across both science and business could help reduce confusion and ensure consistent understanding of these terms.

Key takeaway

Terminology matters. Carbon sequestration refers to the natural process whereby carbon is locked up by soils; carbon removal refers to deliberate, human-managed intervention.

4. Understanding Soil Carbon Saturation and Emissions

Pete explained that soils can only store a limited amount of carbon because carbon binds to soil particles, aggregates, and mineral surfaces. Once these are full—like a bucket filled with water—additional carbon cannot be retained. Grassland soils are often already rich in carbon and therefore closer to this equilibrium or "saturation" point. In contrast, degraded or cropland soils, which may have lost 40–60% of their original carbon, offer greater potential for carbon sequestration because they are "half-empty buckets."

Helaina added that this process is dynamic rather than fixed. Soil carbon levels depend on a balance between inputs (carbon going in) and outputs (carbon released). While soils have an inherent storage capacity, agricultural practices have depleted carbon levels in many areas. To meaningfully increase soil carbon, management practices must change—altering what goes in or reducing what comes out. She emphasised the need for realism: while soils may have theoretical capacity to hold more carbon, in practice, increases depend on sustained changes in land use and management. Saturation may be a limiting factor, but the real challenge lies in managing inputs and outputs to enhance and maintain soil carbon stocks.

Expanding on the bucket analogy, Pete explained how soils operate in a balance between inputs (organic matter entering the soil) and outputs (mainly CO_2 released through respiration of microbes and plant roots). When soils are at or near saturation, additional inputs are offset by equal losses, much like water spilling over the sides of a full bucket. At this point, carbon levels can no longer increase, and the focus shifts to maintenance—preserving existing carbon stocks. Importantly, if soils degrade, large amounts of carbon can be lost quickly as CO_2, worsening climate change. Beyond respiration, other processes drive carbon losses, including erosion losses and through dissolved organic carbon. Even in high-carbon grasslands, while adding more carbon may be difficult, slowing losses is both possible and critical. Management strategies—such as reducing erosion, altering plant types, or improving soil structure—can help minimize outputs and sometimes increase inputs. Ultimately, the challenge is not only about adding carbon but also about protecting what is already stored by understanding where and how losses occur.

Key takeaway

Soils have a carbon saturation/equilibrium point. Carbon-depleted soils have the potential for new sequestration, while high-carbon soils have low capacity to store additional carbon, and for these maintaining carbon stocks must be the priority. Soil carbon storage capacity is a dynamic rather than fixed process - increasing soil carbon requires sustained changes in management.

5. Permanence vs Durability in Climate Strategies

Again, there are different definitions of what 'permanence' refers to. Once more, Helaina recommends looking at existing guidelines. The Integrity Council for the voluntary carbon market recommends any project or anyone reporting carbon removal should be looking at a 40-year period for permanence. Some global soil carbon projects are looking at 100 years. The ultimate goal should be maintaining soil carbon indefinitely for its broader benefits: soil health, agricultural system resilience, and ecosystem services. Whilst the idea of "permanence" in carbon markets exists primarily to prevent gaming the system - claiming credits one year then losing the carbon through poor management the next - "durability" better captures the concept because different storage mechanisms have different timeframes.

Helaina explained the complexity of permanence in cropping systems, where crop rotations naturally cause carbon levels to rise and fall. For example, potato cultivation in Scotland can reduce soil carbon, but within a seven-year rotation the overall carbon stock may still increase. These dynamics challenge rigid interpretations of permanence and highlights the need for more research on the interaction between crop rotations and soil carbon cycling. The European carbon farming regulations actually classify soils as "non-permanent" carbon removal, distinct from "permanent" solutions like biochar or rock weathering. Permanence rules must accommodate this variability while preventing genuine losses.

Key takeaway

"Durability" is a more useful term than "permanence" (which is binary). Soil carbon sequestration timeframes vary by soil type, land management and climate zone. Monitoring soil carbon removals needs to reflect this rather than attempt to operate to rigid time scales. In parallel, there needs to be adequate consideration of preventing long-term losses of soil carbon due to poor management.

