Beyond *caveat emptor*: reducing nitrous oxide risk in the soil carbon offset market

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Abstract

Soil organic carbon (SOC) storage projects are an increasingly prominent natural climate solution, drawing investment from diverse climate-sensitive stakeholders. However, the OC additions that build SOC can alter emissions of the potent greenhouse gas (GHG) nitrous oxide (N_2O). These emission changes can erode the intended GHG benefit when OC inputs fuel spatiotemporally episodic hot spots and hot moments (HSHM), which can dominate annual N_2O emission budgets. Concerningly, HSHM are systematically under-quantified by the emission factors and process-based models that most SOC protocols rely on. This creates a poorly quantified risk to the demonstrable net climate benefit of SOC projects. To address this, we make two novel contributions. First, we introduce an assessment framework that scores the probability of project-induced N_2O increases across distinct domains that are typically conflated in existing frameworks. One domain of the score characterizes N_2O risk based on site and SOC intervention practices while the other evaluates the adequacy of N_2O emission measurement, monitoring, reporting, and verification (MMRV) under the protocol being applied. Second, we propose that credit retirement be linked to the composite N_2O risk score so that N_2O emissions are explicitly factored into SOC accounting protocols. We close with a research-to-practice agenda that proposes two parallel sets of objectives. The first is protocol performance trials, wherein crediting workflows are run under intensive direct field measurements to empirically characterize N_2O accounting accuracy in current protocols. The second is development of direct measurements that comprise “minimum viable MMRV” for robust N_2O accounting in SOC projects right now. Our proposed activities will help prevent the establishment of crediting systems that retire GHG credits that are not representative of true CO_2-equivalent offsets.

Rigorous accounting of N_2O in SOC projects must become a shared responsibility of the research community, project developers, buyers, and registries.

1. The challenge of co-managing N_2O emissions and SOC-building practices in agricultural settings

Nitrous oxide (N_2O) is a potent greenhouse gas (GHG) and a major source of climate pollution, with the majority of anthropogenic N_2O derived from soil microbial metabolism of fertilizer nitrogen (N) in agricultural settings (Lawrence et al. 2021, Tian et al. 2024). Reducing N_2O emissions from agricultural systems would substantially slow the pace of warming but doing so while maintaining productive food systems is a major challenge (Reay et al. 2012, Gernaat et al. 2015). For several reasons, N_2O emissions management is relatively underdeveloped, as compared with management of carbon dioxide (CO_2) and methane (CH_4). First, compared to CO_2 and CH_4, the concentration enhancements associated with N_2O emissions are typically orders of magnitude smaller, requiring more expensive and sophisticated instrumentation to detect and quantify differences in N_2O emissions between agricultural settings (Rapson et al. 2014). Second, N_2O emissions are highly spatiotemporally variable with hot spots and hot moments that vary with agricultural practices and weather, such as fertilization, irrigation, rainfall, and freeze-thaw events (Groffman et al. 2009, Wagner-Riddle et al. 2020, Zhang et al. 2024, Stuchiner et al. 2024, Stuchiner et al. 2025). Together, these features of N_2O create substantial challenges for measurement, monitoring, reporting, and verification (MMRV), which fundamentally constrains N_2O management because we lack the capacity to quantify and predict when and where N_2O emissions will spike at farm and landscape scales (Schelde et al. 2012, Zhang et al. 2024).

Instead, the GHG management of croplands is largely driven by crediting programs that reward interventions that increase SOC storage (Guenet et al. 2020, Brummitt et al. 2024, Reuters 2026). These SOC storage projects, including the use of cover crops, residue retention, compost and manure application, biochar additions, and no-till farming, are being promoted or deployed through voluntary and emerging compliance-oriented carbon markets (Brummitt et al. 2024, Reuters 2026). Although these projects have significant demonstrable benefit for atmospheric CO_2 levels (Poeplau et al. 2024, Singh et al. 2024), their net climate impact is also affected by how N_2O emissions respond to SOC changes.

There is mounting evidence that N_2O responses to OC storage projects are highly variable, depending on OC properties, soil N supply, soil conditions, and management context (Lugato et al. 2018, Abdalla et al. 2019, Guenet et al. 2020). In some cases, the positive N_2O emissions response can significantly diminish the total GHG impact. But concerningly, most carbon accounting protocols for quantifying SOC storage either do not require direct measurement N_2O MMRV or do not mandate N_2O emissions reporting beyond emission factors (EFs) or process-based models. Moreover, these GHG accounting methods are often not required to be calibrated to the specific farms deploying these SOC storage interventions (Eash et al. 2025), raising concern that poorly constrained N_2O emissions could be offsetting SOC storage gains (Guenet et al. 2020).

