Carbon Direct

Challenges and Opportunities in Soil Carbon Credits

Addressing obstacles in soil carbon measurement and durability

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Acronyms and abbreviations

CAR: Climate Action Reserve
CAR SEP: Climate Action Reserve Soil Enrichment Protocol
CCB: Climate, Community & Biodiversity Standards
CDR: carbon dioxide removal
CH_4: methane
CO_2: carbon dioxide
FPIC: free, prior, and informed consent
GHG: greenhouse gases
gSSURGO: Gridded Soil Survey Geographic Database
MMRV: measurement, monitoring, reporting, and verification
N_2O: nitrous oxide
SOC: soil organic carbon
US: United States
USDA: United States Department of Agriculture
VCM: voluntary carbon market

Executive summary

Soils have the potential to remove significant amounts of carbon dioxide from the atmosphere, offering a powerful tool in the fight against climate change. Estimates suggest a global potential of between 0.4[1] and 9.1[2] gigatonnes of additional carbon dioxide removal from soils annually,[3] with much of this potential coming from recovery of degraded agricultural soils. Regenerative agricultural practices like cover cropping and improved grazing management can facilitate this recovery. Regenerative agriculture can build soil carbon and provide co-benefits such as increased yields, improved soil health, and enhanced ecosystem resilience. However, current adoption of these practices remains low due to both technical and financial barriers.

Carbon finance can accelerate the adoption of regenerative practices and facilitate rapid growth of the soil carbon market. Likewise, buyers in the voluntary carbon market (VCM) can provide a strong demand signal for high-quality soil carbon credits. However, high-quality soil carbon projects have been slow to develop and demand signaling from buyers remains weak. Despite the numerous programs and protocols currently in place to generate soil carbon credits, the number of projects that have registered and issued credits for sale in the VCM is still very limited.

While soil carbon projects present many opportunities, including long-term co-benefits for farmers and improved ecosystem health,[4] several key concerns have limited buyer trust and slowed the development and procurement of soil carbon credits. This paper explores the challenges and opportunities around generating high-quality soil carbon credits, focusing specifically on two quality concerns critical for buyers making decisions about credit purchases: (1) rigorous measurement, monitoring, reporting, and verification (MMRV), and (2) the long-term durability of carbon stored in soils. We also provide key takeaways on both issues for buyers looking to leverage opportunities to scale-up soil carbon credit availability and quality in the VCM.

To drive more rigorous MMRV and address uncertainty in generating credits from soil carbon storage, buyers can signal demand for projects that:

- **Support model-based approaches** by focusing on cropping systems (e.g., cash crops), practice changes (e.g., conservation tillage, cover crops); and geographic regions (e.g., North America, Europe, Australia) where ample data are already available to support model-based approaches, and support ambitious data collection in regions where there are limited data to support these approaches.
- **Focus on highly productive systems** where sequestration rates are likely to be detectable sooner against background variability.

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[1] Intergovernmental Panel on Climate Change. 2022. Climate Change and Land: IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems. Cambridge: Cambridge University Press. https://doi.org/10.1017/9781009157988

[2] Lal R. 2018. Digging deeper: A holistic perspective of factors affecting soil organic carbon sequestration in agroecosystems. Global Change Biology. 24(8):3285–3301. https://doi.org/10.1111/gcb.14054.

[3] Intergovernmental Panel on Climate Change. 2023. Climate Change 2022 - Mitigation of Climate Change: Working Group III Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press. https://doi.org/10.1017/9781009157926.

[4] Rehberger E, West PC, Spillane C, McKeown PC. 2023. What climate and environmental benefits of regenerative agriculture practices? an evidence review. Environ Res Commun. 5(5):052001. https://doi.org/10.1088/2515-7620/acd6dc.

- **Aggregate many individual fields into a single, large-scope project**, such that uncertainty in individual fields tends to cancel out and generates lower overall project quantification uncertainty.
- **Employ a measure-and-model approach** leveraging remote sensing, machine learning, and other tools to increase the efficiency of sampling designs.
- **Gather robust datasets from appropriate long-term agricultural experiments** to support the model validation process.
- **Share proprietary collected datasets** to support the development of common benchmarking procedures for process models.
- **Address uncertainty effectively across all of the sources relevant to the project's quantification methodology,** follow best practices for combining sources of uncertainty into estimates of overall quantification uncertainty, and adjust credit volumes to ensure conservativeness in response to uncertainty estimates.

Buyers can take the following actions to bring the priorities of farmers and developers into alignment and increase credit durability:

- **Modify buyer claims to support short-term contracts.** Innovative accounting and crediting approaches such as tonne-year accounting and horizontal stacking can circumvent the need for long-term contracting.
    - For example, buyers who want to invest in soil carbon solutions could take a horizontal stacking approach to reporting that leverages short-term contracts.
    - Similarly, buyers could claim three- to five-year deferred emissions rather than durably stored soil organic carbon (SOC).
- **Create new approaches to contracting to align buyer priorities for durably stored carbon and farmer contract term preferences.**
    - Contracts can be modified to de-risk these concerns. For example, contracts can more flexibly accommodate deviations from regenerative practice changes to accommodate in-year growing conditions as-needed.
- **Signal support for additional novel financing mechanisms to enable practice change and maintenance.**
    - Buyers can help to de-risk practice adoption and sustained upkeep for farmers by signaling a willingness to pay for credits that stack incentives on top of carbon finance. Care should be taken to ensure that practice changes are additional, even with stacked financing sources.
    - Buyers can support innovative crop insurance models that support regenerative practices.

Solving these critical obstacles could unlock the potential for gigatonnes of annual carbon dioxide removal in soils, the availability of more durable soil carbon credits in the VCM, and increased confidence in MMRV approaches for soil carbon projects. Buyers can indicate their preference for projects, research priorities, and government policies that align farmer incentives with project goals, inspire confidence through rigorous MMRV approaches that reduce uncertainty, and support the long-term storage of carbon in soils.

Introduction

Techniques that increase stocks of soil carbon in agroecosystems provide a powerful tool in the fight against climate change. Estimates suggest the additional global carbon dioxide removal (CDR) potential of increased soil carbon stocks is between 0.4[5] and 9.1[6] gigatonnes annually.[7] Much of this potential comes from recovering degraded agricultural soils (including croplands and grazing lands), which are estimated to have lost up to 116 gigatonnes of carbon due to human activity.[8] One of the paths to restoring this lost soil carbon is a set of practices collectively referred to as regenerative agriculture.

Regenerative agricultural practices include multiple techniques that may build soil carbon. These techniques have been studied in a broad range of agricultural systems, from cover cropping in large-scale annual row crops to intensive multi-paddock grazing for livestock to agroforestry techniques for building carbon in smallholder perennial systems.[9] Thousands of studies and more than a hundred meta-analyses have been conducted to explore the efficacy of these techniques in different systems for building soil carbon.[10]

Although use of these techniques is growing around the world, the proportion of farmers using regenerative practices today remains relatively low in many places. Technical and financial barriers still prevent them from being common practice in most places. While in the long run these practices can result in healthier agricultural systems that are more resilient to perturbation, and may even result in increased yields in some instances, they can be expensive to adopt and may require farmer training for implementation. These are significant barriers to entry.

Carbon finance is often cited as one avenue for unblocking the adoption of regenerative practices, with long-term co-benefits including yield increases and improvements in soil and ecosystem health.[11] Soil carbon crediting programs pay farmers to implement carbon-sequestering regenerative practices and generate revenue through the sale of credits for carbon dioxide removal in soil (**figure 1**).

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[5] Intergovernmental Panel on Climate Change. 2022. Climate Change and Land: IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems. Cambridge: Cambridge University Press. https://doi.org/10.1017/9781009157988
[6] Lal R. 2018. Digging deeper: A holistic perspective of factors affecting soil organic carbon sequestration in agroecosystems. Global Change Biology. 24(8):3285–3301. https://doi.org/10.1111/gcb.14054.
[7] Intergovernmental Panel on Climate Change. 2023. Climate Change 2022 - Mitigation of Climate Change: Working Group III Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press. https://doi.org/10.1017/9781009157926.
[8] Sanderman J, Hengl T, Fiske GJ. 2017. Soil carbon debt of 12,000 years of human land use. Proceedings of the National Academy of Sciences. 114(36):9575–9580. https://doi.org/10.1073/pnas.1706103114.
[9] Beillouin D, et al. 2022. A global overview of studies about land management, land-use change, and climate change effects on soil organic carbon. Global Change Biology. 28(4):1690–1702. https://doi.org/10.1111/gcb.15998.
[10] Beillouin D, et al. 2022. A global database of land management, land-use change and climate change effects on soil organic carbon. Sci Data. 9(1):228. https://doi.org/10.1038/s41597-022-01318-1.
[11] Rehberger E, West PC, Spillane C, McKeown PC. 2023. What climate and environmental benefits of regenerative agriculture practices? an evidence review. Environ Res Commun. 5(5):052001. https://doi.org/10.1088/2515-7620/acd6dc.

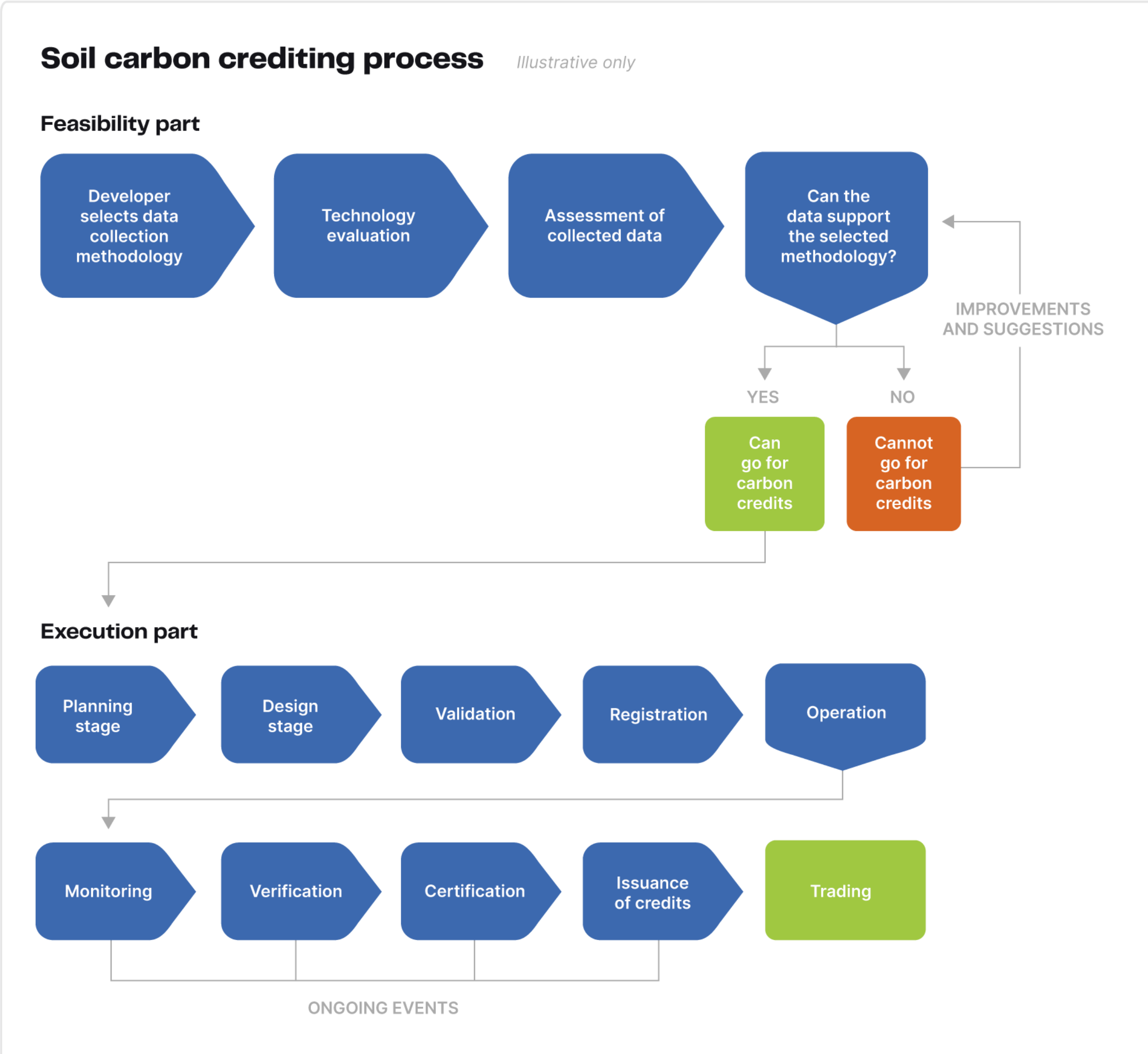

Figure 1. The soil carbon crediting process is similar to other types of carbon credit processes, but incorporates specific considerations for soil carbon projects. For instance, during the first step, when the developer selects a data collection methodology, they will decide whether to use a measurement-driven or model-driven approach. The technology evaluation step will include model selection, gathering of available data, initial measurements, and projections of expected credit generation. During the planning and design stages of project execution, farmers are recruited and networks of service providers are established. Farmers implement new agricultural practices during the operation stage and, during the monitoring stage, ongoing soil measurements are taken and model results are reviewed. The steps shown in the bottom row of the figure are ongoing parts of project operation. Monitoring, verification, certification, and issuance of credits for trade in the VCM can happen in multiple cycles within a single project. Source: Carbon Direct.

To scale successfully, soil carbon crediting programs will require a strong market signal and demand from buyers who are confident in the ability of these programs to deliver high-quality carbon credits with real climate impact. High-quality CDR credits must adhere to multiple principles and criteria, as outlined in Carbon Direct and Microsoft's *Criteria for High-Quality Carbon Dioxide*

Removal.[12] However, buyer confidence in soil carbon credits is frequently limited by two key quality concerns, which we focus on in this report:

1) **Implementing rigorous quantification of soil organic carbon** can be costly, intensive, and limited by the availability of robust benchmarking data.
2) **The durability of stored soil carbon** can easily be compromised and carbon can be returned to the atmosphere if farmers choose not to maintain regenerative practices.

Numerous programs and protocols have been developed to generate soil carbon credits for sale in the VCM. However, the availability of high-quality credits in the VCM from soil carbon projects has been impeded by the key risks described above—reliable measurement of soil carbon changes and long-term durability. High-quality soil carbon measurement is possible, but projects may struggle to achieve it due to financial, geographic, or data limitations. Long-term durability of soil carbon is also possible when farmers maintain regenerative practices over several decades or longer,[13] but farmers are generally averse to signing multi-year contracts.[14] This leaves the risk that farmers in soil carbon programs will revert to conventional practices after contracts end, resulting in a potential release of stored carbon to the atmosphere.

Buyers in the VCM are aware of these risks, and concerns about over-crediting and reversal of removed carbon have led to a lack of trust and slow procurement of soil carbon credits. Hundreds of projects have initiated the registration process with major registries like Verra or Climate Action Reserve (CAR), but only 17 projects have completed the process to become registered, and only 10 have issued credits (**table 1**). Simply completing the registration process does not guarantee that a project will generate high-quality credits, but the number of registered projects does provide a benchmark of how many projects have met the requirements set forth by registries. High-quality or not, the total volume of registered soil carbon credits that have been issued across the major registries included in the Berkeley Carbon Trading Project's Voluntary Registry Offsets Database[15] is 13,309,145 tonnes, representing a tiny fraction of the global annual potential for CDR in grasslands and croplands (0.4–9.1 gigatonnes).[16, 17] This suggests a strong potential for growth in the supply of soil carbon credits, if issues related to soil carbon measurement and durability can be resolved.

Generating high-quality credits from soil carbon will require advancements in measurement and creativity in designing farmer contracts and incentive programs to ensure the long-term durability

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[12] Carbon Direct and Microsoft. 2024. Criteria for High-Quality Carbon Dioxide Removal, 2024 Edition. [accessed 2024 Dec 6]. https://21906989.fs1.hubspotusercontent-na1.net/hubfs/21906989/Report_Criteria-High-Quality-Carbon-Dioxide-Removal_2024.pdf.
[13] Dynarski KA, Bossio DA, Scow KM. 2020. Dynamic Stability of Soil Carbon: Reassessing the "Permanence" of Soil Carbon Sequestration. Front Environ Sci. 8. https://doi.org/10.3389/fenvs.2020.514701.
[14] Gramig BM, Widmar NJO. 2018. Farmer Preferences for Agricultural Soil Carbon Sequestration Schemes. Applied Economic Perspectives and Policy. 40(3):502–521. https://doi.org/10.1093/aepp/ppx041.
[15] Haya BK, Abayo A, Rong X, So IS, Elias M. 2024. Voluntary Registry Offsets Database v2024-08-31. https://gspp.berkeley.edu/research-and-impact/centers/cepp/projects/berkeley-carbon-trading-project/offsets-database.
[16] Intergovernmental Panel on Climate Change. 2022. Climate Change and Land: IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems. Cambridge: Cambridge University Press. https://doi.org/10.1017/9781009157988
[17] Lal R. 2018. Digging deeper: A holistic perspective of factors affecting soil organic carbon sequestration in agroecosystems. Global Change Biology. 24(8):3285–3301. https://doi.org/10.1111/gcb.14054.

of carbon stored in the soil. Measurement uncertainty must be addressed transparently using large, shared datasets for benchmarking. In the case of some crops, practices, or geographies, these shared datasets do not exist today, though the space is rapidly growing. Resolving durability concerns may require novel approaches like tonne-year accounting and horizontal stacking.

Table 1. Current projects registered (or in process) under select crediting protocols for soil carbon

Protocol	Practices included	Registered projects (locations)	Projects in process	Credits issued, tonnes of CO_2
Climate Action Reserve Soil Enrichment Protocol	Agriculture	2 (US)	2	334,309
Verra VM0042	Agriculture	1 (South Africa)	147	0
Verra VM0032	Grassland	1 (Kenya)	11	6,763,174
Verra VM0026	Grassland	7 (US, China, South Africa)	37	5,786,488
Verra VM0017	Agriculture	5 (Kenya, Zambia, India, Mozambique)	28	376,109
Gold Standard Agriculture Smallholder Dairy Methodology	Grassland	1 (Kenya)		49,065

Note: VM0017 and VM0026 are no longer active protocols. Verra inactivated VM0017 on March 31, 2023, after a review identified the need for updates to align with best practices in soil organic carbon and greenhouse gas accounting and to address overlap with VM0042. VM0026 was inactivated on May 30, 2024, as part of a consolidation of grassland methodologies, with projects encouraged to transition to VM0032 for expanded guidance on sustainable grassland management. Sources: Haya et al. 2024;[18] US Soil Enrichment Protocol;[19] VM0042;[20] VM0032;[21] VM0026;[22] VM0017;[23] Smallholder Dairy Methodology.[24]

[18] Haya BK, Abayo A, Rong X, So IS, Elias M. 2024. Voluntary Registry Offsets Database v2024-08-31. https://gspp.berkeley.edu/research-and-impact/centers/cepp/projects/berkeley-carbon-trading-project/offsets-database.
[19] Climate Action Reserve. U.S. Soil Enrichment Protocol v1.1. 2022. [accessed 2025 Feb 4]. https://www.climateactionreserve.org/how/protocols/ncs/soil-enrichment/.
[20] Verra. 2024. VM0042 Improved Agricultural Land Management, v2.1. Verra. [accessed 2025 Feb 4]. https://verra.org/methodologies/vm0042-improved-agricultural-land-management-v2-1/.
[21] Verra. 2015. VM0032 Methodology for the Adoption of Sustainable Grasslands through Adjustment of Fire and Grazing, v1.0. Verra. [accessed 2025 Feb 4]. https://verra.org/methodologies/vm0032-methodology-for-the-adoption-of-sustainable-grasslands-through-adjustment-of-fire-and-grazing-v1-0/.
[22] Verra. 2021. VM0026 Methodology for Sustainable Grassland Management (SGM), v1.1. Verra. [accessed 2025 Feb 4]. https://verra.org/methodologies/vm0026-methodology-for-sustainable-grassland-management-sgm-v1-0/.
[23] Verra. 2011. VM0017 Adoption of Sustainable Agricultural Land Management, v1.0. Verra [accessed 2025 Feb 4]. https://verra.org/methodologies/vm0017-adoption-of-sustainable-agricultural-land-management-v1-0/.
[24] Food and Agriculture Organization. 2016. Methodology for Quantification of GHG Emission Reductions from Improved Management in Smallholder Dairy Production Systems using a Standardized Baseline. [accessed 2025 Feb 4]. https://openknowledge.fao.org/items/8c739e2e-f9d2-4ea4-b921-36d0218eac99.

Measurement and uncertainty challenges

One of the key challenges limiting the supply of high-quality soil carbon credits is the ability to accurately, reliably, and affordably quantify changes in soil carbon in response to agricultural practice changes. While background soil carbon stocks are large and distributed heterogenously across landscapes, practice-driven changes in soil carbon are small and difficult to detect against this background variability.[25] Carbon crediting protocols define methods to quantify soil carbon changes using direct measurement or modeling. However, these methods are not currently viable for all projects, nor are most crediting protocols sufficiently conservative. In this section, we described the conditions that high-quality soil carbon quantification must fulfill, discuss the most common quantification approaches and their limitations across project types, discuss the costs and uncertainty associated with different approaches, and conclude with a description of the project characteristics that are most likely to lead to high-quality soil carbon quantification. Key takeaways for buyers considering measurement and uncertainty challenges in soil carbon projects are:

1) **A quantification approach that combines direct measurement and process-based modeling is likely the most viable approach at scale that minimizes cost and uncertainty.** Buyers should familiarize themselves with the steps and quality considerations involved in this approach, which we discuss in detail below.
2) **Model-based approaches require data from long-term agricultural experiments,** which may limit the geographies and agricultural production systems where model-based approaches are viable to systems where long-term experimental data are available.[26] Temperate systems, cash crops, and well-studied practice changes like no till or cover cropping are more likely to have sufficient data to support model-based approaches. For projects that take a model-based approach, buyers should pay attention to the dataset that the project developer has assembled to support the model validation process and evaluate how appropriate and robust it is.
3) **Even when models are applied using a best-in-class approach, deductions for uncertainty are likely to be large (>10%) and variable from year to year.** However, when these deductions are calculated appropriately, they should increase buyer confidence that credits represent real climate impact. Buyers should be skeptical of projects that report unrealistically low uncertainty estimates or do not report uncertainty at all.