6. Grasslands vs Arable:

While much media attention focuses on livestock and ruminant systems—especially dairy—there is significant progress in low-carbon practices within the arable sector. Commercial companies are increasingly aiming to reduce greenhouse gas emissions from their supply chains, leading to widespread adoption of regenerative practices in arable farming. However, there is often confusion between having large soil carbon stocks in grasslands and actual carbon sequestration.

Pete further clarified that true carbon neutrality in beef production is extremely difficult. Some media claims about "carbon neutral beef" are misleading, confusing the large existing carbon stocks with ongoing sequestration. The presence of high carbon stocks does not equate to net removal of CO_2 from the atmosphere. Methane emissions from cattle cannot be offset merely by soil carbon in pastures – we cannot increase soil carbon enough to offset the warming caused by methane from ruminants. Achieving a carbon-neutral or carbon-negative farm (rather than the beef!) is possible only with additional interventions, such as dedicating a portion of farmland to tree planting, which, for a time, can sequester carbon over time to offset emissions. While grass-fed or pasture-based systems may have benefits for animal welfare, biodiversity, and landscape aesthetics, these should not be conflated with climate mitigation.

Key takeaway

Carbon-neutral beef is misleading. Methane emissions from cattle cannot be offset by existing soil carbon stocks in grasslands (large stocks do not equal large sequestration potential); achieving a carbon-neutral farm requires additional interventions such as tree planting.

7. Tools for Farm-Level Net Zero

Two distinct but overlapping toolsets exists to help farmers move towards Net Zero:

- **Net Zero Guidance Tools:** Simplified (Tier 1 and 2) models help farmers identify emission sources and removal opportunities across whole farming systems. These tools consider the broader farming system, not just soil carbon, and may be used to support voluntary reporting of farm carbon footprints by companies under scope 3 emissions reductions guidelines. Practical examples show the value of these tools. For instance, farmers using the Cool Farm Tool for organic egg production in the U.S. reduced emissions by nearly 25% over three years, not through mandated interventions, but through peer-to-peer learning and system understanding.
- **Carbon Monitoring, Verification and Reporting (MRV) Tools:** In contrast, tools for verifying carbon removals for Scope 3 or Voluntary Carbon Markets are more specialized. Here there is the option to use direct measurement alone or combine measurement with modelling. Direct measurement of soil carbon removals follows strict sampling, analysis, and uncertainty reporting requirements while measure and model approaches requires the use of sophisticated (Tier 3) models with stringent requirements for model validation along with sampling and uncertainty reporting. High-tier models require significant expertise and detailed data, making them challenging for individual farmers to navigate without support.

The key difference is that net zero tools consider entire farming systems while verification tools focus specifically on soil greenhouse gas emissions and removals. Contrary to assumptions, soil carbon projects using model-measure require regular and detailed management data from land managers, creating significant and often underestimated burdens.

Key takeaway

Net Zero tools guide whole-farm emissions reductions, while MRV tools focus on reporting soil carbon removals for defined areas of land.

8. Standards and Guidance: Who Sets the Rules?

Multiple levels of guidance for reporting carbon emissions and reductions exist:

- **International Level:** At the highest level, guidance comes from the IPCC through national greenhouse gas inventories, with tiered methodologies (tier one, two, and three) designed to allow countries with varying capacities to report emissions. There is also the Science Based Target initiative (SBTi) and Land Sector and Removals Guidance (LRSG) for Scope 3 reporting and the Integrity Council for the Voluntary Carbon Market (ICVCM).
- **Voluntary Markets:** VCM protocol organisations develop their own methods through expert input and consultation with obligations to meet international guidance (e.g. ICVCM). These methods vary in relevance and requirements and therefore require careful evaluation for suitability and robustness before use.
- **Regional and National Level:** Countries like Australia have developed robust carbon farming guidelines combining modelling and measurement for their emissions trading systems. The EU is developing methodologies for carbon farming initiatives in compliance markets.