Despite these concerns, commercial and policy momentum around SOC storage is increasing, including large offtake agreements in the European Union, Singapore, and Australia at the time of this writing (ACCC 2023, European Union 2024, Reuters 2026). While the EU and Australia are working to make the expectations of “high-quality” SOC storage claims tighter (ACCC 2023, Reuters 2026, European Union 2024), if N loss and N_2O responses are poorly quantified, the associated crediting systems can still misstate the net climate benefit attributed to SOC storage, distorting incentives and pricing precisely while these markets are still being shaped (Lugato et al. 2018, Brummitt et al. 2024, Angelopoulou et al. 2025).

Although accounting for N_2O fluxes in response to SOC-building practices is weak, it is not because we lack understanding of the foundational N_2O production and consumption processes (Davidson et al. 2000, Groffman et al. 2009, Stuchiner et al. 2024, Zhang et al. 2024). In fact, our foundational biogeochemical understanding of N_2O is well represented by the hole-in-the-pipe framework (Firestone and Davidson 1989), which links N transformations, gaseous loss pathways, and diffusion constraints to observed N_2O fluxes. Net N_2O emissions primarily reflect the balance of nitrification, incomplete denitrification, and complete denitrification, and these processes are regulated by soil oxygen status, carbon and N availability, soil pH, and microbial community composition and activity (Davidson et al. 2000, Burgin and Groffman 2012, Butterbach-Bahl et al. 2013, Stuchiner and von Fischer 2022). Moreover, process-based ecosystem models like DayCent, DNDC, and EPIC have built on this foundational understanding to develop theoretical and pragmatic equations that can predict N_2O fluxes under real-world conditions. However, adding OC to soils can simultaneously change electron donor supply, oxygen status, mineral N dynamics, OM quality, soil pH, and microbial activity (Groffman et al. 2009, Stuchiner and von Fischer 2022, Stuchiner et al. 2024, Zhang et al. 2024), which complicates our ability to predict how OC inputs affect N_2O flux processes in situ. While conceptual models do help clarify how these drivers interact, they are not designed to reduce quantitative uncertainty or represent the episodic events (e.g., rainfall, fertilization, freeze-thaw) that can dominate annual N_2O budgets (Groffman et al. 2009, Saha et al. 2021, Guenet et al. 2020, Tesfaye et al. 2021). Likewise, although process-based ecosystem models are indispensable for scaling and scenario analysis, they struggle to reproduce high-frequency flux dynamics and N_2O responses to different management regimes without strong field constraints (Li et al. 2005, Gaillard et al. 2018, Saha et al. 2021). These limitations to our models are consequential because the short-lived but high-magnitude fluxes characteristics of N_2O can substantially affect net GHG outcomes while remaining easy to miss, smooth out, or represent with weakly constrained assumptions (Groffman et al. 2009, Lugato et al. 2018, Stuchiner et al. 2025).

Consequently, the central challenge is for our process-level understanding of N_2O drivers and our net GHG accounting to evolve fast enough to adequately constrain the risk of N_2O emissions associated with SOC-building practices (Oldfield et al. 2022, Brummitt et al. 2024, Dupla et al. 2024).

Here, we present a novel framing of this uncertainty as ***a risk to demonstrable net climate benefit.*** Net climate benefit is typically characterized as the magnitude of CO_2-equivalent (CO_2e) GHG emissions that are offset by a climate intervention. The empirical and modeling literature already indicate that SOC gains can cause N_2O responses large enough to change the magnitude or even sign of net climate outcomes across different agricultural settings (Li et al. 2005, Mei et al. 2018, Lugato et al. 2018, Guenet et al. 2020, Abdalla et al. 2024). Therefore, there is a risk of systematic bias in GHG accounting for carbon accounting protocols that either weakly constrain N_2O emissions or assume uniform N_2O responses (Lugato et al. 2018, Guenet et al. 2020, Saha et al. 2021, Hergoualc'h et al. 2021, Buma 2024, Dupla et al. 2024). This risk is not only a major issue for crediting frameworks, but it also reflects unresolved biogeochemical and ecological understanding that limit our ability to manage carbon and N together across agricultural settings (Davidson et al. 2000, Groffman et al. 2009, Guenet et al. 2020). A useful strategy for addressing this risk is to treat N_2O accounting as an adaptive co-development challenge in which deployment of SOC projects, measurement infrastructure, empirical synthesis, and model capabilities are all evolving simultaneously (Daly et al. 2024, Mitchell et al. 2024, Brummitt et al. 2024). In laying the foundation for this approach, we present our evaluation of the state of understanding for constraining N_2O emissions under SOC management, and we propose practical guidelines for managing N_2O risk in SOC projects as they continue to scale. In Section 2 we review net GHG emission outcomes under OC interventions, and we summarize how current accounting protocols quantify N_2O emissions in SOC projects. In Section 3 we introduce a framework to evaluate risk to climate intervention and a research-to-practice agenda for evaluating N_2O risk in the evolving landscape of SOC-building practices.