Methods for soil carbon quantification

A high-quality MMRV method for soil carbon credits must accurately estimate small changes in soil carbon on crediting timescales (often annually), and must also address the many sources of uncertainty that can obscure small measured changes in soil carbon. Crediting protocols employ

[25] Bradford MA, et al. 2023. Testing the feasibility of quantifying change in agricultural soil carbon stocks through empirical sampling. Geoderma. 440:116719. https://doi.org/10.1016/j.geoderma.2023.116719.
[26] Soil carbon changes very slowly. Small changes in soil carbon are often difficult to detect against background variability until multiple years have passed and soil carbon changes have accumulated. Because of this, agricultural experiments focused on soil carbon are generally designed to continue for years or decades. The oldest experiments in the world have been ongoing for over a century. The need for multiple years of data to support model-based approaches makes it difficult and slow to establish model-based approaches for crops, ecosystems, or practices changes that do not already have a foundation in multi-year agricultural experiments.

methods for estimating soil carbon change[27] that generally take either a "measure and re-measure" approach, where soil carbon in project fields is measured at the same interval as credit issuances (often resulting in multi-year gaps between credit issuances); or a "measure and model" approach, where direct measurements are taken periodically (often every five years) and used as an input to a validated biogeochemical process-based model[28] to estimate annual soil carbon changes. In either case, changes in soil carbon in project fields must be compared against soil carbon under business-as-usual management conditions, with the difference driving the estimation of creditable CDR (**figure 2**). The *Sources of uncertainty* section of this report provides further detail on baseline selection (static vs. dynamic).

Measurement-based or model-based approaches may not be viable for all project geographies and agricultural production systems. Model-based approaches often cannot be implemented in a scientifically rigorous way due to the absence of sufficient data from long-term agricultural experiments. These data are needed to test the accuracy and reliability of models for a given ecoregion and cropping or management system (see literature review in **Appendix C**). Direct measurement-based methods are not restricted by data availability, but can be prohibitively expensive due to the high number of samples required to achieve accuracy.[29] Also, projects in some parts of the world may not have access to labs that can perform soil carbon analyses using modern methods. Strategies to address these challenges include the development of open access benchmarking datasets for models, emerging technologies that aim to make soil carbon measurements cheaper and faster, advanced stratification and sampling strategies supported by machine learning and remote sensing, and continuous development in high-quality protocol guidance to support project developers in building scientifically rigorous approaches. Government programs and grant opportunities will also be critical to develop capabilities in regions with data and analytical scarcity.

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[27] Smith P, et al. 2020. How to measure, report and verify soil carbon change to realize the potential of soil carbon sequestration for atmospheric greenhouse gas removal. Global Change Biology. 26(1):219–241. https://doi.org/10.1111/gcb.14815.
[28] "Models" in this paper always refers to biogeochemical process-based models, which functionally represent the flow of carbon through various compartments within soil as a system of pools and fluxes, and which are capable of simulating changes in soil carbon resulting from changes in agricultural practice. This category of models does not include statistical models, empirical models, or approaches built solely on remote sensing and machine learning, though such approaches can be used to complement a biogeochemical process-based model approach. The current major registries share this focus on process-based models for the purpose of model-based quantification approaches.
[29] Bradford MA, et al. 2023. Testing the feasibility of quantifying change in agricultural soil carbon stocks through empirical sampling. Geoderma. 440:116719. https://doi.org/10.1016/j.geoderma.2023.116719.

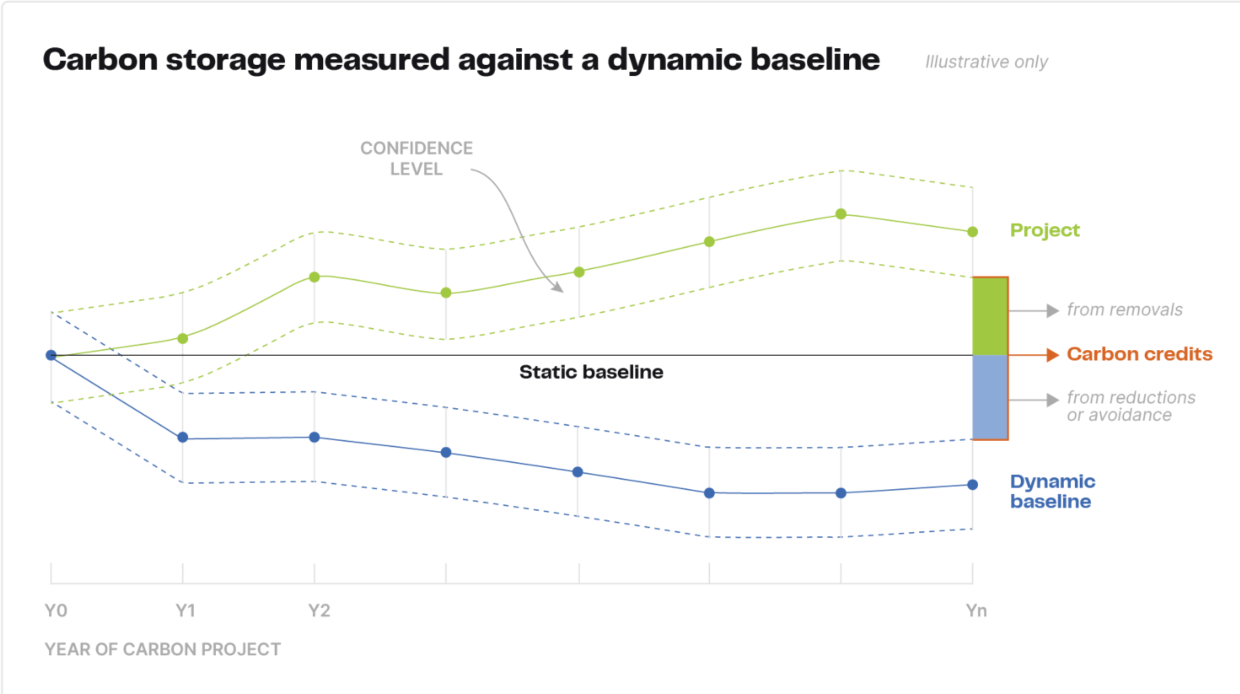

Figure 2. Carbon storage is measured against a business-as-usual baseline scenario. Projects can select either a static or a dynamic baseline to measure against. Carbon gains may accrue from reduced, avoided, or removed emissions. In this illustration, the carbon storage confidence level is indicated by the area contained within the dotted lines around the project and dynamic baseline measurements. Source: Carbon Direct, based on a figure by IndigoAg.

Any method for quantifying soil carbon comes with associated uncertainty from sources like measurement method, sampling strategy, baseline selection, and model prediction uncertainty. High-quality MMRV must include rigorous accounting for these sources of uncertainty, as well as adjustments to credit volumes to reflect this uncertainty. **Figure 3** illustrates a typical framework for project uncertainty accounting: first, sources of uncertainty are estimated individually; then, sources of uncertainty are combined to provide an estimate of overall quantification uncertainty; and finally, a deduction from credit volumes for uncertainty is calculated to increase confidence in the real climate impact of remaining credit volumes. See the *Uncertainty overview* section below, for a description of how uncertainty deductions are calculated based on a probability of exceedance threshold.

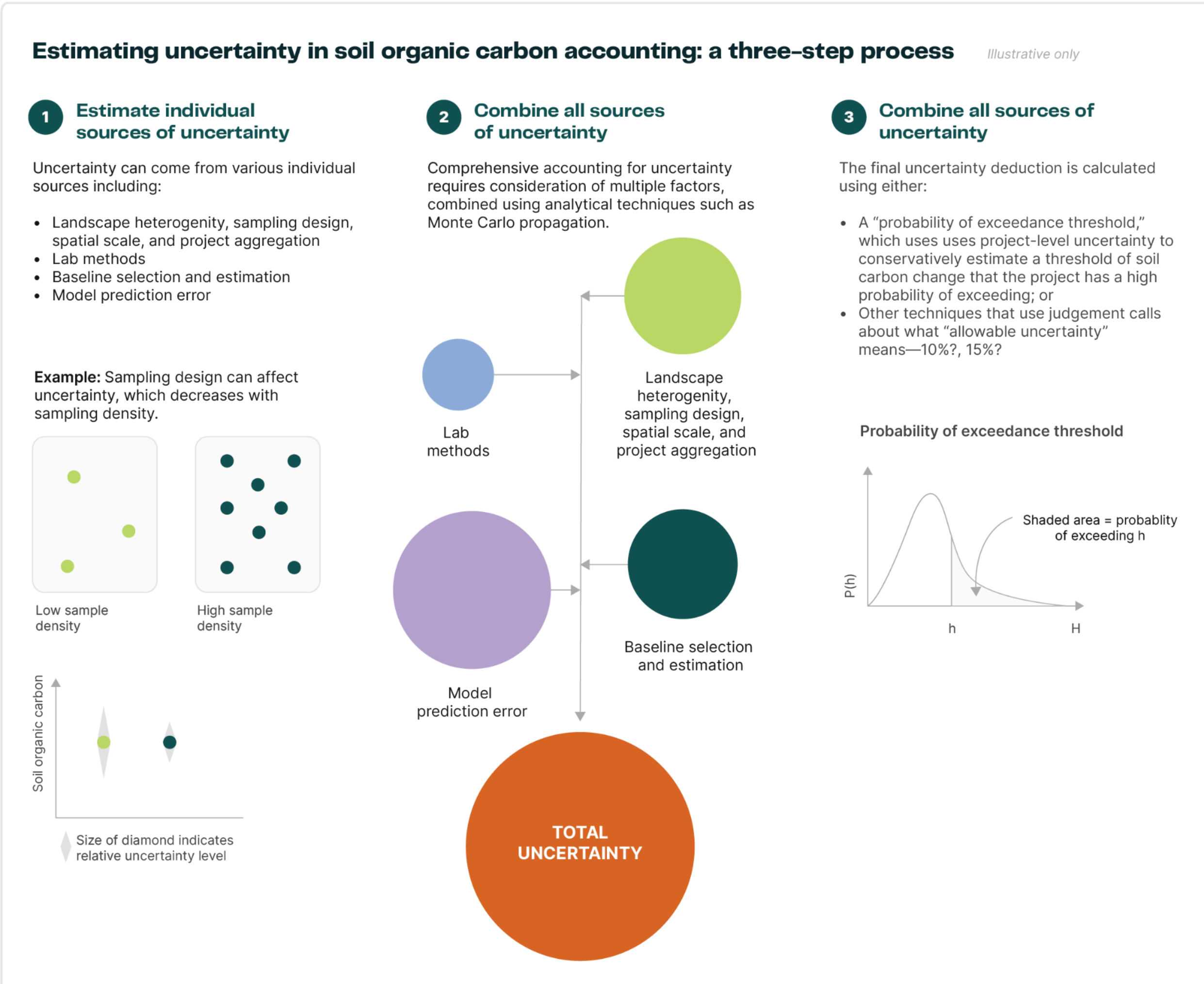

Figure 3. Estimating uncertainty in soil organic carbon accounting requires a three-step process that includes estimating individual sources of uncertainty, combining all sources of uncertainty and calculating an uncertainty deduction. Source: Carbon Direct.

Costs and opportunities for MMRV

Improving MMRV reproducibility and rigour and reducing uncertainty present some of the most salient opportunities for driving down costs and unlocking opportunities to scale high-quality soil carbon projects. Model-and-remeasure approaches provide the clearest path forward. A rough estimation based on soil sampling prices at Colorado State University and assuming row crop agriculture—the most common soil carbon project type, and one with large potential for climate impact given its global scale—indicates that rigorous soil sampling with appropriate replicates could cost anywhere from $4.59–20.29 per acre.[30] Actual cost depends on the size of the farm, the number of strata, and the number of sampling sites. Costs may also be reduced in large projects

[30] Estimates are based on expert solicitation of costs from the Colorado State University Soil Carbon Solutions Center. Calculations approximate a Midwestern US row crop farm and assume a full panel of analyses for a 400-acre farm with: three replicates per sample, two to three strata per farm, two to six samples per stratum, three samples per sampling site, and composite samples by depth (at depths of 0–30 cm, 30–50 cm, and 50–100 cm) and sample site.

aggregated across multiple farms in which only a subset of farms are sampled.[31] When paired with uncertainties ranging from 18.2–37.7%,[32] as seen in best-in-class projects today, this represents both a significant cost for how projects are currently structured and a significant opportunity for improvement to drive down costs, increase confidence, and enable scale (**figure 4**). Cost reduction and increased scale could be achieved through myriad approaches, such as innovation to reduce the costly manual labor components of soil sampling and enable more samples at lower costs,[33, 34] as well as improving model-based approaches and the data underlying them.

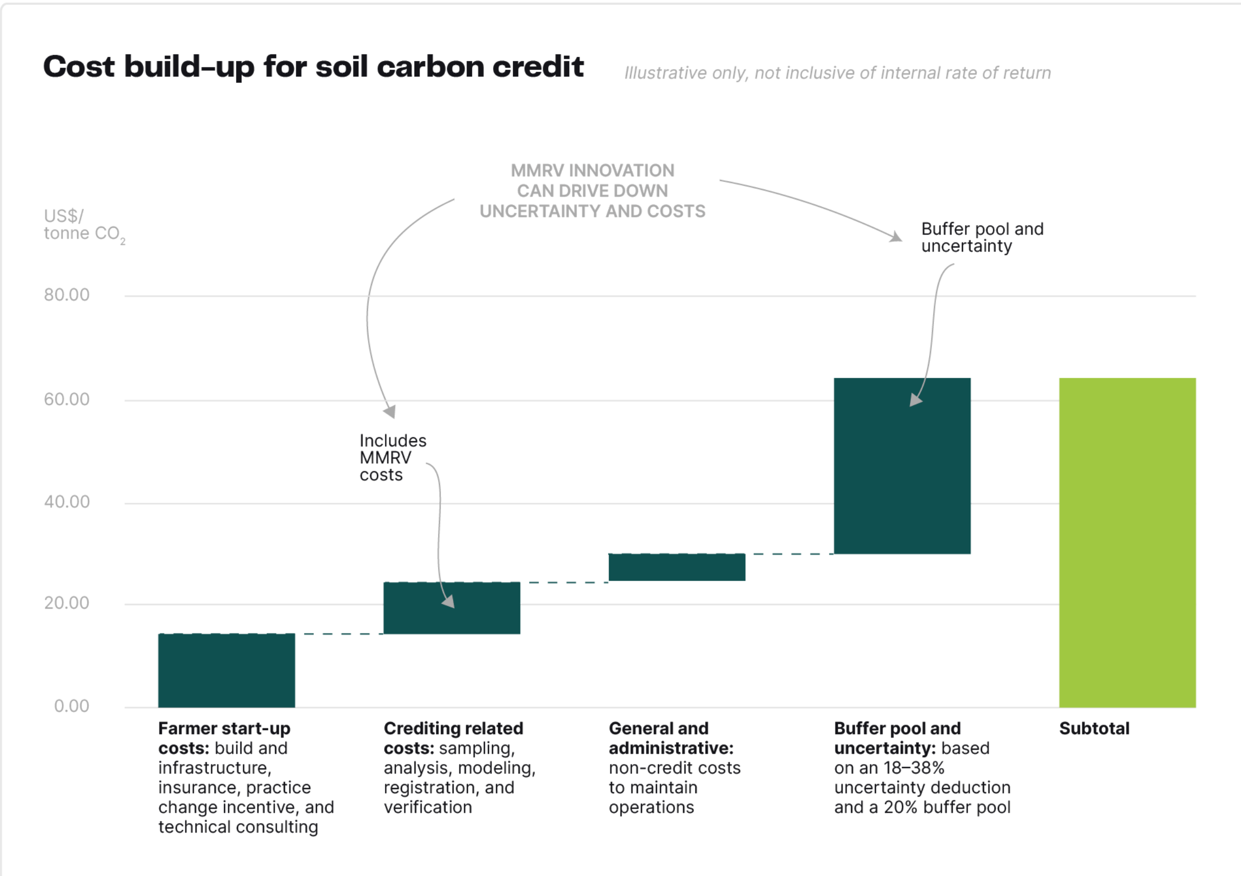

Figure 4. Illustrative cost build-up for a soil carbon credit in row crop agriculture using a model and re-measure approach. MMRV and uncertainty are significant drivers of cost. They also represent significant opportunities for investment to reduce costs and scale soil carbon solutions. Note: Cost estimates are based on expert consultation and knowledge, published literature for practice adoption, and insurance costs from Sustainable Agriculture Research and Education. Soil sampling and analysis costs are from Colorado State

[31] Bradford MA, et al. 2023. Testing the feasibility of quantifying change in agricultural soil carbon stocks through empirical sampling. Geoderma. 440:116719. https://doi.org/10.1016/j.geoderma.2023.116719.
[32] Brummitt CD, et al. 2024. Solutions and insights for agricultural monitoring, reporting, and verification (MRV) from three consecutive issuances of soil carbon credits. Journal of Environmental Management. 369:122284. https://doi.org/10.1016/j.jenvman.2024.122284.
[33] We see promising advances in spectroscopic analyses and other techniques that may support these goals.
[34] Sanderman J, et al. 2023. Diffuse reflectance mid-infrared spectroscopy is viable without fine milling. Soil Security. 13:100104. https://doi.org/10.1016/j.soisec.2023.100104.

University, and published VCM buffer pool and uncertainty deductions. Farmer start-up costs can vary depending on the type of agricultural practice the project uses. Source: Carbon Direct.

Uncertainty overview

Credit deductions for uncertainty often reduce carbon revenue yields from soil carbon projects by a large proportion (>10%). Therefore, strategies for minimizing quantification uncertainty are crucial to developing financially viable projects. In this section, we discuss sources of quantification uncertainty and strategies for minimizing uncertainty in detail. We begin with a focus on sources of uncertainty that are relevant to *measurement-based approaches* (e.g., lab methods for soil carbon estimation, landscape heterogeneity, and sampling strategy), followed by a detailed discussion of uncertainty stemming from *model-based approaches*.

Methods to address uncertainty vary according to the sources of uncertainty included, the statistical methods used to combine these into overall project uncertainty, and the methods used to ensure conservative adjustments to credit volumes. A leading approach used by protocols like Verra's VM0042 and Climate Action Reserve's Soil Enrichment Protocol (CAR SEP) is to calculate an "uncertainty deduction" to credit volumes based on a "probability of exceedance threshold." A probability of exceedance threshold uses project-level uncertainty to conservatively estimate a threshold of soil carbon change that the project has a high probability of exceeding (see **figure 3**). Uncertainty deductions are separate from and in addition to any buffer pool deductions applied to address project reversal risk.

Uncertainty deductions for soil carbon projects can be large and can vary widely from year to year within a project. For example, Indigo Ag is a carbon project developer with one of the largest regenerative agriculture soil carbon crediting programs in the world and a project in the US spanning 48 states, registered under CAR SEP. In its first three reporting periods (ending in 2020, 2021, and 2022 respectively), this project has made estimated uncertainty deductions of 37.7% in 2020, 18.2% in 2021, and 28.0% in 2022.[35] Improvements in sampling and modeling approaches helped to reduce the uncertainty deduction. Smaller uncertainty deductions were required in years when the project's average per-acre credit generation was higher and uncertainty was smaller relative to the magnitude of soil carbon gains.[36]

Sources of uncertainty

Overall project quantification uncertainty in soil carbon projects stems from four key sources: (1) lab methods for measuring soil carbon; (2) landscape heterogeneity, sampling design, spatial scale, and project aggregation; (3) baseline selection and estimation; and (4) model prediction uncertainty (**figure 3**). Each of these sources of uncertainty is highly context- and project-dependent, and it is impossible to make broad generalities about which sources dominate overall uncertainty. However, some types of uncertainty tend to dominate in specific types of projects, and we discuss these trends below. Understanding the nature of these sources of uncertainty is key to designing projects that: (a) rigorously account for uncertainty, and (b) aim to minimize uncertainty. Uncertainties will always be present in heterogeneous ecological systems, but characterizing uncertainty and minimizing it where possible and cost effective is key.

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[35] Brummitt CD, et al. 2024. Solutions and insights for agricultural monitoring, reporting, and verification (MRV) from three consecutive issuances of soil carbon credits. Journal of Environmental Management. 369:122284. https://doi.org/10.1016/j.jenvman.2024.122284.
[36] A.J. Kumar, Indigo Ag, personal communication.

Sample collection and lab methods for measuring soil carbon

One of the major sources of overall quantification uncertainty in SOC comes from how soil samples are collected and processed. The design of any soil sampling strategy begins with a decision about the depth of soil sample collection. Protocols often only require sampling to a depth of 30 cm at most, reflecting an assumption that management impacts on soil carbon will primarily impact the surface layer of soil. Some studies have highlighted that management practices like cover cropping[37] and tillage[38] may increase carbon in surface layers while decreasing carbon in deeper soil layers, though other studies have shown neutral or positive impacts on soil carbon at depth.[39, 40] Only accounting for carbon impacts in surface layers can result in over- or underestimation of carbon gains across the entire soil profile. Deeper sampling depths (60 cm or more) may provide more accurate accounting,[41] but can also significantly increase costs associated with sampling and introduce additional sampling error. Some protocols (e.g., CAR SEP) require that samples be taken deeper than the lowest layer of disturbance in the project, which may necessitate deeper sampling in projects that include deep tillage or deep root systems. Buyers should assess whether project sampling is deep enough to capture the expected impact of the practice changes included in the project.

In addition to choices about sampling depth, error can come from the choice of method for estimating soil carbon stocks from individual samples and comparing stock estimates at multiple points in time.[42] The Fixed Depth method[43] estimates carbon stocks by gathering soil samples at a consistent depth across sample points and using bulk density estimates, assumptions about the volume of soil collected, and measurements of carbon content in samples to calculate carbon stocks. However, management practices can cause changes in bulk density over time, which can introduce error when comparing carbon stock estimates using the Fixed Depth method. The Equivalent Soil Mass method,[44] on the other hand, estimates carbon stocks while adjusting for variations in soil bulk density. The Equivalent Soil Mass method is a superior approach when performed correctly, but is only required by a handful of protocols. In some cases, the added logistical complexity of the Equivalent Soil Mass method may introduce opportunities for mistakes that outweigh the benefits, and a simpler approach may be preferable.