Helaina emphasised that while high-level standards and protocols provide guidance, the real challenge lies in implementation on the ground. This involves field sampling, laboratory analysis, quality assurance, transport of samples, and precise documentation of all procedures. Audits for voluntary carbon markets will scrutinise this documentation, not just the claim that a certain methodology was followed. She stressed that uncertainties must be reported transparently and that small methodological details—like the number of soil cores collected or lab analysis techniques—can determine the credibility of reported carbon removals. While protocols and standards exist for measuring and reporting carbon removals, they often do not provide detailed, actionable guidance for farmers on how to actually achieve those outcomes – and each carbon project is unique, influenced by location, soil type, farming system, and management practices, meaning there is no “one-size-fits-all” recipe.

Key takeaway

Multiple levels of standards exist (international, national, regional) with a wide array of guidance and methods. For all, however, transparency with documentation is a critical component for assurance around soil carbon removals claims. While standards and guidance are continually improved, a real challenge is with implementation on the ground. Therefore, methods need to be consistent but adaptable to ensure that projects are feasible and affordable as well as robust.

9. Operationalising Guidance – the Real Challenge

While current protocols focus heavily on monitoring, verification and reporting (MRV), less attention has been given to helping farmers decide which management practices will maximize soil carbon sequestration in their specific context. Factors such as location, landscape, soil type, soil depth, weather, current practices, and intended future practices all dictate what is feasible. Every Carbon Project is different and every scenario is different. Operationalising guidance—like specifying how to take soil samples, how many, and at what depth—is critical for credibility and success. However, it is challenging and potentially unrealistic to provide definitive detailed operational guidance that can meet every project's needs. Peer-to-peer knowledge exchange and expert support can be essential in helping to bridge the gap between more generic guidance and project specific implementation. The academic and scientific communities could play a key role in providing trusted, practical advice—essentially acting as guides to help farmers navigate these complexities, make pragmatic decisions, and implement effective practices that are achievable, affordable, and reliable.

Helaina also highlighted that soil carbon methodologies are constantly evolving, reflecting a unique moment in soil science. Current carbon projects are generating unprecedented amounts of data at scales between individual farms and broader regions—scales that historically lacked sufficient data. This new information helps answer practical questions about sampling intensity, soil depths, and other field-level details, which in turn informs the refinement of methodologies and guidance. An example highlighted was Verra's collaboration with the scientific community to produce a soil sampling handbook for improved agricultural management, aiming to bridge the gap between high-level standards and on-the-ground practice. While no methodology is perfect, Helaina stressed the importance of community engagement and iterative feedback. By participating in consultations and sharing insights, scientists and practitioners can help refine methodologies, reduce uncertainties, and improve reporting, rather than fixating on finding a single flawless standard from the outset.

Key takeaway

Scientific research is critical to understanding which management practices could deliver reliable soil carbon removals for different farming systems. While standards provide guidance on how to measure, monitor and verify soil carbon removals claims, continual engagement of the scientific community is essential for providing trusted, practical advice on how to implement, and therefore improve, standards and guidance.

10. Understanding Models and their Applications

Pete emphasised that models are only as good as the data fed into them and should not be relied upon in isolation. Their primary value lies in projecting carbon sequestration potential over longer time frames, given knowledge of soil type, local climate, and current and planned management practices. Models can help compare management options, plan strategies, and anticipate outcomes, but measurements in the field must remain the primary source of truth, with models validated against actual observations. Any claims of carbon removals, especially for crediting, must eventually be confirmed with real measurements, rather than relying solely on modelled projections.

Current methodologies often require baseline measurements and a re-sampling period (e.g., five years), but detecting changes in soil carbon over such short periods can be challenging. There is uncertainty and a lack of clarity about how well model predictions should align with measured outcomes, creating a gap in standards that the academic community could help address. A proposed solution is to combine the strengths of modelling and repeated measurement, using models to project trajectories and guide management, while using remeasurements as the definitive verification of carbon removals. This hybrid approach allows for realistic tracking of carbon sequestration over time, providing both guidance for farmers and confidence in reported outcomes.