2. Evidence for variable N_2O emissions responses to SOC-building practices and gaps in N_2O emissions accounting in SOC crediting protocols

Many empirical studies and syntheses have evaluated how SOC-building practices influence N_2O emissions, and they collectively show that overall N_2O flux responses to OC inputs are not readily predictable, but that OC additions can induce large N_2O emissions in some contexts. Increasing SOC alters substrate availability for microbes, which can impact soil redox and oxygen supply such that N_2O production potential via incomplete denitrification increases (Stuchiner and von Fischer 2022), but the relative stimulation of N_2O production vs consumption is highly variable (Davidson et al. 2000, Groffman et al. 2009, Guenet et al. 2020). Across empirical studies and syntheses, the impacts of OC interventions on N_2O emissions can have no detectable effect, a small positive or negative effect, or a large positive or negative effect, with observed outcomes also sensitive to sampling design and study duration (Basche et al. 2014, Abdalla et al. 2019, Guenet et al. 2020, Abalos et al. 2022). Case studies illustrate the full spread of outcomes, including long-term compost additions that increased SOC and N_2O emissions, residue additions that increased SOC and N_2O, and management changes with SOC gains but limited or variable N_2O responses (Ding et al. 2013, Chen et al. 2013, Krause et al. 2017, Wang et al. 2019, Shakoor et al. 2021). Some OC-addition interventions, such as biochar additions, have suppressed N_2O emissions in many contexts, but effects are hard to predict due to the inherently wide variation with feedstock, pyrolysis conditions, application rate, soil properties, and nitrogen management (Cayuela et al. 2014, Guenet et al. 2020).

Numerous studies also document that the conditions that elevate N_2O risk are also unevenly distributed across practices and environments. Higher-risk practices include amending soils with N-rich OC inputs, such as manure, and higher-risk environments include situations where OC inputs coincide with high fertilizer N inputs, OM-rich soils, or wetter/well-irrigated soils that can support higher incomplete denitrification rates (Ding et al. 2013, Wang et al. 2019, Guenet et al. 2020, Kelley et al. 2024). Practices intended to reduce mineral N surplus or prevent NO_3^- from getting denitrified (e.g.,4R nutrient management, nitrification inhibitors, cover crops) are intended to keep N_2O emissions neutral or lower while supporting SOC gains, but the N_2O abatement outcomes from these interventions are variable (Ding et al. 2013, Lugato et al. 2018, Abdalla et al. 2019, McNunn et al. 2020, Shakoor et al. 2021). For example, a widely cited metanalysis found no consensus on whether SOC inputs from cover crops increased or decreased N_2O emissions or meaningfully managed NO_3^- leaching because different cover crop strategies altered both soil NO_3^- availability or moisture conditions (Basche et al. 2014), further showcasing that N_2O outcomes can be diverse and depend strongly on site and management contexts.