Once soil samples are collected, they are sent to a lab to be processed and measured for carbon content. Variations between labs in sample preparation methods can introduce considerable

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[37] Tautges NE, et al. 2019. Deep soil inventories reveal that impacts of cover crops and compost on soil carbon sequestration differ in surface and subsurface soils. Global Change Biology. 25(11):3753–3766. https://doi.org/10.1111/gcb.14762.

[38] Luo Z, Wang E, Sun OJ. 2010. Can no-tillage stimulate carbon sequestration in agricultural soils? A meta-analysis of paired experiments. Agriculture, Ecosystems & Environment. 139(1):224–231. https://doi.org/10.1016/j.agee.2010.08.006.

[39] Nicoloso RS, Rice CW. 2021. Intensification of no-till agricultural systems: An opportunity for carbon sequestration. Soil Science Society of America Journal. 85(5):1395–1409. https://doi.org/10.1002/saj2.20260.

[40] Córdova SC, Kravchenko AN, Miesel JR, Robertson GP. 2025. Soil carbon change in intensive agriculture after 25 years of conservation management. Geoderma. 453:117133. https://doi.org/10.1016/j.geoderma.2024.117133.

[41] Raffeld AM, et al. 2024. The importance of accounting method and sampling depth to estimate changes in soil carbon stocks. Carbon Balance and Management. 19(1):20. https://doi.org/10.1186/s13021-024-00249-1.

[42] Raffeld AM, et al., The importance of accounting method.

[43] Verra. 2012. VMD0021 Estimation of Stocks in the Soil Carbon Pool, v1.0. Verra. [accessed 2025 Feb 4]. https://verra.org/methodologies/vmd0021-estimation-of-stocks-in-the-soil-carbon-pool-v1-0/.

[44] Wendt JW, Hauser S. 2013. An equivalent soil mass procedure for monitoring soil organic carbon in multiple soil layers. European Journal of Soil Science. 64(1):58–65. https://doi.org/10.1111/ejss.12002.

uncertainty.[45] Processing methods generally involve sieving to remove large rocks and plant matter, grinding to a fine powder, and drying to remove moisture. These steps can be performed with a range of different tools and methods, leading to different results for measured SOC values depending on the lab performing the analysis.

A wide variety of methods have been developed for measuring carbon in soil samples. These methods can broadly be grouped into three categories:

1) Methods that have been used historically but have largely been replaced by more accurate, reliable modern combustion methods (e.g., Walkley-Black, Loss on Ignition)
2) Modern standard total combustion methods (e.g., DUMAS, elemental analyzers)
3) Emerging methods that promise faster, cheaper, and/or more accurate results, but that are not yet widely accepted as substitutes for total combustion methods (e.g., spectroscopic methods, various chemical digestions, sample fractionation by particle size or density)

Modern methods for measuring soil carbon in the lab are generally very accurate and not major contributors to overall uncertainty, though older methods may introduce bias that can go undetected. Protocols like CAR SEP and VM0042 require the use of dry combustion methods by competent laboratories, reducing risk in this category somewhat. Emerging methods may be allowable under protocols like VM0042, but the accuracy of such methods must first be established against approved dry combustion methods.

Project developers may face challenges finding labs with appropriate testing capabilities and available capacity. Labs that are equipped to conduct soil carbon testing with modern methods are not geographically accessible in all parts of the world. Some projects may only have the option of sending samples to a lab that uses an older, less accurate method. Where labs with modern equipment are available, sample throughput and lab capacity can also create a bottleneck for project MMRV.

Landscape heterogeneity, sampling design, spatial scale, and project aggregation

Soil carbon is distributed unevenly across landscapes, and a key challenge of measuring changes in soil carbon is detecting small differences within a noisy, variable background. Measurements for SOC generally involve destructive sampling, so a different set of representative subsamples from an area are evaluated at each sampling event. Samples must be taken at a sufficient density to distinguish between natural variability in soil carbon amounts across a landscape and real changes in mean soil carbon values over time.[46]

The sampling density needed to detect soil carbon change is not the same across all projects. Larger changes in soil carbon and lower background variability make it easier to differentiate the two, so projects that accumulate soil carbon faster or take place in more homogeneous soils may require fewer samples and incur lower measurement costs. There are many factors that determine how quickly soils accumulate carbon or how heterogeneously that carbon is distributed.[47] The

[45] Even RJ, et al. 2025. Large errors in soil carbon measurements attributed to inconsistent sample processing. SOIL. 11(1):17–34. https://doi.org/10.5194/soil-11-17-2025.
[46] Bradford MA, et al. 2023. Testing the feasibility of quantifying change in agricultural soil carbon stocks through empirical sampling. Geoderma. 440:116719. https://doi.org/10.1016/j.geoderma.2023.116719.
[47] Lessmann M, Ros GH, Young MD, de Vries W. 2022. Global variation in soil carbon sequestration potential through improved cropland management. Global Change Biology. 28(3):1162–1177. https://doi.org/10.1111/gcb.15954.

necessary sampling density for a given area is also difficult to determine unless an initial round of sampling has occurred (or sufficiently granular datasets exist from previous sampling) and an initial estimate of background variability has been established.

One common approach to addressing heterogeneity in soils is stratification. Stratification involves parsing sampling locations into areas with similar characteristics to maximize information retrieval and minimize the number of samples required.[48] Stratification methods vary. Strata may be assigned before or after sampling events, and strata may remain constant or change from one sampling event to the next. Common variables used to stratify areas include soil characteristics like clay content or pH, landscape characteristics like topography or plant cover, remotely sensed characteristics like soil color, or historical land management practices. Stratification is widely recognized as a helpful strategy for minimizing soil sampling requirements and is required by some soil carbon crediting protocols, but protocol guidance for how to employ stratification is often general and open-ended. Guidance exists for effective stratification approaches that could be employed by protocols.[49]

The effect of landscape heterogeneity on overall quantification uncertainty also depends on the spatial extent of a project. Soil carbon projects can vary from the scale of a single ranch or farm to multinational projects that aggregate many ranches or farms into a single project. Uncertainty estimation methods and magnitudes vary with the spatial scale of a project, with larger projects generally benefiting from lower uncertainty.[50] In an individual field, even if soil carbon changes are large and sampling density is high, inaccuracies in estimating the magnitude of soil carbon changes are typically large due to within-field heterogeneity. In an individual field, it may not be possible to distinguish between real soil carbon change and statistical artifacts for the small changes that take place on an annual basis. On the other hand, projects that span multiple fields can generate project-level estimates of soil carbon change that are more accurate than individual field-level estimates.[51] In large, aggregated projects, relative uncertainty can be reduced to a fraction of the uncertainty that exists on individual fields (**figure 5**). In one study on US croplands, uncertainty at the site scale was estimated at seven times the uncertainty at the regional scale.[52]

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[48] Potash E, et al. 2023. Multi-site evaluation of stratified and balanced sampling of soil organic carbon stocks in agricultural fields. Geoderma. 438:116587. https://doi.org/10.1016/j.geoderma.2023.116587.
[49] Potash E, et al. Multi-site evaluation of stratified.
[50] Bradford MA, et al. 2023. Testing the feasibility of quantifying change in agricultural soil carbon stocks through empirical sampling. Geoderma. 440:116719. https://doi.org/10.1016/j.geoderma.2023.116719.
[51] Bradford MA, et al. Testing the feasibility of quantifying change.
[52] Ogle SM, et al. 2010. Scale and uncertainty in modeled soil organic carbon stock changes for US croplands using a process-based model. Global Change Biology. 16(2):810–822. https://doi.org/10.1111/j.1365-2486.2009.01951.x.

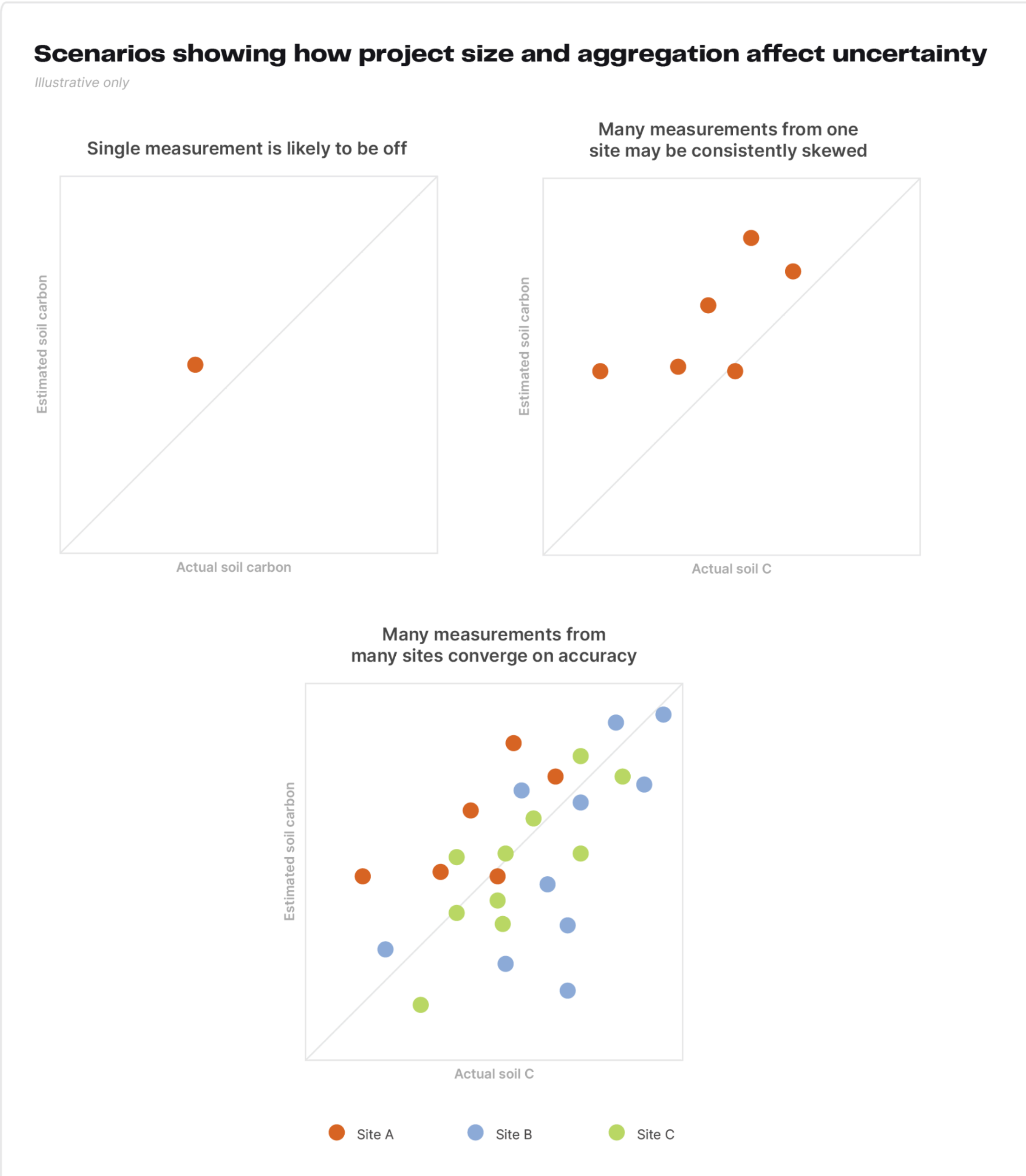

Figure 5. Project size and aggregation can affect uncertainty. A single measurement is likely to be off (left), many measurements from a single site may be consistently skewed (center), but many measurements taken from many sites tend to converge on accuracy (right). Source: Carbon Direct.

Baseline selection and estimation
Estimating the additional carbon impacts of a regenerative agricultural practice requires quantifying the change in soil carbon in a field over time and comparing it against fluctuations in soil carbon over time in a similar field under a baseline set of practices. Under business-as-usual management without new regenerative practices, soil carbon may be degrading or recovering naturally, and credits must only represent carbon removal in excess of what would have taken place under business-as-usual conditions. Soil carbon stocks also fluctuate with seasonal changes. Identifying an appropriate counterfactual is critical.

It is possible to use a set of control fields under business-as-usual management practices to provide a measured dynamic baseline for projects, but doing so is logistically challenging. Identifying paired fields that match on relevant characteristics is difficult, and variations in characteristics like slope or crop rotation can introduce uncertainty. Instead, projects typically either assume a static baseline (in which soil carbon values are assumed to remain constant under business-as-usual conditions) or generate a modeled dynamic baseline. Generally, the same model is used to provide simulations of soil carbon values over time in the baseline scenario and in the project.

Modeled baselines pose a challenge to verification. While the modeled soil carbon values in active project fields can be periodically verified against direct measurements, the baseline soil carbon values exist only in a hypothetical alternate world where project activities do not take place. Therefore, hypothetical baseline values (and differences between baseline and project values over time) cannot be measured directly. Protocols and projects vary in how they address this conundrum, but uncertainty in baseline estimations is often simply ignored in soil carbon credit calculations or estimated alongside model prediction uncertainty during validation exercises. A transition to measured dynamic baselines using control fields could provide higher confidence that credited soil carbon changes are real and additional. However, this approach would also incur higher sampling costs and could introduce additional error to overall project error estimates through sampling or mismatched project and control fields.[53]

Model prediction uncertainty
Not all projects use process-based models as part of an overall MMRV approach. However, given the noisy background conditions present in measurements of soil carbon and the high number of samples often required to meaningfully detect small changes from year to year, the "measure and model" approach can be much less expensive in circumstances that support the use of process-based models. While process-based models can reduce MMRV costs, they are technically challenging to implement effectively and require considerable amounts of data.

Biogeochemical process-based models represent the flow of carbon through various compartments within soil as a system of pools and fluxes. They are capable of simulating changes in soil carbon resulting from changes in agricultural practice. This category of models does not include statistical models, empirical models, or approaches built solely on remote sensing and machine learning, though such approaches can be used to complement a biogeochemical

[53] Bradford MA, et al. 2023. Testing the feasibility of quantifying change in agricultural soil carbon stocks through empirical sampling. Geoderma. 440:116719. https://doi.org/10.1016/j.geoderma.2023.116719.

process-based model approach. The current major registries share this focus on process-based models for the purpose of model-based quantification approaches.

To use a process-based model as part of an overall MMRV strategy, project developers must complete several steps:

1) **Select an appropriate process-model** that has been evaluated in peer-reviewed literature and shown to perform well for the project's ecoregion and agricultural production system. Project developers may also need to consider the ease of acquiring licensing agreements for models developed in the public domain.
2) **Gather the necessary input data to support model setup and initialization.** Such data likely include climate variables like temperature and precipitation, edaphic factors like soil clay content, management data supplied by participating farmers, and initial measurements of soil carbon content on project fields.
3) **Gather the necessary data to support model calibration and validation.** Data must come from agricultural experiments that evaluate changes in soil carbon following changes in agricultural management practice, and must include measurements of soil carbon from at least two different time points. Data sources must be matched to project characteristics on ecoregion, agricultural production system (e.g. crop type), and practice change (e.g., no till). Calibration and validation datasets must be independent to avoid misrepresenting model accuracy. Project developers may be able to generate appropriate data themselves, but the need for measurements at multiple time points across years can make generating new datasets very slow and expensive.
4) **Use the model validation process to estimate model prediction uncertainty**, which is then incorporated into estimates of overall quantification uncertainty.
5) **Decide how periodic direct measurements will be used to "true up" model results.** Protocols like CAR SEP and VM0042 that require periodic measurements in conjunction with models often leave this step open to interpretation. Direct measurements after five years could be used to re-initialize, re-calibrate, or re-validate models, with different implications for overall uncertainty estimation at remeasurement events.[54]

Projects that use process models as part of a "measure and model" approach must incorporate estimates of model prediction uncertainty into overall project uncertainty calculations. Model prediction uncertainty is a measure of how well a model can reproduce patterns in soil carbon change from historical long-term agricultural experiments, and therefore an estimate of how likely

[54] Lavallee JM, et al. 2024. Modeling Soil Carbon and Greenhouse Gas Emissions: Identifying challenges and advancing guidance for using process-based models in soil emission reduction and removal projects. Environmental Defense Fund. https://library.edf.org/AssetLink/henw61p8uk181u34rh2bk8y3dwe7lp68.pdf.

a model is to accurately predict soil carbon changes due to project activities.[55] Model prediction uncertainty can be a dominant portion of overall quantification uncertainty in projects that use a model-based approach. In Indigo Ag's US project, for example, model variance was at least an order of magnitude larger than sample variance in each of the project's initial three years.[56]

CLIMATE AND SOIL PROPERTY DATASETS FOR MODEL SETUP AND INITIALIZATION

Process-based models generally require a number of input variables to run, including field-specific information on weather (e.g., temperature and precipitation), soil properties (e.g., clay content and pH), and farm management practices (e.g., historical tillage regime or current cover cropping practices). Information on farm management practices is typically supplied by participating farmers and can be confirmed using remote sensing. Sufficiently accurate weather and soil property data are widely available around the world through meteorological information services and national or international soil survey data products. In the US, for example, the Gridded Soil Survey Geographic Database (gSSURGO) can provide location-specific values for soil properties built on samples collected by the National Cooperative Soil Survey over the course of a century.

LONG-TERM AGRICULTURAL EXPERIMENTS FOR MODEL CALIBRATION AND VALIDATION

To provide an appropriate estimate of model prediction uncertainty, a model must be tested against data from experiments that are well-matched on project activities, cropping system, and ecoregion. For example, a model that was built to simulate soil carbon in a tropical system growing soy with cover crops would not be expected to perform as well in a semi-arid pasture system. Therefore, a project in a semi-arid pasture system should only use a model that has been tested against data from other semi-arid pasture systems. Project developers must also use independent datasets for calibration (adjusting model parameters to train a model to reproduce data) and validation (using a calibrated model to simulate a new set of data to evaluate its performance and fidelity) to avoid obfuscating true model prediction error during the model calibration and validation process.

The availability of appropriate data for model calibration and validation limits the geographies and project types that can successfully employ a model-based approach. Historical long-term agricultural experiments are unevenly distributed around the world and across agricultural production systems, and many parts of the world do not have access to long-term datasets from experiments in the same region (**figure 6;** see **Appendix C** for a limited review of such studies around the world). Project developers can contribute to the generation of calibration and validation datasets through data collection at participating farms, but the need for multiple measurements

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[55] Different types of uncertainty related to models are often described in peer-reviewed literature. *Structural uncertainty* refers to uncertainty in the selection and arrangement of pools and fluxes to represent a system. *Parameter uncertainty* refers to uncertainty in the values of constants that are used as part of a model system, like the value chosen for the proportion of carbon that is returned to the atmosphere as it flows from one pool to another. *Initialization uncertainty* refers to uncertainty in the initial conditions (including initial measured values of soil carbon) that are used as the starting values for model simulations. For the purposes of credit quantification, *model prediction uncertainty* integrates these other sources and provides the most useful measure of how well a model can replicate real patterns in soil carbon change. Some protocols call for the evaluation of model *parameter* uncertainty in lieu of model *prediction* uncertainty by varying model parameters and evaluating the impact on model output, but this is not an accurate measure of how well a process model replicates real changes in soil carbon over time.

[56] Brummitt CD, et al. 2024. Solutions and insights for agricultural monitoring, reporting, and verification (MRV) from three consecutive issuances of soil carbon credits. Journal of Environmental Management. 369:122284. https://doi.org/10.1016/j.jenvman.2024.122284.

separated in time can prevent such data from being useful for several years. This poses a core challenge for project developers looking to identify appropriate datasets.

The concentration of studies on large-scale row cash crops, particularly in North America and Australia, highlights a significant gap in understanding how various practices affect other crop types essential for diversified agricultural systems and long-term soil health (**figure 6**). Current research heavily emphasizes no-till and variable tillage in staple crops such as corn, wheat, and soy, while other row and specialty crops remain underrepresented. For instance, conservation tillage is largely absent in specialty row crops, accounting for only nine studies in our review and pointing to limited exploration of minimal-tillage methods in more diverse crop types.

Decades-long agricultural experiments can provide stronger evidence for long-term patterns in soil carbon change than short-term experiments, given that small changes in soil carbon are often difficult to differentiate from background variability until several years of changes have accumulated.[57] However, decades-long experiments are rare and highly concentrated in Europe and North America. Overall, the average study duration across all regions in our review was 21 years, reflecting a general preference for mid- to long-term studies that capture substantial soil carbon changes. Study durations vary widely, with the longest average durations in Europe (29 years) and North America (25 years) and the shortest durations in Africa (2 years) and Asia (10 years). This discrepancy underscores regional differences in research priorities and funding availability. Encouraging the flow of funds to underrepresented regions could help establish and maintain long-term studies, providing a more comprehensive understanding of soil carbon dynamics across diverse agricultural contexts.

[57] Smith P, et al. 2020. How to measure, report and verify soil carbon change to realize the potential of soil carbon sequestration for atmospheric greenhouse gas removal. Global Change Biology. 26(1):219–241. https://doi.org/10.1111/gcb.14815.

Figure 6. The map employs a combination of marker fill and outline colors to convey information about practice changes and cropping systems related to long-term agricultural experiments assessing soil carbon. The fill color indicates the cropping system type, while the outline color differentiates the practice change assessed by the study. Regional concentrations of studies are shown as denser clusters (locations where eight or more studies are concentrated). Source: Carbon Direct.

Some management practices and cropping systems also have a much longer history of study than others. Our review found that conservation tillage, variable practices, and grazing management have been the most extensively studied, with long durations and broad spatial representation, reflecting sustained research focus and strong interest in their long-term impacts on soil health and carbon retention. Managing tillage regimes and no-till practices also have broad spatial representation and relatively long study histories, though they are somewhat shorter in duration compared to the most extensively studied practices. In contrast, reduced tillage has been examined over shorter periods. Across cropping systems, row cash crops are the primary focus, reflecting their global agricultural significance and an emphasis on sustainable management for high-yield systems. Mixed systems and livestock agriculture also have substantial long-term representation, underscoring the potential of integrated crop-livestock approaches for soil carbon enhancement. However, specialty row crops and rice remain significantly underrepresented, with relatively few long-term studies. This highlights a clear need for further data generation in these systems.