Key takeaway

Models must be integrated with on-the-ground sampling. Models can be used as planning tools to project the long-term potential for soil carbon sequestration, but they must be validated by repeated field measurements, which remain the definitive source of truth for carbon removal claims.

11. Policy-maker Guidance on Models

Models are often misunderstood as a cheaper, easier alternative to field measurements, but in reality, both are essential. Direct measurements provide the primary data to verify carbon removals, while models help project trajectories, explore management options, and fill gaps over time. Neither can operate effectively in isolation: models require real-world measurements for calibration and validation, and measurements alone cannot provide a forward view of trends or scenario outcomes for specific management changes. Policy discussions must reflect that modelling is a support tool, not a replacement for field data.

Collecting the detailed management, meteorological, and auxiliary data required to run models can be time-consuming, making engagement with projects more onerous than it may appear. The burden on farmers, in particular, to provide that information, can be underestimated and undervalued. One solution could be gaining better access to pre-existing, consistent farm data, such as the information already submitted for subsidies or other schemes, which could reduce the effort and cost for both farmers and projects. Models and measurements must be integrated carefully, with proper recognition of the data requirements and practical challenges on the ground.

Key takeaway

Modelling can act as a support tool, not as a replacement for field data. Commercial carbon verification projects (Tier 3) demand extensive data, creating a significant and often underestimated burden on farmers.

12. Key Messages for the Modelling Community

Helaina and Pete suggested the following improvements could be made:

- **Simplicity**: Keep models parsimonious and simple enough to understand and document transparently, rather than trying to include every possible process.
- **Transparency**: Most models do not provide sufficient information about prediction errors, making it hard to design cost-effective sampling strategies that help to reduce reporting uncertainties. Models need clear documentation of prediction errors and how they function.
- **Using ensemble modelling approaches:** Similar to those used in climate science, where multiple models are run in parallel to provide a more robust picture of expected outcomes. This reduces reliance on a single model and improves confidence in predictions, as well as allowing us to better quantify uncertainty.
- **Performance criteria**: Develop standardised metrics allowing non-experts to select appropriate models for their circumstances.

Key takeaway

Model reliability requires simplicity and transparent documentation of prediction errors. The use of more than one model (called ensemble modelling) can reduce reliance on a single model projection and can help to quantify uncertainty.

13. Inventory and Intervention Scope 3 Reporting Explained

Two approaches exist for reporting soil carbon removals under corporate scope 3 reporting:

- **Inventory reporting**: Measuring changes against the baseline at the start of a project without accounting for what would have happened under business-as-usual management. This approach is simpler because it focuses solely on the observed change following the project's interventions.
- **Intervention reporting**: Calculating the difference between business-as-usual (BAU) versus the new management regime. This method is more involved but often preferred by those seeking to demonstrate the direct impact of their actions, especially when the results are tied to financial or other incentives.

Inventory reporting in scope 3 provides a simplified route, while intervention reporting captures the actual contribution of project interventions to carbon removals. Companies seeking value for their management changes typically prefer intervention reporting to demonstrate their specific contribution to carbon removal.

Key takeaway

Scope 3 soil carbon removals can be reported via inventory reporting (the difference between a baseline at a specific time point and subsequent resampling events) or intervention reporting (soil carbon removals attributable to a change in management). Intervention reporting requires more information and effort but is also used to deliver incentives associated with specific management practices.

14. The Scale Integration Challenge

A significant disconnect exists between commercial carbon projects operating at farm/regional scales and national-level reporting requirements. Projects generate valuable data at field to regional scales, but unclear mechanisms exist for integrating this information into national reporting systems. Some European countries are already looking to integrate carbon removals from land management into national reporting, but developing mechanisms that capture project-level information while providing appropriate national aggregation remains a crucial policy development need.

Key takeaway

Farm-level carbon projects produce rich data, but links to national reporting are unclear. Bridging this gap with mechanisms to aggregate project data into national inventories is an urgent policy priority.