This distribution demonstrates a broader trend in soil research toward dominant cropping systems and low-disturbance practices, as well as an emerging interest in integrated, multi-practice systems that better capture the complexity of real-world agriculture. The underrepresentation of specialty crops and rice shows a need for expanded research across diverse agricultural systems and regions, as well as a limitation that may challenge the use of model-based approaches with these characteristics. Projects in regions with more baseline data are better positioned to minimize uncertainty, as they can leverage existing datasets for model calibration and validation. In contrast, initiating projects in regions with limited data requires additional data collection, which can increase costs and slow project development. In particular, expanding research efforts in tropical and arid climates would help build the baseline data necessary to support high-quality soil carbon projects in these less represented regions.

The ideal data for model calibration and validation involves taking soil carbon measurements at multiple time points following an agricultural practice change. However, generating new long-term datasets can take several years or more, so creative solutions are in development to address data limitations on shorter timelines. One solution that could increase the viability of model-based approaches in data-limited regions is referred to as "space-for-time substitution." Under space-for-time substitution, adjacent fields that have similar characteristics but divergent management histories (such as where one field has been managed following conventional practices but another has been transitioned to regenerative practices for a number of years) can be measured at the same time. These different spatial measurements are then compared as though they represented two different time points on a single field that is transitioning to regenerative practices. CAR SEP explicitly allows this approach, though guidance is still needed on practical implementation. For instance, the space-for-time substitution approach relies on identifying adjacent fields with appropriate characteristics, which are still not well-defined. The method is still underdeveloped and has not been widely applied. However, if rigorous guidelines are developed for its application, new measurements using space-for-time substitution could potentially unlock model-based approaches in many more geographies.

One way buyers might support this effort, and advance climate justice, is by helping fund more expensive measure-remeasure projects in these geographies, using crops and practices that are underrepresented in existing datasets. Making these datasets public could further enable their use in model calibration and validation, ultimately expanding project feasibility and reducing costs in these regions. This approach may be more appealing to buyers than simply underwriting research and development costs, as it allows them to not only generate credits but also contribute to a broader increase in credit supply and a reduction in future credit costs. In the short term, projects taking place in temperate regions and focusing on well-studied production systems (e.g., row cash crops, livestock agriculture) and practice changes (e.g., conservation tillage, grazing management) may be more successful in minimizing uncertainty using a model-based approach.

Summary of MMRV challenges and opportunities

Measurement-based approaches can be expensive but are more easily deployed
Relative to model-based approaches, measurement-based approaches can be deployed in many more systems that may lack adequate data to support model calibration and validation. In some cases, measurement-based approaches may be the only viable option. Measurement-based approaches are most limited by the cost of frequent, high-density sampling and the availability of appropriate direct measurement technologies. These challenges could be alleviated by technological developments in direct measurement technologies or by efficient sampling strategies driven by remote sensing or machine learning approaches.

Model-based approaches present the lowest barrier to entry and opportunity for scale
Opportunities and barriers in model-based approaches are important to highlight because they pose the most likely avenue for scaling soil carbon projects. Model-based approaches may provide sufficiently accurate estimates of soil carbon change in large-scale projects while avoiding the costs and labor involved with annual direct sampling.[58] However, model-based approaches require data from appropriate, long-term agricultural experiments to support calibration and validation, which may prevent projects in some locations and cropping systems from implementing this approach. Alternatively, project developers may be forced to collect their own datasets for calibration and validation, which can take years and incur significant costs.

Models are only as good as the data that supports them
Model-based approaches to quantifying soil carbon are currently only feasible for projects in locations and systems where adequate data can be found to support model use. Model-based approaches require different types of data, which vary in their availability and ease of access around the world. Some types of data, like climate variables or soil clay content, can be retrieved from publicly accessible sources with reasonable accuracy around the world. Other necessary data, like SOC measurements from long-term agricultural experiments needed to calibrate and validate process models, are much sparser and more limited in scope. Project developers often face challenges in identifying datasets for model calibration and validation that match their project's ecoregion, practice changes, and agricultural production systems. Because model prediction uncertainty is calculated using these experimental data, projects with insufficient available data may be unable to fulfill protocol requirements or may generate such high model prediction uncertainty that no saleable credits remain after uncertainty deductions are made.

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[58] Smith P, et al. 2020. How to measure, report and verify soil carbon change to realize the potential of soil carbon sequestration for atmospheric greenhouse gas removal. Global Change Biology. 26(1):219–241. https://doi.org/10.1111/gcb.14815.

Projects should select the best approach and strategically minimize MMRV uncertainty
Due to the uneven distribution of long-term agricultural experiments and modern soil testing labs around the world, optimal and available approaches to soil carbon MMRV vary based on project type. For large, aggregated projects in cropping systems and regions where data are widely available, model-based approaches may significantly reduce sampling costs and credit deductions for uncertainty may be smaller. On the other hand, smaller projects, projects in regions with sparser long-term data from agricultural experiments, or projects that use specialty cropping systems may have to rely instead on a measurement-based approach with more frequent and repeated sampling. For this reason, projects over a small spatial area may incur high sampling costs and struggle to overcome sampling uncertainty relative to large, aggregate projects. Generally, projects in which soil carbon accumulates quickly are more likely to overcome sampling uncertainty challenges. Across all project types, and especially in those that use measurement-based MMRV, effective approaches to stratification and sampling design are critical to reducing sampling requirements and managing sampling uncertainty. New technologies that decrease the cost of high-density sampling may transform the range of project types that are feasible in terms of sampling costs and uncertainty management.

The path forward for MMRV

Projects of different scale and scope face different challenges in generating high-quality soil carbon credits. Over time, collective efforts to improve measurement technologies and generate shared benchmarking datasets may lower this burden and enable cost-effective, high-quality soil carbon credit generation for a wider range of projects. In the short term, buyers can look for projects that are most likely to minimize uncertainty, reduce costs, and deliver high-quality MMRV at scale. Buyers can prioritize projects that:

- **Support model-based approaches** by focusing on cropping systems (e.g., cash crops), practice changes (e.g., conservation tillage, cover crops); and geographic regions (e.g., North America, Europe, Australia) where ample data are already available, and support ambitious data collection in regions where there are limited data to support these approaches.
- **Focus on highly productive systems** where sequestration rates are likely to be detectable sooner against background variability.
- **Aggregate many individual fields into a single, large-scope project**, such that uncertainty in individual fields tends to cancel out and generates lower overall project quantification uncertainty.
- **Employ a measure-and-model approach** leveraging remote sensing, machine learning, and other tools to increase the efficiency of sampling designs.
- **Gather robust datasets from appropriate long-term agricultural experiments** to support the model validation process.
- **Share proprietary collected datasets** to support the development of common benchmarking procedures for process models.
- **Address uncertainty effectively across all of the sources relevant to the project's quantification methodology,** follow best practices for combining sources of uncertainty into estimates of overall quantification uncertainty, and adjust credit volumes to ensure conservativeness in response to uncertainty estimates.

Projects that focus on agricultural production systems, practice changes, and regions outside this scope may face challenges in identifying appropriate datasets to inform a model-based approach to soil carbon credit quantification. These projects may incur higher costs by needing to rely on measurement-based approaches or generate the necessary datasets to support model-based approaches. **Appendix A** includes illustrative examples of project types that may face varied MMRV challenges. However, investment in data-sparse or economically challenged regions remains important to broaden access to carbon revenue for diverse farmers and ranchers.

Socioeconomic vs. biophysical durability

Durability of soil carbon credits is challenged by a misalignment between the priorities of project developers (and credit buyers), who assume that the farming practices required by the project will continue long after carbon payments have stopped, and those of farmers who face socioeconomic pressures that drive their decision-making around farming practices. In general, regenerative agricultural practices must be maintained to maintain increases in soil carbon. The durability of soil carbon credits relies on the assumption that farmers will continue new practices long after they have stopped receiving carbon payments for doing so. As such, the conservative assumption from a buyer's perspective is that farmer attrition from a project constitutes a reversal, whether or not the farmer actually reverts practices (farmers may continue practices due to the agronomic benefits they receive). Furthermore, there is an assumption that practice reversal leads to a total loss of carbon accrued from regenerative practices previously implemented, regardless of whether this is the case.

Carbon crediting protocols and programs vary widely in their durability requirements and in the terminology they use to describe project timelines as they relate to durability, creating confusion. Programs may have requirements for project crediting periods (i.e., the period of time over which new credits are issued and farmers receive payments) or project lifetimes (i.e., the total duration of a project, including the initial crediting period and any additional monitoring period beyond). For example, new projects under any of the relevant Verra methodologies (VM0042, VM0032, etc.) must fulfill a 40-year project lifetime, which could include a 20-year project crediting period followed by a 20-year monitoring period. From a theoretical perspective, a carbon credit's durability is determined by the period of time after the credit is issued during which monitoring for reversals is taking place, sometimes described as the durability monitoring period. In the example described above, the durability monitoring period could be 39 years for a credit issued in the first year of the project, or 20 years for a credit issued in the last year (**figure 7**).

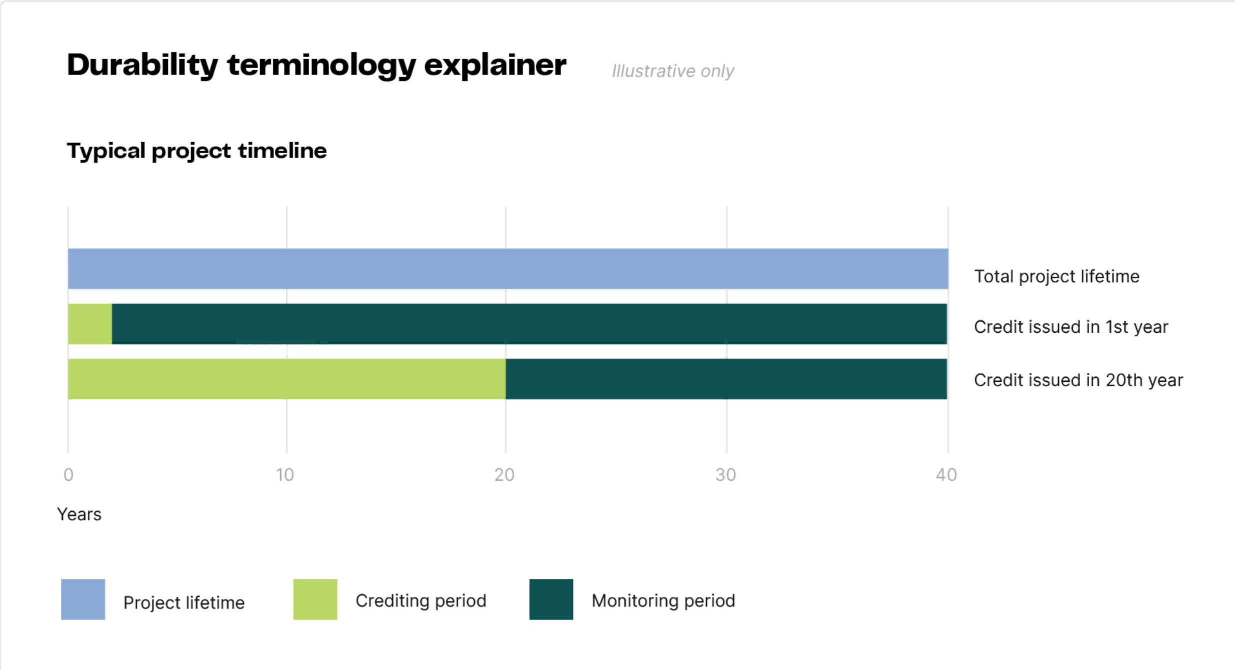

Figure 7. The durability of a carbon credit is ensured by ongoing monitoring for reversals in carbon storage, which takes place for a period after a credit is issued. In the example above, the project lifetime is 40 years. A credit issued in the first year will have a 39-year monitoring period, and a credit issued in the 20th year of the project will have a 20-year monitoring period. Source: Carbon Direct.

Because project durability depends on farmer retention, project developers design carbon program contracts that incentivize farmers to re-enroll continuously and maintain regenerative agricultural practices over the long term. Farmers generally receive a share of carbon revenue during the contract period. However, farmers are not typically required to return carbon payments if they choose not to renew carbon contracts and revert to previous agricultural practices.

Upon reaching the end of a project crediting period, a farmer that continues regenerative practices is doing the important work of maintaining stored carbon rather than sequestering additional volumes. Some protocols, such as CAR, require 100-year durability terms, to support continued maintenance of restored soil function and stored carbon.

Longer contract lengths can increase tension between soil carbon project durability and farmer decision-making. Carbon project developers and buyers have a vested interest in ensuring that farmers continue practices and prevent reversals for the duration of the project durability term, which can be as long as 100 years. Farmers, on the other hand, are generally averse to multi-year carbon contracts[59] and concerned about their legal liability in the event of carbon contract

[59] Gramig BM, Widmar NJO. 2018. Farmer Preferences for Agricultural Soil Carbon Sequestration Schemes. Applied Economic Perspectives and Policy. 40(3):502–521. https://doi.org/10.1093/aepp/ppx041.

non-compliance.[60] Typical carbon contracts range from 1-year agreements to 20-year terms,[61] which can be renewed to reach the full durability term. Longer terms may be especially restrictive for farmers on leased lands, where land lease terms may be shorter than the required carbon contract term.

How do tradeoffs between farmer autonomy and contract length affect credit quality?

Developers today generally resolve this tension between the project's target durability term and the ability to offer acceptable contract lengths to farmers by signing contracts that last 3-5 years, with the option for repeated renewals. These agreements vary in the severity of the limitations placed on farmers in terms of how they can manage their lands and whether there are any penalties for reversals that occur during the contract period. This strategy is risky for both farmers and buyers as it promises a durability term that relies on the continuous re-enrollment of farmers (though some programs mitigate this risk by using newly enrolled farmers to offset program attrition or by maintaining an additional buffer pool of credits).

From a farmer's perspective, signing on to a carbon project carries several perceived risks:[62]

- The farmer might not recoup costs incurred from implementing new agricultural practices through carbon revenue, but will still be required to continue practices.
- Program restrictions might not allow the farmer to respond to emerging challenges in farming like weed encroachment or extreme climate events.
- The farmer might be excluded from a future program that may offer more value to the farmer for implementing the same practice but requires evidence that a practice is novel (e.g., some programs allow stacking with federal programs like the Environmental Quality Incentives Program in the US, but others prohibit this).[63]

From a credit buyer's perspective, there is risk that purchased credits will be reversed and become worthless or be replaced from a buffer pool with credits from a project that may or may not meet the same standards of quality. Often, the greatest risk is borne by project developers, who are responsible for the value of any credits sold if farmers drop out of the program en masse and soil carbon is returned to the atmosphere.

Evidence regarding practice cessation and soil carbon changes

Buyer concerns about the durability of soil carbon credits center on the fear that farmers will not continue regenerative practices beyond their short-term contracts and sequestered soil carbon will return to the atmosphere. While this is a conservative assumption to make, reality is likely less stark. Some farmers are likely to continue regenerative practices after carbon payments cease,[64] and newly sequestered soil carbon may not immediately return to the atmosphere upon practice

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[60] Thompson NM, et al. 2022. Opportunities and Challenges Associated with "Carbon Farming" for U.S. Row-Crop Producers. Choices. 37(3):1–10. https://www.jstor.org/stable/27201707
[61] Bruner E, Brokish J. 2021. Ecosystem Market Information: Opportunity and Program Comparison. Illinois Sustainable Ag Partnership. https://ilsustainableag.org/download/ecomarkets-program-comparison/.
[62] Thompson NM, et al. Opportunities and Challenges Associated with "Carbon Farming".
[63] Bruner E, Brokish J. Ecosystem Market Information.
[64] [CTIC] Conservation Technology Information Center, [SARE] Sustainable Agriculture Research and Education, [ASTA] American Seed Trade Association. 2023. National Cover Crop Survey Report, 2022-2023. CTIC, SARE, ASTA National Cover Crop Survey Report No.: 7. https://www.sare.org/wp-content/uploads/2022-2023-National-Cover-Crop-Survey-Report.pdf.

cessation.[65] The magnitude of each of these risks is difficult to define with current research, but we discuss the available evidence below.

Evidence for farmers continuing regenerative practices

Many soil carbon project developers argue that farmers will continue regenerative agricultural practices beyond the period supported by the carbon project because such practices offer other benefits including increased yields,[66] resilience to extreme weather events,[67] and improved soil and ecosystem health.[68] There is limited evidence available to understand whether farmers are likely to continue regenerative practices beyond incentive payments, but some insights can be drawn from farmer surveys and regional studies of practice adoption and disadoption rates over time. On the one hand, according to the results of the recent 2022–2023 Cover Crop Survey[69] conducted by the United States Department of Agriculture on US farmers, 90% of respondents who previously received incentive payments for cover cropping stated that they intend to continue using cover crops. One study in the Mississippi Delta[70] exploring shifts in acreage under conservation practices found that acres being managed with cover crops or conservation tillage each had approximately a 70% likelihood of remaining under those practices, although the remaining 30% was more likely to shift to another type of conservation practice than to revert to no conservation practices at all. On the other hand, a recent study of cover crop and no-till adoption and disadoption in the continental US[71] found that, despite a generally increasing trend in US acreage under no-till or cover crops from 2017–2022, approximately 45% of counties in the US experienced a net reduction of acres under cover cropping and no-till management during that period. Studies on this subject are sparse and all three of these studies are based in the US. Farmers in other parts of the world may face different drivers in their decision-making and may follow different patterns of adoption and disadoption of regenerative agricultural practices. Additional studies are needed around the world to understand the likelihood of farmers continuing regenerative practices beyond the initial payments they receive for shifting practices.

Evidence for soil carbon changes following practice cessation

If a farmer discontinues a regenerative practice (e.g., tilling after a period of no-till), it will not necessarily lead to the immediate loss of all newly sequestered carbon. Evidence suggests that the rate and magnitude of soil carbon losses following practice cessation varies based on the cropping

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[65] Dynarski KA, Bossio DA, Scow KM. 2020. Dynamic Stability of Soil Carbon: Reassessing the "Permanence" of Soil Carbon Sequestration. Front Environ Sci. 8. https://doi.org/10.3389/fenvs.2020.514701.
[66] The Soil Health Institute, Cargill. 2021. Economics of soil health systems on 100 farms: A comprehensive evaluation across nine states.
https://soilhealthinstitute.org/app/uploads/2022/01/100-Farm-Fact-Sheet_9-23-2021.pdf.
[67] Aglasan S, Rejesus RM, Hagen S, Salas W. 2024. Cover crops, crop insurance losses, and resilience to extreme weather events. American Journal of Agricultural Economics. 106(4):1410–1434.
https://doi.org/10.1111/ajae.12431.
[68] Rehberger E, West PC, Spillane C, McKeown PC. 2023. What climate and environmental benefits of regenerative agriculture practices? an evidence review. Environ Res Commun. 5(5):052001.
https://doi.org/10.1088/2515-7620/acd6dc.
[69] CTIC, SARE, ASTA. 2023. National Cover Crop Survey Report, 2022-2023. CTIC, SARE, ASTA National Cover Crop Survey Report No.: 7.
https://www.sare.org/wp-content/uploads/2022-2023-National-Cover-Crop-Survey-Report.pdf.
[70] Pathak S, Wang H, Tran DQ, Adusumilli NC. 2024. Persistence and disadoption of sustainable agricultural practices in the Mississippi Delta region. Agronomy Journal. 116(2):765–776. https://doi.org/10.1002/agj2.21519.
[71] Plastina A, Sawadgo W, Okonkwo E. 2024. Pervasive Disadoption Substantially Offsets New Adoption of Cover Crops and No-Till. Choices. 39(2):14.
https://www.choicesmagazine.org/UserFiles/file/cmsarticle_906.pdf

system, practice, soil texture, practice duration, and numerous other variables (see **table 9** in **Appendix C**). Research indicates that SOC does not simply vanish when carbon-building practices stop; instead, it often declines slowly over time.[72, 73, 74, 75] This highlights the role of soil minerals and microbial activity in moderating the rate of carbon loss.[76, 77] Several studies have shown minimal immediate changes in SOC after practice cessation, demonstrating that protective mechanisms within the soil—such as stable aggregates, microbial processes, and mechanisms that regulate SOC mineralization—play a crucial role in preserving carbon.[78, 79, 80, 81] For instance, finer-textured soils are particularly effective at stabilizing SOC, which helps prevent rapid decomposition.[82] In many cases, losses in the upper soil layers are balanced by gains in deeper layers, suggesting dynamic processes underpinning the stability of SOC.[83, 84, 85, 86] The duration of carbon-building practices may impact SOC stability, with longer practice durations leading to more gradual changes after cessation.

However, other studies have documented immediate and substantial SOC losses following the cessation of carbon-building practices, particularly in scenarios involving intensive tillage. Tillage has been shown to disrupt soil aggregates and expose previously protected organic matter to microbial decomposition, resulting in rapid carbon dioxide (CO_2) emissions. Quantitative modeling has identified significantly higher decay constants in tilled plots compared to no-till plots, illustrating the accelerated breakdown of SOC under these conditions.[87] Additionally, tillage-induced physical release from soil pores and solution has been linked to rapid losses, with up to 20% of total CO_2 flux

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[72] Dynarski KA, Bossio DA, Scow KM. 2020. Dynamic Stability of Soil Carbon: Reassessing the "Permanence" of Soil Carbon Sequestration. Front Environ Sci. 8. https://doi.org/10.3389/fenvs.2020.514701.
[73] Diop M, et al. 2024. Effects of occasional tillage on soil physical and chemical properties and weed infestation in a 10-year no-till system. Front Environ Sci. 12. https://doi.org/10.3389/fenvs.2024.1431822.
[74] Li Q, et al. 2022. Re-visiting soil carbon and nitrogen stocks in a temperate heathland seven years after the termination of free air CO2 enrichment (FACE). Geoderma. 428:116185. https://doi.org/10.1016/j.geoderma.2022.116185.
[75] Melero S, et al. 2011. Implementation of chiselling and mouldboard ploughing in soil after 8 years of no-till management in SW, Spain: Effect on soil quality. Soil and Tillage Research. 112(2):107–113. https://doi.org/10.1016/j.still.2010.12.001.
[76] Li Q, et al. Re-visiting soil carbon and nitrogen stocks.
[77] Kettler TA, et al. 2000. Soil Quality Assessment after Weed-Control Tillage in a No-Till Wheat–Fallow Cropping System. Soil Science Society of America Journal. 64(1):339–346. https://doi.org/10.2136/sssaj2000.641339x.
[78] Diop M, et al. Effects of occasional tillage.
[79] Dynarski KA, Bossio DA, Scow KM. Dynamic Stability of Soil Carbon
[80] Yang XM, Drury CF, Reynolds WD, Tan CS. 2008. Impacts of long-term and recently imposed tillage practices on the vertical distribution of soil organic carbon. Soil and Tillage Research. 100(1):120–124. https://doi.org/10.1016/j.still.2008.05.003.
[81] VandenBygaart AJ, Kay BD. 2004. Persistence of Soil Organic Carbon after Plowing a Long-Term No-Till Field in Southern Ontario, Canada. Soil Science Society of America Journal. 68(4):1394–1402. https://doi.org/10.2136/sssaj2004.1394.
[82] VandenBygaart AJ, Kay, BD. Persistence of soil organic carbon.
[83] Yang XM, et al. Impacts of long-term and recently imposed tillage practices.
[84] Kettler TA, et al. Soil Quality Assessment after Weed-Control Tillage.
[85] Dimassi B, Cohan J-P, Labreuche J, Mary B. 2013. Changes in soil carbon and nitrogen following tillage conversion in a long-term experiment in Northern France. Agriculture, Ecosystems & Environment. 169:12–20. https://doi.org/10.1016/j.agee.2013.01.012.
[86] Melero S, et al. Implementation of chiselling and mouldboard.
[87] La Scala N, et al. 2008. Short-term temporal changes of soil carbon losses after tillage described by a first-order decay model. Soil and Tillage Research. 99(1):108–118. https://doi.org/10.1016/j.still.2008.01.006.

occurring within the first two hours after tillage.[88] In tropical regions, conventional tillage has been associated with the release of approximately 30% of annual crop carbon residues to the atmosphere within four weeks, demonstrating the pronounced impact of tillage on soil carbon loss in these climates.[89] Notably, the transition from no-till to intensive tillage is generally detectable with remote sensing, making monitoring for this form of practice reversal more feasible. This capability may allow for targeted interventions to mitigate or address carbon losses in landscapes where such shifts occur.

These findings show that, in some cases, SOC declines gradually after practice cessation, while in others there is the potential for rapid loss, particularly in surface layers after the reintroduction of tillage.[90, 91] For example, converting from no-till practices to moldboard plowing has been shown to cause SOC losses of 10–24% in the 0–5 cm layer and 3–13% in the 5–10 cm layer, with minimal changes in the 10–20 cm layer and stable or even increased SOC in the 20–30 cm layer. Across the 0–30 cm profile, total SOC stocks often remained stable or showed modest declines, as losses in surface layers were offset by gains in deeper layers.[92] This redistribution mitigates overall system-level SOC loss, demonstrating that SOC dynamics after practice cessation can involve shifts within the soil profile rather than immediate carbon release. Nonetheless, reductions in surface layers can still constitute a "reversal" in the context of SOC crediting, as these programs emphasize surface carbon stocks within the top 30 cm.

These findings underscore that many unknowns remain about the factors that drive slow or rapid depletion of sequestered carbon following the cessation of carbon-building practices. Evidence indicates that rapid declines in SOC can occur under certain conditions, particularly with intensive tillage, emphasizing the need for further research to refine our understanding of these dynamics.[93, 94, 95] From a credit buyer's perspective, it may be more conservative to assume that farmer attrition and/or practice reversion will lead to complete, immediate reversal of credited carbon, but the real carbon impacts may not be this dire. As monitoring techniques improve, it may be possible to constrain these potential losses. For example, expanded datasets on SOC following practice cessation could support reliable model estimates of soil carbon loss, which could be used to estimate partial reversals over time rather than assuming a total loss of carbon gains made during a project's crediting period.

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[88] Reicosky DC, Dugas WA, Torbert HA. 1997. Tillage-induced soil carbon dioxide loss from different cropping systems. Soil and Tillage Research. 41(1):105–118. https://doi.org/10.1016/S0167-1987(96)01080-X.
[89] La Scala N, Bolonhezi D, Pereira GT. 2006. Short-term soil CO2 emission after conventional and reduced tillage of a no-till sugar cane area in southern Brazil. Soil and Tillage Research. 91(1):244–248. https://doi.org/10.1016/j.still.2005.11.012
[90] Melero S, et al. 2011. Implementation of chiselling and mouldboard ploughing in soil after 8 years of no-till management in SW, Spain: Effect on soil quality. Soil and Tillage Research. 112(2):107–113. https://doi.org/10.1016/j.still.2010.12.001.
[91] Dimassi B, Cohan J-P, Labreuche J, Mary B. 2013. Changes in soil carbon and nitrogen following tillage conversion in a long-term experiment in Northern France. Agriculture, Ecosystems & Environment. 169:12–20. https://doi.org/10.1016/j.agee.2013.01.012.
[92] Yang XM, Drury CF, Reynolds WD, Tan CS. 2008. Impacts of long-term and recently imposed tillage practices on the vertical distribution of soil organic carbon. Soil and Tillage Research. 100(1):120–124. https://doi.org/10.1016/j.still.2008.05.003.
[93] La Scala N, et al. 2008. Short-term temporal changes of soil carbon losses after tillage described by a first-order decay model. Soil and Tillage Research. 99(1):108–118. https://doi.org/10.1016/j.still.2008.01.006.
[94] Reicosky DC, Dugas WA, Torbert HA. Tillage-induced soil carbon dioxide loss.
[95] La Scala N, Bolonhezi D, Pereira GT. Short-term soil CO2 emission after conventional and reduced tillage.

Considerations in designing long-term contracts with farmers

Farmers cite long-term contract obligations as a major barrier to enrollment in carbon projects due to both perceived and real risk.[96] The cost of adopting new practices may not be readily repaid by carbon revenue, as levels of carbon sequestration can vary inter-annually and with climate, meaning that payments may not be predictable. Restrictions on farmer's land use and management could limit commercial purposes or appropriate stewardship given in-year weather variability. They could also impact intergenerational management considerations.

A successful long-term contract (i.e., 20–40 years rather than five) would need to mitigate these risks for farmers. For example, contracts could more flexibly accommodate practice changes (e.g., allowing for periodic partial or conservation tillage, or alterations to cover cropping regimens). Similarly, projects could attempt to even out payments over time.

Bridging the opportunity cost of practice adoption presents a challenge regarding misaligned incentives. To enable adoption, farmers seek economic incentives in the near-term. To incentivize long-term enrollment, practice maintenance, and practice improvement, the optimal strategy might be to design payment plans that increase with time.

Alternative approaches: tonne-year accounting and horizontal stacking

Two potential solutions to the challenge of durability in soil carbon projects are tonne-year accounting and horizontal stacking. One existing soil carbon protocol, CAR SEP, already includes an option for project developers to leverage tonne-year accounting. The CAR SEP protocol requires a 100-year durability term for permanent credits. Tonne-year accounting under CAR SEP assigns value to credits according to the fraction of this 100-year term for which soil carbon remains sequestered. Thus, 10 tonnes of CO_2 that remain stored for 10 years would be the equivalent of one permanent credit. Horizontal stacking is the strategy of sequentially buying carbon credits as they expire to permanently neutralize a tonne of CO_2. Through a horizontal stacking approach, organizations seeking to permanently neutralize their emissions would "stack" credits to create a continuous sequence of one tonne stored over time (**figure 8**). Importantly, new commitments must be made prior to retiring short-term credits, to avoid creating a gap in storage. Large, aggregated projects may be able to implement a horizontal stacking approach internally by continuously enrolling new farmers to replace any that leave the program. However, any project that uses this approach should have strong and transparent safeguards in place to avoid double-counting.

[96] Pudasaini K, Bhattarai T, Rolfe J. 2024. Exploring the barriers to farmer participation in soil carbon projects under the Australian Carbon Credit Unit Scheme. Australasian Journal of Environmental Management. 0(0):1–19. https://doi.org/10.1080/14486563.2024.2393246.

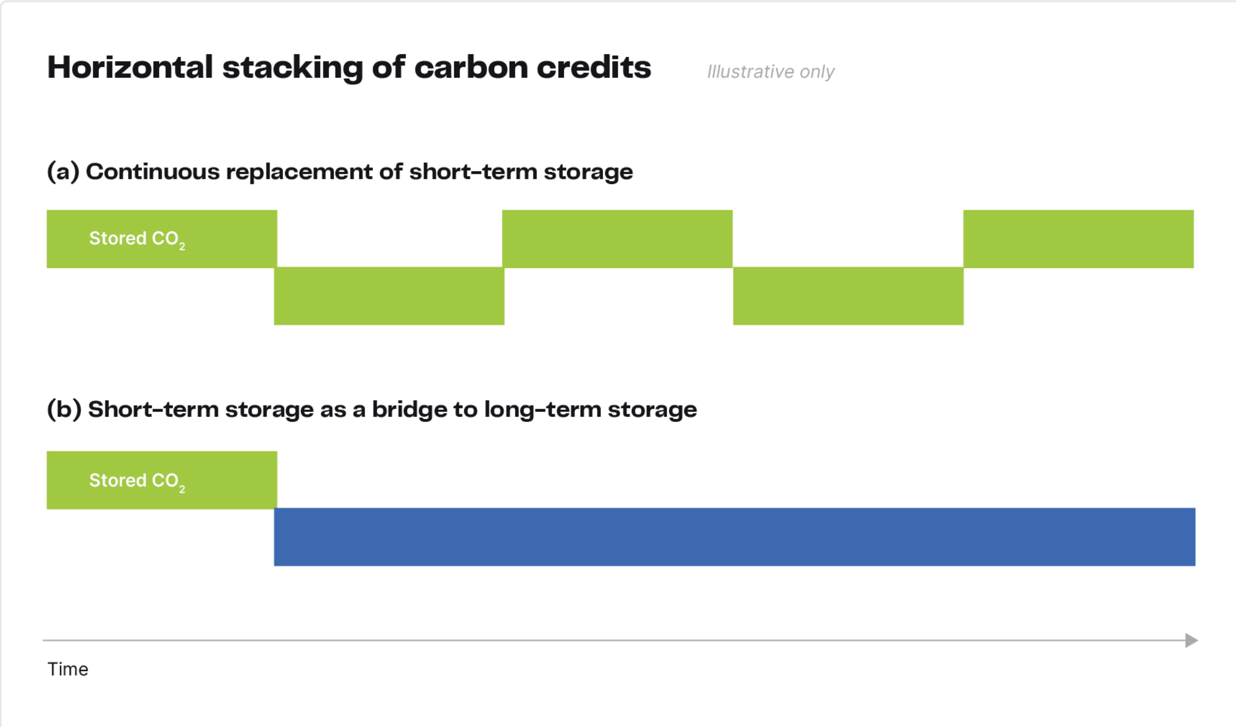

Figure 8. Examples of horizontal stacking, in which carbon credits are sequentially combined over time to achieve permanent carbon removal. This can be done by (a) continuously replacing short-term storage or (b) using short-term storage as a bridge to long-term storage. Source: Carbon Direct.

The path forward for durability and farmer contracts

Buyers can take the following actions to bring the priorities of farmers and developers into alignment and increase credit durability:

- **Modify buyer claims to support short-term contracts.** Innovative accounting and crediting approaches such as tonne-year accounting and horizontal stacking can circumvent the need for long-term contracting.
    - For example, buyers who want to invest in soil carbon solutions could take a horizontal stacking approach to reporting that leverages short-term contracts.
    - Similarly, buyers could claim three- to five-year deferred emissions rather than durably stored SOC.
- **Create new approaches to contracting to align buyer priorities for durably stored carbon and farmer contract term preferences.**
    - Contracts can be modified to de-risk these concerns. For example, contracts can more flexibly accommodate deviations from regenerative practice changes to accommodate in-year growing conditions as-needed.
- **Signal support for additional novel financing mechanisms to enable practice change and maintenance.**
    - Buyers can help to de-risk practice adoption and sustained upkeep for farmers by signaling a willingness to pay for credits that stack incentives on top of carbon finance. Care should be taken to ensure that practice changes are additional, even with stacked financing sources.

- Buyers can support innovative crop insurance models that support regenerative practices.[97]

Conclusion

Soils have the potential to remove and store significant amounts of carbon dioxide from the atmosphere through adoption of regenerative agricultural practices. These practices can not only build soil carbon, but also provide co-benefits such as increased yields, improved soil health, and enhanced ecosystem resilience. However, increasing the supply of high-quality credits from soil carbon projects in the VCM will require innovative solutions and collaborative effort among many stakeholders including farmers, project developers, buyers, and policymakers. The two quality concerns critical for buyers making decisions about credit purchases are rigorous MMRV and the long-term durability of carbon stored in soils.

The ability to accurately, reliably, and affordably quantify changes in soil carbon in response to agricultural practice changes, or MMRV, is one of the key challenges limiting the supply of high-quality soil carbon credits in the VCM. Over time, collective efforts to improve measurement technologies and generate shared benchmarking datasets may enable more cost-effective, high-quality soil carbon credit generation for a wider range of projects. In the short term, buyers can look for projects that are most likely to minimize uncertainty, reduce costs, and deliver high-quality MMRV at scale. Buyers can prioritize projects that support model-based approaches, focus on highly productive systems, aggregate many individual fields into a single, large-scope project, employ a measure-and-model approach, gather robust datasets from appropriate long-term agricultural experiments, publicly share proprietary collected datasets, and address uncertainty effectively across all of the sources relevant to the project's quantification methodology.

The second key challenge to increasing the supply of high-quality soil carbon credits in the VCM is ensuring carbon storage durability. Soil carbon durability is challenged by a misalignment between the priorities of project developers (and credit buyers), who assume that the farming practices required by a project will continue long after carbon payments have stopped, and those of farmers who face socioeconomic pressures that drive their decision-making around farming practices. In many cases, regenerative agricultural practices may lead to improved long-term economics for farmers and ranchers. However, there is not yet enough evidence to be confident that farmers and ranchers will maintain practices for decades, even with their economic benefits. Buyers can bring the priorities of farmers and developers into alignment and increase credit durability by taking actions such as modifying buyer claims to support short-term contracts, creating new approaches to contracting that align buyer priorities for durably stored carbon with farmers' contract term preferences, and signaling support for additional novel financing mechanisms to enable practice change and maintenance.

Solving these critical obstacles could unlock the potential for gigatonnes of annual CDR in soils, the availability of more high-quality soil carbon credits in the VCM, and increased confidence in MMRV approaches for soil carbon projects. Buyers can give a strong demand signal to the VCM by

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[97] Jeyaretnam M. 2024 Jul 30. Crop insurance won't let some farmers adapt to climate change. Farm Progress. https://www.farmprogress.com/conservation-and-sustainability/crop-insurance-won-t-let-some-farmers-adapt-to-climate-change.

indicating their preference for projects, research priorities, and government policies that align farmer incentives with project goals, inspire confidence through rigorous MMRV approaches that reduce uncertainty, and support the long-term storage of carbon in soils.

Appendix A: Illustrative case studies

In this section, we describe five archetypal soil carbon offset credit projects and compare the unique challenges faced by each. Projects face different challenges based on cropping system (e.g., crops vs. livestock, annual vs. perennial), project size, location-specific regulations surrounding land tenure and carbon project rights, and the extent of prior scientific examination of the practice changes and agricultural production systems included in the project. Costs of MMRV and uncertainty vary in their contribution to credit generation based on project context (**figure 9**). In all cases, investment in innovation and research creates opportunities to improve MMRV and lower uncertainties to drive down costs and enable scale-up.

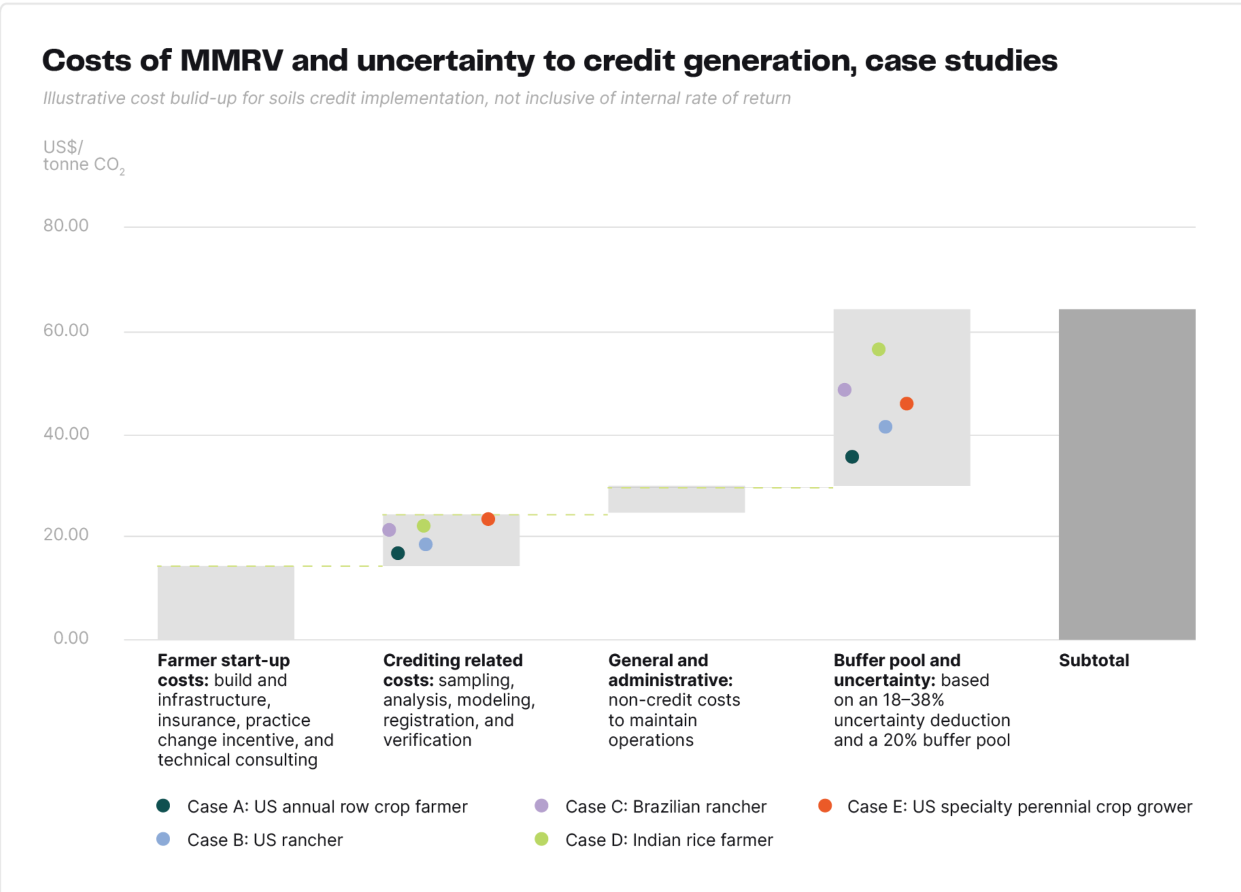


Figure 9: Costs of MMRV and uncertainty to credit generation vary under different project scenarios as illustrated in case studies A through E. Estimates are qualitative. Source: Carbon Direct.

Case A: US annual row crop farmer

A corn farmer operating on 500 acres of leased land in the midwestern US wants to participate in a large, aggregated soil carbon project (containing many distinct farms and fields across multiple states) by planting cover crops. In many ways, this farmer is in the ideal circumstance for accurate soil carbon credit quantification for several reasons:

- Studies on cover crops in corn production systems are widely available in the US to inform a modeling approach.

- Labs are widely available in the region that can conduct SOC measurements using modern combustion methods.
- Joining a large, aggregated project will help to manage quantification uncertainty.

Cost and scale considerations:

- Given this farmer's location in an area with existing underlying datasets, and the aggregated nature of the project, this represents an opportunity with relatively lower cost and lower uncertainty (**figure 9**).

The project will still face challenges:

- Leased farmland adds complexity to legal agreements between the land manager, land owner, and project developer. This introduces risk to credit durability because of the potential for shorter-term contracts and turnover of land managers.

Case B: US rancher

A rancher raising beef cattle on 250 acres of privately-held land in the southwestern US wants to generate soil carbon credits on their land by implementing intensive rotational grazing. Several project strengths will support the ranch's inclusion in a high-quality soil crediting program:

- Some studies on intensive rotational grazing are available in the US to inform a modeling approach.
- Labs are widely available in the region that can conduct SOC measurements using modern combustion methods.
- Conducting measurements over a large land area may reduce sampling requirements and uncertainty relative to a smaller individual field.

Cost and scale considerations:

- This rancher is located in an area with existing underlying datasets. However, they are limited in their ability to aggregate and thereby reduce uncertainty. This represents a medium-to-low cost opportunity for sampling and uncertainty relative to current market capabilities (**figure 9**).

The project will still face challenges:

- Slow plant growth in the region will likely lead to lower sequestration rates than those observed in more productive systems. Low rates of soil carbon change are more difficult to detect against a noisy, heterogeneous background, so uncertainty deductions may constitute a large proportion of generated credits.
- Conducting a project on a single ranch, rather than as part of an aggregated project, may increase necessary sampling density and uncertainty deductions.

Case C: Brazilian rancher

A rancher raising beef cattle on 3,000 acres of privately held land in Mato Grosso, Brazil wants to generate soil carbon offset credits by implementing adaptive multi-paddock grazing. Several project strengths will support the ranch's inclusion in a high-quality soil crediting program:

- Strong plant productivity in the region may support higher rates of soil carbon sequestration.

- Conducting measurements over a large land area may reduce sampling requirements and uncertainty relative to a smaller individual field.

Cost and scale considerations:

- This rancher is located in an area with few underlying datasets, and without the ability to aggregate and thereby reduce uncertainty. This represents a medium cost opportunity for sampling and uncertainty relative to current market capabilities (**figure 9**).

The project will still face challenges:

- Studies on intensive rotational grazing are less common in Brazil, and the project may need to rely on less ideally matched studies to inform a modeling approach.
- Conducting a project on a single ranch, rather than as part of an aggregated project, may increase necessary sampling density and uncertainty deductions.

Case D: Indian rice farmer

A smallholder rice farmer in rural India is looking to generate carbon offset credits by implementing water and nutrient management. The project is likely to face significant challenges:

- Most registry methodologies for soil carbon are not designed with methane production in rice in mind. While separate methodologies do exist for methane production in rice, these methodologies do not provide consistent, reliable guidance on quantification. The project may struggle to identify and apply an appropriate methodology, even if protocols like CAR SEP and VM0042 are technically inclusive of the relevant practice changes and greenhouse gas (GHG) fluxes.
- While studies on methane production in rice in India exist, methane emissions vary far more in time and space than soil organic carbon, and model prediction uncertainty may overwhelm any credits generated.
- Methane production can be measured directly at the time of production using gas flux chambers or towers, but avoided emissions cannot be measured at periodic intervals to true up models the way SOC can. Large pulses of methane following specific management events may not be captured by monitoring methods. Nitrous oxide emissions are also likely an important part of the project's emissions profile, and nitrous oxide production is highly variable and very difficult to predict with models.

Cost and scale considerations:

- This farmer is located in an area without existing underlying datasets, where lab infrastructure may be limited, and where measurement techniques remain nascent. This represents a medium-to-high cost opportunity for sampling and uncertainty relative to current market capabilities (**figure 9**).

Case E: US specialty perennial crop grower

A tree fruit grower in the southern US is looking to generate carbon offset credits by implementing nutrient management and cover cropping. The project is likely to benefit from regional support for soil carbon projects:

- Labs are widely available in the region that can conduct SOC measurements using modern combustion methods. This may facilitate a "measure and re-measure" approach, rather than a modeling approach.

- A farmer managing a long-lived orchard may be more willing to commit to management changes over a longer period of time, alleviating some durability concerns.

Cost and scale considerations:

- This grower is located in an area with existing underlying datasets. However, they are limited in their ability to aggregate and in their ability to scale due to a reliance on physical samples. This represents a medium-to-high cost opportunity for sampling and uncertainty relative to current market capabilities (**figure 9**).

The project will still face challenges:

- Studies on soil carbon responses to cover cropping and nutrient management in a specialized tree fruit production system may be rare (see **Appendix C**), which may impede a modeling approach and instead require a direct measurement approach that may be more expensive.
- Soil carbon may be distributed more heterogeneously in a tree production system and detecting small changes in response to cover cropping and nutrient management may be very difficult and require a large number of samples.

Appendix B: Protocol comparison and gap analysis

This analysis of soil carbon methodologies focuses on identifying the most common protocols utilized by developers and evaluated by Carbon Direct, drawing insights from Carbon Direct and from Berkeley's Voluntary Registry Offsets Database.[98] Four methodologies have been selected for detailed examination, including BCarbon, CAR SEP, VM0042, and VM0032.

The rationale for choosing these specific protocols lies in their prevalence and relevance in current carbon offset markets. By concentrating on these methodologies, Carbon Direct ensures that the analysis encompasses a range of practices that reflect industry standards and best practices in carbon accounting. This selection also facilitates alignment with Microsoft's operational goals and sustainability objectives, allowing for a more targeted evaluation of methodologies that are directly applicable to ongoing and future projects.

The comparison of the four selected protocols will be based on several key criteria that align with Carbon Direct and Microsoft's *Criteria for High-Quality Carbon Dioxide Removal*.[99] These criteria include additionality, assessing whether the carbon benefits are genuinely additional; baselines, evaluating the robustness and adaptability of baseline methodologies; carbon accounting and MMRV, examining the rigor of measuring, monitoring, reporting, and verifying soil carbon changes; durability, analyzing permanence requirements for carbon storage; leakage, reviewing how well each methodology addresses potential leakage; and social and environmental safeguards, considering commitments to community engagement and environmental integrity (**table 2**). Color coding reflects project scores based on Carbon Direct and *Microsoft's Criteria for High-Quality Carbon Dioxide Removal.* Green indicates projects likely meet or exceed quality criteria, yellow suggests most objectives are met with some uncertainties, orange signals deficiencies or critical uncertainties, and red denotes projects unlikely to meet scientific or technical standards.

Table 2. Gap analysis of common soil carbon credit protocols against criteria for high-quality CDR

	VM0042	CAR SEP	BCarbon	VM0032
Additionality	Sets a 20% adoption threshold, identification of barriers preventing project activities and performance standard tests. Strong performance-based additionality but lacks financial dependence test.	Requires common practice, legal, regional, and social and cultural barriers tests with a 50% adoption threshold and options for stacked practices. Strong exclusion of common practices, but lacks a strict financial need test at	Credits issued only for soil and root carbon exceeding initial measurements. No financial additionality test or regional adoption threshold.	Four-step assessment: identifying alternative land-use scenarios, investment analysis, barrier analysis, common practice test. Strong structure for demonstrating additionality but lacks requirements for dynamic soil

[98] Haya BK, Abayo A, Rong X, So IS, Elias M. 2024. Voluntary Registry Offsets Database v2024-08-31. https://gspp.berkeley.edu/research-and-impact/centers/cepp/projects/berkeley-carbon-trading-project/offsets-database.
[99] Carbon Direct and Microsoft. 2024. Criteria for High-Quality Carbon Dioxide Removal, 2024 Edition. [accessed 2024 Dec 6]. https://21906989.fs1.hubspotusercontent-na1.net/hubfs/21906989/Report_Criteria-High-Quality-Carbon-Dioxide-Removal_2024.pdf.

	VM0042	CAR SEP	BCarbon	VM0032
		the project level.		carbon baselines and region-specific agricultural-system benchmarks, introducing uncertainties.
Baselines	Dynamic baseline calculation with periodic calibration every five years; uses models or control sites (e.g., DNDC, DAYCENT). Dynamic baseline updates ensure accurate crediting.	Dynamic baseline updated annually, recalibrated with site-specific data, using control plots and models like DAYCENT and DNDC. Conservative, aligning well with high-quality criteria.	Static baseline based on initial SOC measurements, with no periodic updates or control plants. Limits accuracy in tracking long-term soil carbon changes.	Modeled baseline using soil carbon models (e.g., Century, SNAP CENTURY, EPIC), reassessed every 5–10 years. Strong use of historical data but lacks fully dynamic updates.
Carbon accounting and MMRV	Three quantification approaches. Approach 1: Measure and Model combines five-year soil resampling with biogeochemical models to estimate GHG fluxes and SOC changes; uncertainty deductions via Monte Carlo uncertainty deductions and analytical error propagation; requires 30 cm minimum sampling depth and calibration against independent datasets. Approach 2: Measure and Re-Measure ensures high empirical accuracy by directly measuring SOC stocks using baseline control sites, requiring periodic sampling. Approach 3: Default Factors estimates emissions using IPCC factors, prioritizing project-specific or regional data and periodic updates for conservativeness; no direct measurement.	Employs validated models, five-year stratified sampling, and ISO-standard verification to ensure conservative and transparent carbon accounting. Its MRV framework meets or exceeds best practices, with georeferenced sampling locations, robust uncertainty deductions, and a 70% probability exceedance threshold for crediting. Minimum soil sampling depths (30 cm–1m) and sensitivity analyses further enhance accuracy, demonstrating a high level of rigor in monitoring and verification.	Applies a margin-of-error deduction but lacks strict periodic sampling requirements, weakening its ability to track long-term SOC changes reliably. It does not specify clear stratification by soil type, crop, or climate conditions, and its MRV guidance is less transparent compared to other protocols. Without robust uncertainty quantification or well-defined verification cycles, confidence in long-term carbon tracking is lower.	Combines measured and modeled approaches, requiring soil resampling every 5–10 years and Monte Carlo uncertainty analysis to ensure accuracy. While it mandates stratification by soil type, grazing intensity, and fire history, reliance on models introduces some risk. Longer verification intervals and potential uncertainties in modeled estimates may impact precision, but overall, the protocol provides comprehensive documentation and multiple quantification options.

	VM0042	CAR SEP	BCarbon	VM0032
Durability	100-year permanence assessed with agriculture, forestry, and other land use (AFOLU) Risk Tool; project crediting period ranges from 20 to 100 years, with a minimum 40-year project length. Strong permanence measures with risk-based assessments but lacks adaptive management flexibility.	100-year permanence period or TYA[100], with 10-year crediting renewable up to 30 years. The 100-year permanence standard ensures long-term durability, but the TYA option introduces flexibility that may weaken durability commitments.	Five-year "true-up" adjustments and allocates 10% of credits to a buffer but lacks a specified permanence period. No long-term permanence requirement or clear reversal mechanisms, making durability weaker.	[See VM0042][101]
Leakage	Tracks activity-shifting and market leakage, assessing land market shifts and livestock displacement. Comprehensive quantification methods ensure robust leakage accounting.	Assesses activity-shifting and market leakage at the field and project levels. Strong methodology, but the use of TYA may delay leakage detection, reducing immediate accountability.	Provides a basic framework for leakage, but lacks structured quantification methods. No tracking of indirect effects, making leakage assessment weak.	Monitors grazing displacement and defines activity-shifting leakage with quantification methods but does not include a standalone land market assessment. Quantification of activity-shifting leakage is sound, but the lack of a standalone land market assessment creates risks for broader land-use shifts.
Social harms and benefits	Uses Verra's CCB Standards to address FPIC, Indigenous rights, and community assessments. However, it lacks explicit environmental justice considerations beyond CCB and provides weak	Covers stakeholder engagement, labor, gender, human rights, and benefit-sharing but lacks specificity in ensuring equitable benefit distribution, lessee protections, revenue-sharing transparency, and mitigation of	No explicit provisions for social harms or benefits.	[See VM0042][102]

[100] Tonne-year accounting
[101] VM0032 assesses durability using the same AFOLU Non-Permanence Risk Tool v4.2 as VM0042
[102] VM0032 uses Verra's Climate, Community, and Biodiversity (CCB) Standards v3.1 to assess social harms and benefits

	VM0042	CAR SEP	BCarbon	VM0032
	monitoring of benefit-sharing.	agricultural input-related health risks.		
Environmental harms and benefits	Guided by CCB Standards for soil, biodiversity, and water safeguards. However, it lacks long-term adaptive monitoring to assess ongoing ecosystem impacts.	Safeguards for pollution prevention, biodiversity conservation, and land and water quality, but no mandates for long-term biodiversity monitoring or proactive ecosystem risk mitigation. Projects must address harms, but voluntary co-benefit tracking limits accountability for long-term environmental impacts.	No explicit provisions for environmental harms or benefits.	[See VM0042][103]

Source: Carbon Direct

The selected soil carbon project protocols permit diverse practices aimed at enhancing soil carbon and ecosystem health, with variations in scope and specificity (**table 3**). VM0042 is the most comprehensive, covering advanced fertilizer use, precision irrigation, reduced tillage, diverse cropping systems, alternate wetting and drying in rice, avoidance of residue burning, and improved grazing management. Similarly, CAR SEP supports a broad array of practices, including fertilizer and water management, crop diversity, reduced tillage, improved grazing, manure management, and fossil fuel reduction. BCarbon is the most flexible, requiring only that practices enhance belowground carbon and improve soil health without prescribing specific methods. Eligible practices under VM0032 focus on improving grazing and fire management to enhance soil carbon sequestration and reduce methane and nitrous oxide emissions. These include rotational grazing, adaptive multi-paddock grazing, grassland restoration without mechanical tillage, fire and woody vegetation management, shifting livestock species composition, and forage enhancement via seeding. They exclude tillage, fertilizer application, and land-use changes like afforestation or agroforestry.

Table 3. Eligible practice changes across select soil carbon protocols

Practice	VM0042	CAR SEP	BCarbon	VM0032
Fertilizer optimization (4R practices)[104]	Yes	Yes	Yes	No

[103] VM0032 uses Verra's Climate, Community, and Biodiversity (CCB) Standards v3.1 to assess environmental harms and benefits
[104] The 4R practices refer to nutrient stewardship—right source, right rate, right time, right placement.

Use of organic fertilizers (e.g., manure, compost)	Yes	Yes	Yes	No
Enhanced efficiency nitrogen fertilizers	Yes	Yes	Yes	No
Precision irrigation	Yes	Yes	Yes	No
Alternate wetting and drying in Rice	Yes	Yes	No	No
Groundwater level management	Yes	No	No	No
Reduced/conservation tillage	Yes	Yes	Yes	No
No-till	Yes	Yes	Yes	No
Crop residue retention	Yes	Yes	Yes	No
Avoidance of residue burning	Yes	No	No	No
Rotational grazing	Yes	Yes	Yes	Yes
Adaptive multi-paddock grazing	Yes	Yes	Yes	Yes
Grassland restoration (replanting)	No	No	No	Yes[105]
Afforestation, reforestation, and revegetation	No	No	Yes	No
Agroforestry	Yes	No	Yes	No
Cover cropping	Yes	Yes	Yes	No
Manure management (>20% dry matter)	No	No	No	No
Fossil fuel reduction	No	Yes	No	No
Cover rotation	Yes	Yes	Yes	No
Fire & woody vegetation management	No	No	No	Yes
Shifting livestock species composition	No	No	No	Yes
Forage enhancement via seeding	No	No	No	Yes

Source: Carbon Direct

The protocols differ in their treatment of carbon pools (**table 4**). VM0042 and VM0032 both require SOC measurement and conditionally include aboveground woody biomass. Aboveground woody biomass is conditionally included under VM0042 if project activities significantly reduce the pool, while belowground woody biomass is optional. Under VM0032 aboveground woody biomass is conditionally included if project activities change fire management or woody biomass is burned for soil sequestration. If project activity reduces fire frequency, increased removals from woody

[105] Only if no mechanical tillage is involved.

biomass must be quantified and monitored. If there are no fire management changes, aboveground woody biomass is optional. All other pools, including aboveground non-woody biomass, dead wood, litter, and wood products, are excluded from both VM0042 and VM0032. CAR SEP and BCarbon focus exclusively on SOC, requiring its measurement and excluding all other pools. Wood products are excluded across all protocols.

Table 4. Treatment of carbon pools across the protocols

Carbon pools	VM0042	CAR SEP	BCarbon	VM0032
Soil organic carbon	Required	Required	Required	Required
Aboveground woody biomass	Conditionally included[106]	Excluded	Excluded	Conditionally included[107]
Aboveground non-woody biomass	Excluded	Excluded	Excluded	Excluded
Belowground woody biomass	Optional	Excluded	Not mentioned	Not mentioned
Belowground non-woody biomass	Excluded	Excluded	Not mentioned	Excluded
Dead wood	Excluded	Excluded	Not mentioned	Excluded
Litter	Excluded	Excluded	Not mentioned	Excluded
Wood products	Excluded	Excluded	Not mentioned	Excluded

Source: Carbon Direct

The eligible GHG fluxes vary significantly across the protocols, reflecting different approaches to measurement, inclusion, and exclusion of specific emissions sources (**table 5**). VM0042 and CAR SEP are the most comprehensive, requiring most fluxes to be measured. VM0042 conditionally includes fluxes such as biomass burning, fossil fuel use, liming, and soil methanogenesis, depending on project-specific thresholds. In contrast, CAR SEP requires measurement of all these fluxes except liming, which is not explicitly addressed. Both protocols require the inclusion of emissions from fertilizers, manure deposition, and enteric fermentation. BCarbon, by contrast, does not require quantitative assessment of GHG emissions from land management changes but encourages qualitative analysis of potential impacts. Under VM0032, methane (CH_4) from grazing animals is included, while CH_4 from burning biomass is conditionally included, required only if fire is increased to enhance SOC. Nitrous oxide (N_2O) from burning biomass is excluded as negligible, and other GHG fluxes (e.g., fertilizers, manure, fossil fuels, enteric fermentation, liming) are not required.

[106] Required if project activities significantly reduce the pool compared to the baseline. Optional otherwise.
[107] Required if project activities change fire management, woody biomass is burned for soil sequestration, or fire frequency is reduced (requiring quantified removals). Optional if no fire management changes.

The contrasting treatment of GHG fluxes across the protocols underscores differing priorities and levels of precision in emissions accounting.

Table 5. Measurement, inclusion, and exclusion of GHG fluxes

GHG Fluxes	VM0042	CAR SEP	BCarbon	VM0032
Fertilizers (N_2O)	Included	Included	Excluded	Not mentioned
Use of N-fixing species (N_2O)	Included	Included	Excluded	Not mentioned
Burning of Biomass (CH_4)	Conditionally Included[108]	Included	Excluded	Conditionally Included[109]
Burning of Biomass (N_2O)	Conditionally Included[6]	Included	Excluded	Excluded
Manure deposition (CH_4)	Included	Included	Excluded	Not mentioned
Manure deposition (N_2O)	Included	Included	Excluded	Not mentioned
Fossil Fuels (CO_2)	Conditionally Included[6]	Included	Excluded	Not mentioned
Enteric fermentation (CH_4)	Included	Included	Excluded	Included
Liming (CO_2)	Conditionally Included[6]	Not mentioned	Excluded	Not mentioned
Soil methanogenesis (CH_4)	Conditionally Included[6]	Included	Excluded	Not mentioned

Source: Carbon Direct

[108] If the project results in >5% emissions increase, optional if the project results in emissions decrease.
[109] Excluded if reducing or maintaining fire. Otherwise, must be calculated to assess net carbon stock changes from increased fire for SOC.

Appendix C: Literature review results

Methods

Practice changes were defined based on the type of tillage, soil, and grazing management methods employed in the studies. *Conservation tillage* refers to a broad category of tillage systems that reduce soil disturbance compared to conventional tillage and retain a portion of crop residues on the soil surface. Conservation tillage includes reduced tillage and, in some definitions, no-till, but the key distinction is that it focuses on maintaining surface residue cover rather than specifying a particular tillage method. Conservation tillage may involve subsoiling, chiseling, or shallow tillage operations but avoids intensive soil disturbance like moldboard plowing. *Managing tillage regime* encompasses studies that evaluate or transition between multiple tillage practices (e.g., no-till, reduced tillage, shallow tillage, conservation tillage) rather than consistently applying a single approach. *No-till* is a distinct practice in which soil remains completely undisturbed, and crop residues stay on the surface. It is categorized separately when a study explicitly states it as the applied practice. However, if a study includes no-till within its definition of conservation tillage, it is classified accordingly. Unlike conservation tillage, which allows some soil disturbance, no-till eliminates tillage entirely. *Reduced tillage* is a form of conservation tillage that further limits soil disruption by restricting tillage to shallow depths (e.g., chiseling, disc harrowing) while still incorporating some level of residue into the soil. It differs from conservation tillage and no-till by allowing mechanical disturbance while focusing on minimizing soil disruption rather than maintaining high surface residue levels. *Grazing management* includes strategies that control grazing intensity, duration, and timing to optimize soil health and carbon retention. Practices range from seasonal adjustments to multi-species grazing and grazing exclusion for soil recovery. Studies that include multiple practice changes, such as no-till, grazing management, and stubble retention, are categorized as *variable*.

For cropping systems, the classification includes *row cash crops*, which consist of crops like corn, wheat, soy, and grains; *specialty crops*, encompassing crops that do not fall into the cash crop or rice categories, such as peppers, cucumbers, and lettuce, as well as crops grown for fruit farming; *rice*, which includes cropping systems where rice is the primary crop and is often grown under specific water management practices, such as controlled flooding, distinguishing it from other row crops; and *livestock agriculture*, which encompasses systems managed primarily for grazing or forage production, including permanent grasslands and pastures, and includes studies focusing on grazing management and forage crops used for livestock. *Mixed systems* are used for studies that integrate multiple systems, including combinations of row crops and pastures or rotations blending annual and perennial species. This mixed category serves as a catch-all for studies that do not fit neatly into the other classifications.

Results

The distribution of practice changes in long-term soil research highlights a significant emphasis on diverse and integrated management approaches (see **table 6** and **figures 10–14**). The most studied category, *managing tillage regime*, spans various tillage practices, including no-till, reduced tillage, shallow tillage, and conservation tillage, underscoring a broad interest in evaluating multiple methods to optimize soil health. Similarly, studies under the *variable* category, which include combinations of no-till, grazing management, and stubble retention practices, reveal a trend toward exploring complex, multi-practice systems. This category's strong representation suggests that researchers are increasingly interested in understanding the cumulative effects of combined practices on soil carbon retention and health. *No-till* and *grazing Management* practices also show similar study counts, reflecting the growing focus on practices that minimize soil disturbance and leverage natural processes. *No-till* aligns with conservation agriculture's emphasis on protecting soil structure, while grazing management supports carbon retention through controlled grazing intensities and recovery periods. Both practices illustrate a shift toward strategies that encourage natural soil regeneration and carbon conservation. See **table 10** for a complete list of the studies included.

Conversely, *conservation tillage* and *reduced tillage* are notably under-represented, with only seven and six studies, respectively. *Conservation tillage*, which aims to balance soil health with minimal disturbance, appears to receive less attention than fully non-disturbing or integrated systems. This limited focus may reflect either lower adoption in practice or a perception that its benefits are less distinct than those of no-till or mixed systems. *Reduced tillage's* niche representation may suggest it is seen as a transitional or intermediate approach rather than a primary soil management practice. The emphasis on fully non-disturbing practices and integrated approaches aligns with a broader trend in soil research toward regenerative practices that maximize soil resilience and carbon retention, essential goals in the context of climate change and sustainable agriculture.

Table 6. Distribution of practice changes by country

	Practice change						
Location	**Conservation tillage**	**Grazing management**	**Managing tillage regime**	**No till**	**Reduced tillage**	**Variable**	**Total**
Argentina	0	1	0	0	0	0	1
Australia	1	0	3	8	3	3	18
Belgium	0	0	0	0	1	0	1
Brazil	0	0	5	4	0	1	10
Canada	0	5	4	1	0	3	13
China	1	3	5	1	0	0	10
Columbia	0	0	0	0	0	3	3
England	0	0	0	0	0	1	1
Ethiopia	0	1	0	0	0	0	1
Finland	0	0	1	0	1	0	2
France	0	0	4	0	0	0	4
India	0	0	2	0	0	0	2

	Practice change						
Location	**Conservation tillage**	**Grazing management**	**Managing tillage regime**	**No till**	**Reduced tillage**	**Variable**	**Total**
Italy	0	0	1	0	0	0	1
New Zealand	0	0	2	0	0	1	3
Spain	1	0	1	0	0	0	2
The Netherlands	0	0	0	0	0	3	3
UK	0	0	2	0	0	2	4
USA	4	6	7	6	1	6	30
Total	**7**	**16**	**37**	**14**	**6**	**18**	**109**

Source: Carbon Direct

The distribution of practice changes across cropping systems reveals several trends in long-term soil research. Row cash crops are the most frequently studied system, with a strong emphasis on diverse tillage practices, particularly *managing tillage regime* and *no-till* approaches (**table 7**). This suggests a focused effort to understand how various levels of soil disturbance—from minimal to complete avoidance—affect soil carbon retention in widely cultivated crops like corn, wheat, and soy. The emphasis on grazing management within *livestock agriculture* similarly highlights an interest in sustainable grazing practices, such as rotational and seasonal adjustments, which aim to enhance soil health and carbon levels in grasslands and pastures. Notably, *specialty row crops* and *rice* systems are underrepresented in soil management studies, pointing to a potential research gap in understanding how conservation and reduced tillage practices impact these systems. This gap may stem from the unique environmental and management needs of these diverse crops.

An increased focus on integrated and multi-practice approaches is also apparent within the *mixed systems* and *variable* categories, indicating a shift toward more holistic research that better captures real-world agricultural practices. These categories reflect an interest in combining practices, such as no-till and grazing management, to assess their cumulative impact on soil health, suggesting that researchers recognize the potential of integrated systems to provide substantial soil carbon benefits. In contrast, *conservation tillage* and *reduced tillage* practices are less frequently studied, especially within more specialized systems, implying a tendency to prioritize no-till or variable practices over minimal tillage methods. Overall, these patterns suggest that long-term soil research is focused on dominant cropping systems and low-disturbance management approaches, with a growing appreciation for realistic, mixed-use landscapes that more accurately reflect complex farming systems. However, the lack of studies on specialty crops, rice, and conservation tillage may indicate opportunities for further research to ensure comprehensive insights into soil carbon dynamics across diverse agricultural systems.

Table 7. Practice changes across cropping systems

	Cropping System					
Practice change	**Livestock Agriculture**	**Mixed**	**Rice**	**Row cash crops**	**Specialty row crops**	**Total**
Conservation tillage	0	2	1	3	1	7
Grazing management	16	0	0	0	0	16
Managing tillage regime	0	8	1	26	2	37
No till	0	3	0	14	3	20
Reduced tillage	0	0	0	4	2	6
Variable	10	9	0	3	1	23
Total	**26**	**22**	**2**	**50**	**9**	**109**

Source: Carbon Direct

The distribution of cropping systems studied across regions reveals key trends in long-term soil research. *Row cash crops* receive the most focus, especially in the US and Australia, reflecting the importance of understanding soil dynamics in staple crops like corn, wheat, and soy (**table 8**). This emphasis underscores a drive to optimize soil health in systems central to food security. In contrast, *specialty row crops* and *rice* are significantly underrepresented, pointing to a research gap. The limited studies on these systems suggest a need to better explore the unique soil requirements of diverse fruits, vegetables, and water-intensive rice cultivation, especially in regions heavily reliant on these crops.

Livestock agriculture has a moderate presence, particularly in the US and Canada, highlighting regional interest in sustainable grazing practices to support soil health in grasslands and pastures. Meanwhile, *mixed systems*, which incorporate rotations of row crops, pastures, and annual/perennial species, show a balanced distribution across regions, indicating a trend toward more holistic studies that capture diverse agricultural landscapes.

Overall, these patterns suggest that soil research is largely focused on high-yield row crops and grazing systems, with a growing interest in integrated systems. The underrepresentation of specialty crops and rice, however, signals a need for expanded research to fully understand soil dynamics across all major agricultural systems.

Table 8. Cropping system distribution by country

	Cropping system					
Location	**Livestock agriculture**	**Mixed**	**Rice**	**Row cash crops**	**Specialty row crops**	**Total**
Argentina	1	0	0	0	0	1
Australia	0	3	0	10	5	18
Belgium	0	0	0	1	0	1
Brazil	0	3	1	4	2	10
Canada	6	4	0	3	0	13
China	3	0	1	6	0	10
Columbia	2	1	0	0	0	3
England	1	0	0	0	0	1
Ethiopia	1	0	0	0	0	1
Finland	0	0	0	2	0	2
France	0	2	0	1	1	4
India	0	1	0	1	0	2
Italy	0	0	0	1	0	1
New Zealand	1	1	0	1	0	3
Spain	0	1	0	1	0	2
The Netherlands	3	0	0	0	0	3
UK	0	1	0	3	0	4
USA	8	5	0	16	1	30
Total	**26**	**21**	**2**	**50**	**9**	**109**

Source: Carbon Direct

Table 9 provides a summary of soil carbon dynamics after cessation of carbon-building practices, ranked by certainty of conclusion based on number of supporting studies for each evidence category. The number of supporting studies serves as a proxy for confidence in each finding.

Table 10 provides a comprehensive list of studies included in this literature review, detailing the country, duration, type of practice change, and cropping system associated with each study's assessment of agricultural practice impacts on soil carbon.

Table 9. Evidence for soil carbon changes following practice cessation

Evidence category	Supporting studies	Description	Key findings
Rapid Change	**7 studies,** listed below: Implementation of chiseling and mouldboard plowing in soil after 8 years of no-till management in SW, Spain: Effect on soil quality Changes in soil carbon and nitrogen following tillage conversion in a long-term experiment in Northern France Impacts of long-term and recently imposed tillage practices on the vertical distribution of soil organic carbon Soil Quality Assessment after Weed-Control Tillage in a No-Till Wheat–Fallow Cropping System Short-term temporal changes of soil carbon losses after tillage described by a first-order decay model Tillage-induced soil carbon dioxide loss from different cropping systems Short-term soil CO2 emission after conventional and reduced tillage of a no-till sugar cane area in southern Brazil	Rapid declines in SOC are seen, particularly in surface layers, when tillage was reintroduced in no-till systems. Redistribution rather than total loss of carbon is observed.	• Quick drop in topsoil SOC after reintroducing tillage • Redistribution of SOC from surface to deeper layers • Coarser soils experienced faster losses • Tillage-induced disruption of soil aggregates and exposure of labile organic matter led to rapid SOC losses, with up to 20% of CO_2 flux occurring within the first two hours of tillage • In tropical systems, conventional tillage releases approximately 30% of annual crop carbon residues to the atmosphere within four weeks
Role of protection mechanisms	**5 studies,** listed below: Dynamic stability of soil carbon: Reassessing the "permanence" of soil carbon sequestration	Biological and physical mechanisms, like microbial processes and soil aggregates, buffer SOC, slowing	• Protective mechanisms contribute to the slow loss of SOC after practice cessation • Stability of carbon in soil is maintained through these mechanisms

Evidence category	Supporting studies	Description	Key findings
	Effects of occasional tillage on soil physical and chemical properties and weed infestation in a 10-year no-till system Persistence of soil organic carbon after plowing a long-term no-till field in southern Ontario Short-term temporal changes of soil carbon losses after tillage described by a first-order decay model Tillage-induced soil carbon dioxide loss from different cropping system	decomposition and preventing rapid loss.	
No change or minimal immediate change	**4 studies**, listed below: Effects of occasional tillage on soil physical and chemical properties and weed infestation in a 10-year no-till system Dynamic stability of soil carbon: Reassessing the "permanence" of soil carbon sequestration Impacts of long-term and recently imposed tillage practices on the vertical distribution of soil organic carbon Persistence of soil organic carbon after plowing a long-term no-till field in southern Ontario	Studies found no significant or immediate SOC change after cessation of carbon-building practices. Stability is attributed to soil texture and protective aggregates.	• Minimal SOC losses observed even with occasional tillage • SOC gains in deeper layers offset losses in upper layers • Finer-textured soils retained SOC
Slow decline	**4 studies,** listed below: Dynamic stability of soil carbon: Reassessing the "permanence" of soil carbon sequestration Re-visiting soil carbon and nitrogen stocks in a temperate heathland seven years after the termination	Gradual SOC declines are observed over several years, often due to protective mechanisms regulating carbon mineralization.	• SOC remained stable in deeper layers post-practice cessation • Long-term practices led to slower declines • Microbial processes contributed to stability

Evidence category	Supporting studies	Description	Key findings
	of free air CO2 enrichment (FACE) Implementation of chiseling and mouldboard plowing in soil after 8 years of no-till management in SW, Spain: Effect on soil quality Impacts of long-term and recently imposed tillage practices on the vertical distribution of soil organic carbon		
Influence of soil texture	**4 studies**, listed below: Persistence of soil organic carbon after plowing a long-term no-till field in southern Ontario Dynamic stability of soil carbon: Reassessing the "permanence" of soil carbon sequestration Short-term temporal changes of soil carbon losses after tillage described by a first-order decay model Short-term soil CO2 emission after conventional and reduced tillage of a no-till sugar cane area in southern Brazil	Finer-textured soils (clay/silt) stabilize SOC more effectively, leading to slower declines compared to coarser-textured soils.	• Stable aggregates in finer soils protect carbon from loss • Coarser soils experience more rapid carbon loss after cessation of practices
Redistribution of soil carbon	**3 studies,** listed below: Persistence of soil organic carbon after plowing a long-term no-till field in southern Ontario Changes in soil carbon and nitrogen following tillage conversion in a long-term experiment in Northern France Soil Quality Assessment after Weed-Control Tillage in a No-Till Wheat–Fallow Cropping System	SOC experiences a slow redistribution between soil layers rather than immediate loss. Surface layers lose carbon while deeper layers gain carbon, resulting in overall stability.	• Vertical movement of SOC suggests carbon is relocated within the soil profile rather than lost • Total carbon stocks remain stable over time

Evidence category	Supporting studies	Description	Key findings
Depth of soil carbon storage	**2 studies,** listed below: Impacts of long-term and recently imposed tillage practices on the vertical distribution of soil organic carbon Dynamic stability of soil carbon: Reassessing the "permanence" of soil carbon sequestration	SOC stored in deeper layers is more stable and less susceptible to loss, ensuring minimal immediate changes after cessation.	• Deeper SOC acts as a long-term carbon reservoir, less prone to depletion compared to surface SOC • Greater persistence in soil over time
Importance of practice duration	**2 studies,** listed below: Dynamic stability of soil carbon: Reassessing the "permanence" of soil carbon sequestration Effects of occasional tillage on soil physical and chemical properties and weed infestation in a 10-year no-till system	The duration of carbon-building practices impacts SOC stability, with longer practices leading to more gradual changes after cessation.	• Extended practice periods contribute to SOC stability • Longer maintenance of practices results in slower declines in SOC after cessation

Source: Carbon Direct

Table 10. Summary of studies included in the literature review

Title	Country	Duration	Practice change	Cropping system
Achieving Soil Organic Carbon Sequestration with Conservation Agricultural Systems in the Southeastern United States	USA	11 years	No-till	Mixed
Aggregate distribution and soil organic matter under different tillage systems for vegetable crops in a red latosol from brazil	Brazil	3 years	No-till	Specialty row crops
Alternative arable cropping systems: a key to increase soil organic carbon storage? results from a 16 year field experiment	France	16 years	Managing tillage regime	Mixed
Biochemical changes in a yellow-brown loam and a central gley soil converted from pasture to maize in the Waikato area	New Zealand	60 years	Managing tillage regime	Row cash crops

Table 10. Summary of studies included in the literature review

Title	Country	Duration	Practice change	Cropping system
Biologically defined soil organic matter pools as affected by rotation and tillage	USA	27 years	Managing tillage regime	Row cash crops
Biophysical indicators of sustainability of North Island hill pasture systems	New Zealand	20 years	Variable	Livestock agriculture
Carbon accumulation in soil. ten-year study of conservation tillage and crop rotation in a semi-arid area of castile-leon, spain	Spain	10 years	Managing tillage regime	Row cash crops
Carbon dynamics under long-term conservation and disk tillage management in a Norfolk loamy sand	USA	24 years	Conservation tillage	Row cash crops
Carbon inventory for a cereal cropping system under contrasting tillage, nitrogen fertilisation and stubble management practices	Australia	33 years	No-till	Row cash crops
Carbon sequestration in a Brown Chernozem as affected by tillage and rotation	Canada	12 years	Managing tillage regime	Row cash crops
Carbon sequestration in irrigated vertisols under cotton-based farming systems	Australia	13 years	Reduced tillage	Specialty row crops
Carbon sequestration in native prairie, perennial grass, no-till, and cultivated palouse silt loam	USA	28 years	Variable	Mixed
Carbon Sequestration in Rangelands Interseeded with Yellow-Flowering Alfalfa (Medicago sativa ssp. falcata)	USA	36 years	Variable	Livestock agriculture
Carbon Storage by introduced deep-rooted grasses in the South American savannas	Columbia	5 years	Variable	Mixed
Carbon stock and its compartments in a subtropical oxisol under long-term tillage and crop rotation systems	Brazil	19 years	Managing tillage regime	Row cash crops
Changes in soil carbon and nitrogen following tillage conversion in a long-term experiment in northern france	France	20 years	Managing tillage regime	Row cash crops
Combined role of no-tillage and cropping systems in soil carbon stocks and stabilization	Brazil	18 years	Managing tillage regime	Mixed

Table 10. Summary of studies included in the literature review

Title	Country	Duration	Practice change	Cropping system
Comparison of three tillage systems in the wheat-maize system on carbon sequestration in the north china plain	China	10 years	Managing tillage regime	Row cash crops
Cover crop effect on soil carbon fractions under conservation tillage cotton	USA	3 years	Variable	Row cash crops
Cover crop effects increasing carbon storage in a subtropical no-till sandy acrisol	Brazil	8 years	No-till	Row cash crops
Cover crops and no-till effects on physical fractions of soil organic matter	Brazil	3 years	Managing tillage regime	Rice
Distribution of nitrogen fractions in grazed and ungrazed fescue grassland Ah horizons	Canada	38 years	Grazing management	Livestock agriculture
Dynamics and turnover of soil organic matter as affected by tillage	Canada	11 years	No-till	Mixed
Dynamics of soil organic-matter and corn residues affected by tillage practices	Canada	11 years	Managing tillage regime	Row cash crops
Effect of grazing and cultivation on some chemical properties of soils in the mixed prairie	Canada	5 years	Variable	Mixed
Effect of no-tillage on turnover of organic matter in a rhodic ferralsol	Brazil	21 years	No-till	Row cash crops
Effect of tillage system and straw management on organic matter dynamics	UK	23 years	Managing tillage regime	Row cash crops
Effects of 11 years of conservation tillage on soil organic matter fractions in wheat monoculture in loess plateau of china	China	11 years	Managing tillage regime	Row cash crops
Effects of 27 years of reduced tillage practices on soil properties and crop performance in the semi-arid subtropics of Australia	Australia	27 years	Managing tillage regime	Row cash crops
Effects of clay minerals and land use on organic matter pools	New Zealand	21 years	Managing tillage regime	Mixed
Effects of crop rotation, crop type and tillage on soil organic carbon in a semiarid climate	Canada	11 years	Managing tillage regime	Mixed

Table 10. Summary of studies included in the literature review

Title	Country	Duration	Practice change	Cropping system
Effects of different tillage and straw return on soil organic carbon in a rice-wheat rotation system	China	2 years	Conservation tillage	Rice
Effects of soil texture and grassland management on soil organic C and N and rates of C and N mineralization	The Netherlands	2 years	Variable	Livestock agriculture
Effects of soil texture and grassland management on soil organic C and N and rates of C and N mineralization	The Netherlands	3 years	Variable	Livestock agriculture
Effects of soil texture and grassland management on soil organic C and N and rates of C and N mineralization	The Netherlands	9 years	Variable	Livestock agriculture
Grazing impacts on litter and soil organic matter in mixed prairie and fescue grassland ecosystems of Alberta	Canada	37 years	Grazing management	Livestock agriculture
Greenhouse gas contributions and mitigation potential of agriculture in the central USA	USA	34 years	Conservation tillage	Row cash crops
Impact of grazing around a watering point on soil status of a semi-arid rangeland in Ethiopia	Ethiopia	2 years	Grazing management	Livestock agriculture
Impact of grazing management on the carbon and nitrogen balance of a mixed-grass rangeland	USA	12 years	Grazing management	Livestock agriculture
Impact of grazing on soil nutrients in a Pampean grassland	Argentina	13 years	Grazing management	Livestock agriculture
Impact of long-term no-tillage and cropping system management on soil organic carbon in an oxisol: a model for sustainability	Brazil	19 years	Managing tillage regime	Row cash crops
Impact of no-till and reduced tillage on aggregation and aggregate-associated carbon in northern european agroecosystems	Finland	11 years	Managing tillage regime	Row cash crops
Impact of organic no-till vegetables systems on soil organic matter in the Atlantic Forest biome	Brazil	3 years	Variable	Specialty row crops
Impact of tillage and crop rotation on aggregate-associated carbon in two oxisols	Brazil	15 years	Managing tillage regime	Mixed

Table 10. Summary of studies included in the literature review

Title	Country	Duration	Practice change	Cropping system
Impact of tillage and crop rotation on light fraction and intra-aggregate soil organic matter in two oxisols	Brazil	15 years	No-till	Mixed
Impacts of agricultural management practices on C sequestration in forest-derived soils of the eastern Corn Belt	USA	30 years	Managing tillage regime	Mixed
Impacts of grazing intensity on soil carbon and nitrogen in an alpine meadow on the eastern Tibetan Plateau	China	8 years	Grazing management	Livestock agriculture
improved grazing management may increase soil carbon sequestration in temperate steppe	China	4 years	Grazing management	Livestock agriculture
Influence of 90 Years of Protection From Grazing on Plant and Soil Processes in the Subalpine of the Wasatch Plateau, USA	USA	90 years	Grazing management	Livestock agriculture
Influence of sorghum residues and tillage on soil organic matter and soil microbial biomass in an Australian Vertisol	Australia	6 years	No-till	Specialty row crops
Influences of grazing and exclosure on carbon sequestration in degraded sandy grassland, Inner Mongolia, north China	China	10 years	Grazing management	Livestock agriculture
Lignin and carbohydrate alteration in particle-size separates of an oxisol under tropical pastures following native savanna	Columbia	15 years	Variable	Livestock agriculture
Long-term changes in soil organic carbon and nitrogen under semiarid tillage and cropping practices	USA	86 years	Conservation tillage	Specialty row crops
Long-term conservation tillage effect on soil organic carbon and available phosphorus content in vertisols of central india	India	12 years	Managing tillage regime	Row cash crops
Long-term cropping systems and tillage management effects on soil organic carbon stock and steady state level of c sequestration rates in a semiarid environment	Italy	19 years	Managing tillage regime	Row cash crops

Table 10. Summary of studies included in the literature review

Title	Country	Duration	Practice change	Cropping system
Long-term effect of contrasted tillage and crop management on soil carbon dynamics during 41 years	France	41 years	Managing tillage regime	Specialty row crops
Long-term effects of conservation tillage on organic fractions in two soils in southwest of spain	Spain	25 years	Conservation tillage	Mixed
Long-term effects of no-tillage management practice on soil organic carbon and its fractions in the northern china	China	17 years	No-till	Row cash crops
Long-term effects of no-tillage, crop residue, and nitrogen application on properties of a Vertisol	Australia	13 years	No-till	Row cash crops
Long-term effects of tillage and crop rotations on soil organic c and total n in a clay soil in southwestern saskatchewan	Canada	11 years	Managing tillage regime	Row cash crops
Long-Term Grazing Effects on Fescue Grassland Soils	Canada	17 years	Grazing management	Livestock agriculture
Long-term grazing effects on Stripa-Bouteloua prairie soils	Canada	19 years	Grazing management	Livestock agriculture
Long-term soil organic carbon as affected by tillage and cropping systems	USA	24 years	Managing tillage regime	Row cash crops
Long-term tillage impacts on soil organic matter components and related properties on a typic argiudoll	USA	33 years	Managing tillage regime	Row cash crops
Modelling the dynamics of organic carbon in fertilization and tillage experiments in the North China Plain using the Rothamsted Carbon Model—initialization and calculation of C inputs	China	18 years	Managing tillage regime	Row cash crops
No-till effects on organic matter, pH, cation exchange capacity and nutrient distribution in a Luvisol in the semi-arid subtropics	Australia	9 years	Managing tillage regime	Row cash crops
No-tillage and nitrogen application affects the decomposition of 15N-labelled wheat straw and the levels of mineral nitrogen and organic carbon in a Vertisol	Australia	11 years	No-till	Row cash crops

Table 10. Summary of studies included in the literature review

Title	Country	Duration	Practice change	Cropping system
No-tillage increases soil profile carbon and nitrogen under long-term rainfed cropping systems	USA	20 years	Managing tillage regime	Row cash crops
Organic carbon and associated soil properties of a red earth after 10 years of rotation under different stubble and tillage practices	Australia	10 years	Reduced tillage	Row cash crops
Organic carbon and total nitrogen stocks in a Vertisol following 40 years of no-tillage, crop residue retention and nitrogen fertilisation	Australia	40 years	No-till	Row cash crops
Organic matter and microbial biomass in a vertisol after 20 yr of zero-tillage	Australia	20 years	No-till	Row cash crops
Rangeland soil carbon and nitrogen 'responses to grazing	USA	11 years	Grazing management	Livestock agriculture
Recalcitrant and labile carbon pools in a sub-humid tropical soil under different tillage combinations: a case study of rice-wheat system	India	8 years	Managing tillage regime	Mixed
Response of organic matter to reduced tillage and animal manure in a temperate loamy soil	France	8 years	Managing tillage regime	Mixed
Rothamsted Long-Term Experiments - Broadbalk Winter Wheat Experiment	UK	180 years	Variable	Row cash crops
Rothamsted Long-Term Experiments - Highfield and Fosters Ley-Arable Experiments	UK	70 years	Variable	Mixed
Seasonal Variation in Chemical Characteristics of Soil Organic Matter of Grazed and Ungrazed Mixed Prairie and Fescue Grassland	Canada	22 years	Grazing management	Livestock agriculture
Soil aggregation and carbon and nitrogen storage under soybean cropping sequences	USA	20 years	No-till	Row cash crops
Soil carbon and nitrogen accumulation with long-term no-till versus moldboard plowing overestimated with tilled-zone sampling depths	USA	28 years	Managing tillage regime	Row cash crops
Soil carbon and nitrogen of Northern Great Plains grasslands as influenced by long-term grazing	USA	78 years	Grazing management	Livestock agriculture

Table 10. Summary of studies included in the literature review

Title	Country	Duration	Practice change	Cropping system
Soil carbon and nitrogen storage in aggregates from different tillage and crop regimes	USA	20 years	No-till	Row cash crops
Soil carbon change factors for the Canadian agriculture national greenhouse gas inventory	Canada	25 years	Variable	Mixed
Soil carbon dynamics under different cropping and pasture management in temperate Australia: results of three long-term experiments.	Australia	25 years	Variable	Mixed
Soil carbon lost from Mollisols of the North Central U.S.A. with 20 years of agricultural best management practices	USA	20 years	Variable	Mixed
Soil Carbon Sequestration Potential: A review for Australian agriculture	Australia	37 years	Variable	Row cash crops
Soil carbon sequestration with continuous no-till management of grain cropping systems in the Virginia Coastal Plain	USA	14 years	No-till	Row cash crops
Soil chemical changes following manure application on irrigated alfalfa and rainfed timothy in southern Alberta	Canada	5 years	Variable	Livestock agriculture
Soil CO2 fl ux from a Norfolk loamy sand aft er 25 years of conventional and conservation tillage	USA	25 years	Conservation tillage	Row cash crops
Soil microbial biomass and activity in long-term grassland: Effects of management changes	England	11 years	Variable	Livestock agriculture
Soil organic C and N pools under long-term pasture management in the Southern Piedmont USA	USA	24 years	Variable	Livestock agriculture
Soil Organic Carbon Composition in a Northern Mixed-Grass Prairie: Effects of Grazing	USA	21 years	Grazing management	Livestock agriculture
Soil organic carbon fractions and aggregation in the Southern Piedmont and Coastal Plain	USA	30 years	Variable	Mixed
Soil properties, nutrient uptake and crop growth in an irrigated Vertisol after nine years of minimum tillage	Australia	9 years	Reduced tillage	Specialty row crops

Table 10. Summary of studies included in the literature review

Title	Country	Duration	Practice change	Cropping system
Stratification and storage of soil organic carbon and nitrogen as affected by tillage practices in the north china plain	China	9 years	Managing tillage regime	Row cash crops
The effect of reduced tillage agriculture on carbon dynamics in silt loam soils	Belgium	20 years	Reduced tillage	Row cash crops
The effect of tillage on soil surface properties and the water balance of a xeralfic alfisol	Australia	6 years	Managing tillage regime	Row cash crops
The effects of stubble burning and tillage on soil carbon sequestration and crop productivity in southeastern Australia	Australia	19 years	No-till	Row cash crops
The influence of alternative tillage systems on the distribution of nutrients and organic carbon in some common Western Australian wheatbelt soils	Australia	9 years	Reduced tillage	Row cash crops
The influence of land use and management on soil carbon levels for crop-pasture systems in Central New South Wales, Australia	Australia	6.8 years	Variable	Mixed
The potential for carbon sequestration in Australian agricultural soils is technically and economically limited	Australia	20 years	Conservation tillage	Mixed
The potential to increase soil carbon stocks through reduced tillage or organic material additions in England and Wales: A case study	UK	23 years	Managing tillage regime	Row cash crops
The use of carbon isotope ratios to evaluate legume contribution to soil enhancement in tropical pastures	Columbia	43 years	Variable	Livestock agriculture
Tillage and crop residue management affect Vertisol properties and grain sorghum growth over seven years in the semi-arid sub-tropics	Australia	7 years	No-till	Specialty row crops
Tillage and crop residue management methods had minor effects on the stock and stabilization of topsoil carbon in a 30-year field experiment	Finland	30 years	Reduced tillage	Row cash crops

Table 10. Summary of studies included in the literature review

Title	Country	Duration	Practice change	Cropping system
Tillage and nitrogen effects on soil organic matter fractions in wheat-based systems.	Texas	20 years	No-till	Row cash crops
Tillage system affects phosphorus form and depth distribution in three contrasting Victorian soils	Australia	8 years	Managing tillage regime	Specialty row crops
Tillage, cropping systems, and nitrogen fertilizer source eff ects on soil carbon sequestration and fractions.	Alabama	10 years	No-till	Row cash crops
Transition from intensive tillage to no-till enhances carbon sequestration in microaggregates of surface soil in the north china plain	China	6 years	Managing tillage regime	Row cash crops
Vegetation and Soil Responses to Cattle Grazing Systems in the Texas Rolling Plains	USA	20 years	Grazing management	Livestock agriculture

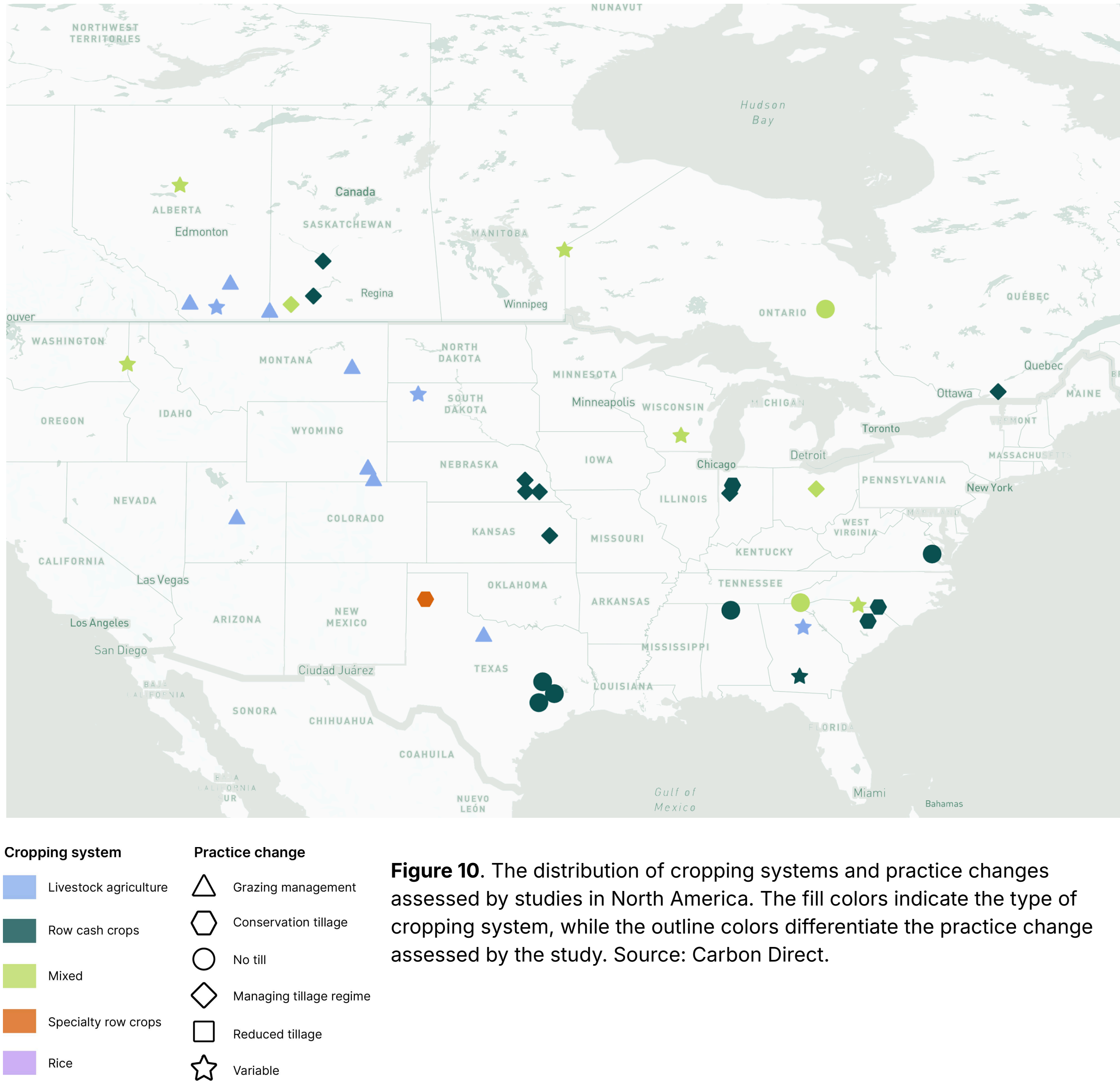


Figure 10. The distribution of cropping systems and practice changes assessed by studies in North America. The fill colors indicate the type of cropping system, while the outline colors differentiate the practice change assessed by the study. Source: Carbon Direct.

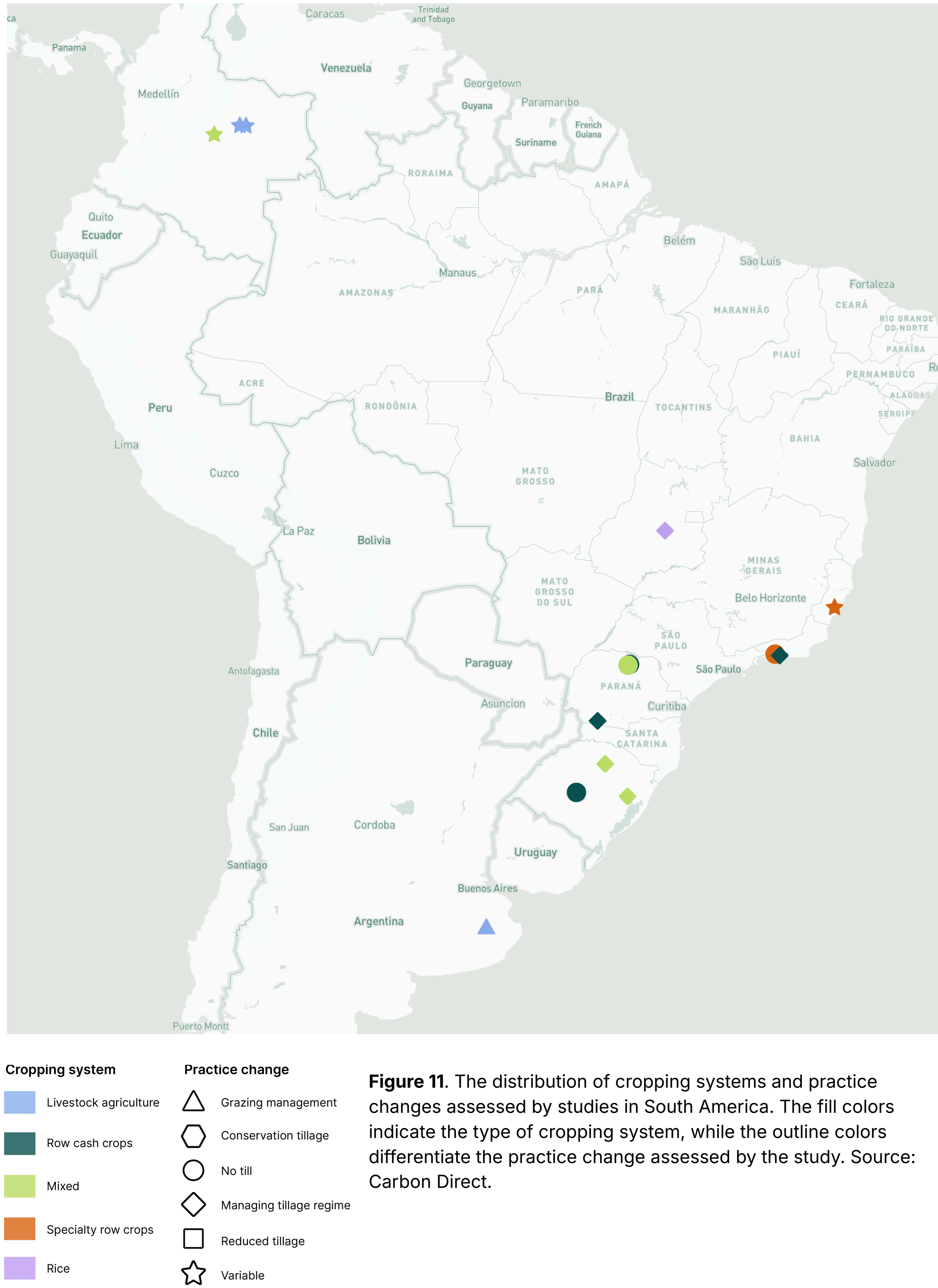
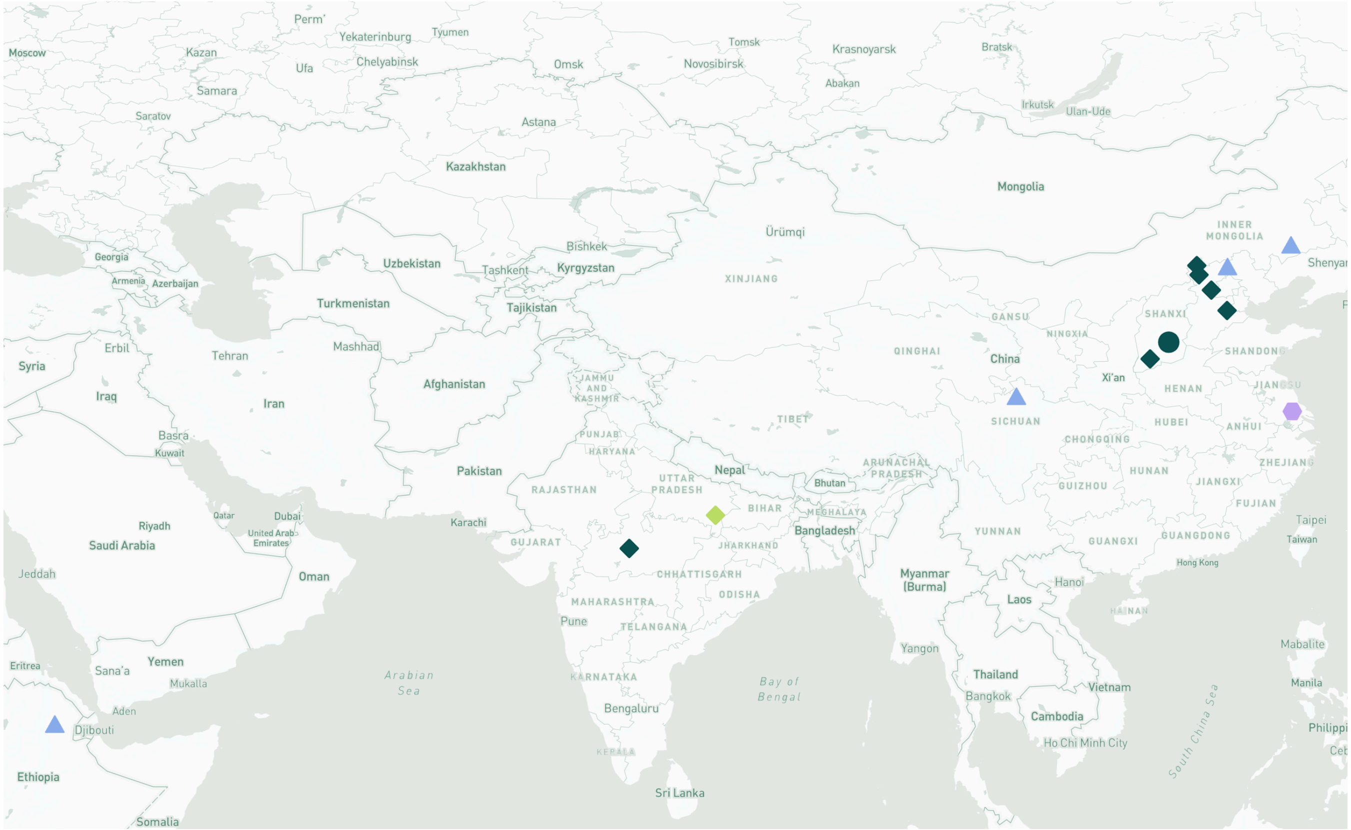


Figure 11. The distribution of cropping systems and practice changes assessed by studies in South America. The fill colors indicate the type of cropping system, while the outline colors differentiate the practice change assessed by the study. Source: Carbon Direct.

Figure 12. The distribution of cropping systems and practice changes assessed by studies in Europe. The fill colors indicate the type of cropping system, while the outline colors differentiate the practice change assessed by the study. Source: Carbon Direct.



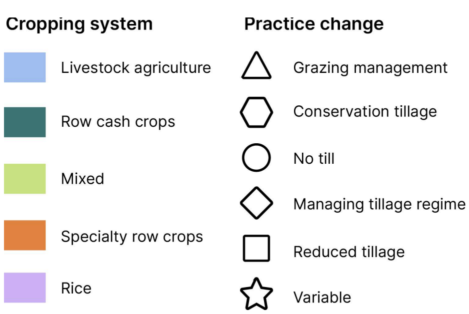
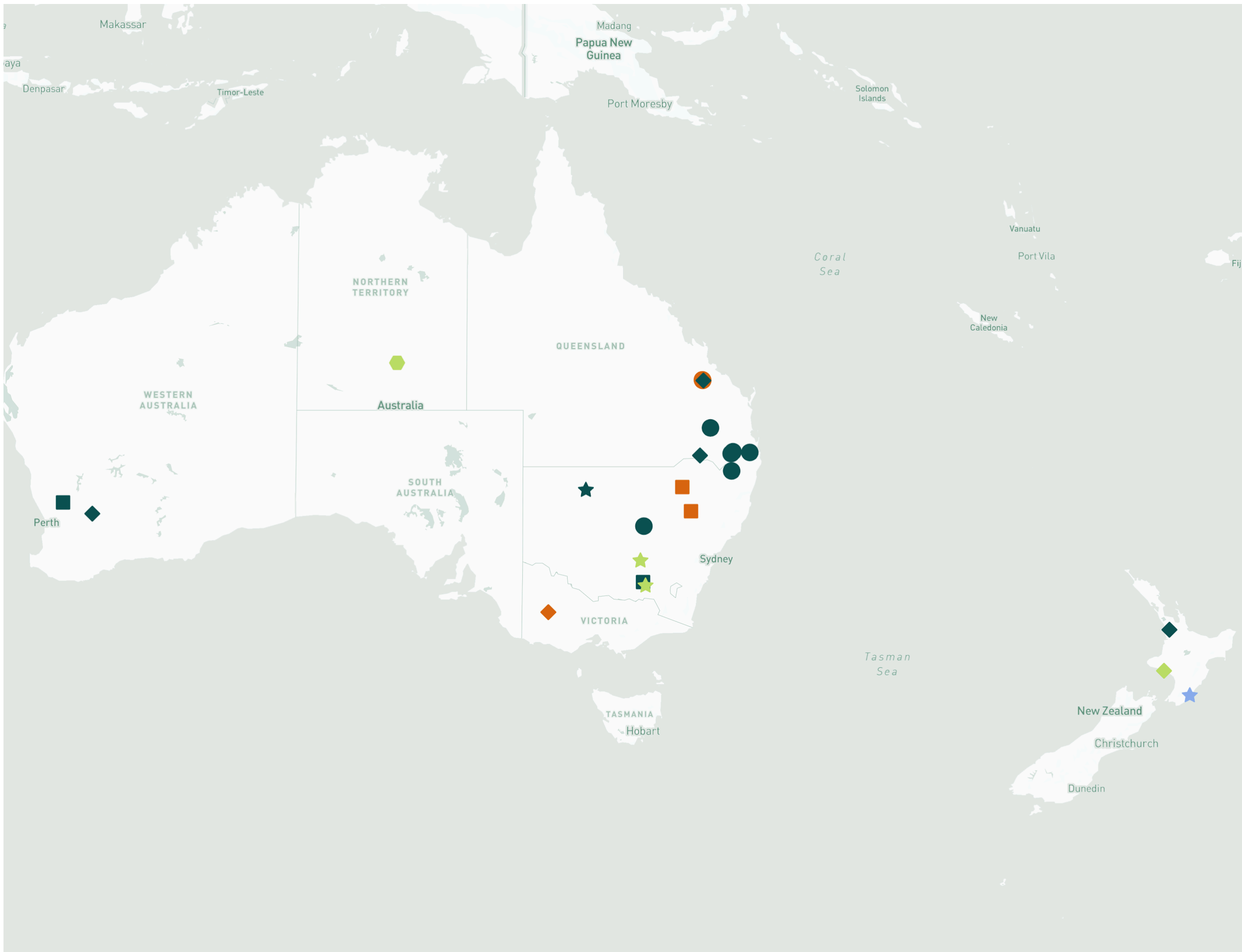


Figure 13. The distribution of cropping systems and practice changes assessed by studies in Asia and Africa. The fill colors indicate the type of cropping system, while the outline colors differentiate the practice change assessed by the study. Source: Carbon Direct.



Cropping system

- Livestock agriculture
- Row cash crops
- Mixed
- Specialty row crops
- Rice

Practice change

- Grazing management
- Conservation tillage
- No till
- Managing tillage regime
- Reduced tillage
- Variable

Figure 14. The distribution of cropping systems and practice changes assessed by studies in Oceania. The fill colors indicate the type of cropping system, while the outline colors differentiate the practice change assessed by the study. Source: Carbon Direct.

Acknowledgements

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Carbon Direct contributors:
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About Carbon Direct

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