Despite the risk of enhanced N_2O emissions, storing more OC in croplands continues to be promoted as a natural climate solution because it has been marketed both as a means of supporting soil function and resilience, and because net climate benefit from SOC-building practices remain plausible, even if decidedly conditional (Powlson et al. 2014, Paustian et al. 2016, Lugato et al. 2018). Indeed, the research community has long argued that SOC-building has co-benefits beyond compliance and voluntary carbon markets (Lal, 2004, Powlson et al. 2014, Paustian et al. 2016, McNunn et al. 2020, Maenhout et al. 2024). Increasing SOC is associated with improved soil structure and water regulation and can support yield stability and resilience in some contexts, motivating adoption independent of offsets (Paustian et al. 2016). In addition, many SOC-building practices reduce N leaching risk, which supports downstream water quality goals, even when direct N_2O emissions outcomes are mixed (Abdalla et al. 2019, Maenhout et al. 2024). However, soils are deeply context-dependent such that variation in soil texture or drainage, climate, management timing, soil C:N ratios, OC input chemistry, and management history can drive divergent SOC persistence and N_2O emission responses, and that needs to be accounted for (Groffman et al. 2009, Guenet et al. 2020, Stuchiner et al. 2024). This context dependence means that credible climate claims will require field-stratified risk assessment and pairing of SOC practices with N_2O risk controls that reduce N surplus and wet anaerobic exposure, but to date such management guidance is generally absent from SOC project protocols.

A handful of SOC protocols require N_2O accounting to some extent, but it remains unclear if the accounting is sufficient to support defensible net GHG offset claims. To our knowledge, no SOC accounting protocols require direct measurement of N_2O fluxes from project fields. Instead, when SOC protocols do include N_2O accounting, they account for N_2O indirectly using activity data paired with EFs or process-based models, rather than requiring direct field flux measurements (Table 1, Eash et al. 2025). Projects generally report management inputs such as fertilization rate, timing, placement, amendment inputs, or grazing activity, which are then translated into estimated N_2O emissions using equations, EFs, or approved models (Table 1). Therefore, what gets reviewed during verification is typically documentation of management activities, model outputs, or EFs, rather than direct evidence that field N_2O fluxes behaved as estimated (Table 1), despite growing evidence that process-based models and EF estimates vary widely in their accuracy (Eash et al. 2025, Lu et al. 2026). For example, studies frequently reveal that process models struggle to capture the spatiotemporal peaks in emission that dominate total N_2O fluxes (Groffman et al. 2009, Anthony and Silver 2024, Liu et al. 2022). Likewise, EF approaches are not designed to capture the event-driven peaks (e.g., fertilization, rainfall, freeze-thaw) that are features of the N_2O emissions phenomena that cause N_2O emissions to be large and (at this point) difficult to predict (Barton et al. 2015, IPCC 2021, Lawrence et al. 2021, Qian et al. 2025, Lu et al. 2026). Moreover, current protocols differ substantially in how they mandate N_2O quantification. Verra VM0042 and the Climate Action Reserve (CAR) Soil Enrichment Protocol explicitly include estimated N_2O in project accounting, whereas other protocols either include N_2O only conditionally if management practices are presumed to significantly affect soil N dynamics, or do not require N_2O accounting for crediting at all (Table 1).

To properly credit demonstrable net GHG benefit, protocols need to address two sources of uncertainty. One source of uncertainty, which appears to be completely absent from protocols, is the lack of consideration for executing SOC projects in sites that could have vulnerability for heightened N_2O emissions. The other source of uncertainty is the actual amount of N_2O emissions generated from a given SOC project. Verra and CAR do include uncertainty procedures intended to support conservative crediting, which represents important progress toward incorporating N_2O into SOC accounting. However, the uncertainty is derived largely from the existing models and EFs, which, as discussed above, are widely recognized to be inadequate for characterizing actual N_2O emissions. This diagnostic gap motivates the risk assessment framework we introduce in Section 3, which separates risk arising from project context from risk arising from the N_2O quantification approach.

While improving agricultural SOC-storage MMRV is an extremely active area of research that is working to improve sampling design, model-data fusion, and remote sensing integration, accurate net accounting in SOC projects will depend on comparable progress for N_2O, too (Smith et al. 2019, Oldfield et al. 2022, Brummitt et al. 2024, Angelopoulou et al. 2025). Credible SOC crediting relies on conservative treatment of leakage, permanence and durability, and uncertainty, yet those same safeguards are limited by weak observational capacity for N_2O (Guenet et al. 2020, Davidson 2022, Dupla et al. 2024). Until we can establish metrics like dynamic N_2O baselines using direct measurements under SOC management, it will remain difficult to improve understanding of in-situ N_2O flux dynamics and improve models for estimating N_2O and other N losses (Saha et al. 2021, Davidson 2022, Lavallee et al. 2024, Yang et al. 2026).

3. A risk assessment framework and research-to-practice agenda for constraining N_2O risk in SOC projects

SOC-building projects risk inappropriately claiming net climate benefits when they lack direct N_2O emissions accounting and fail to explicitly quantify N_2O fluxes. In response, we here present a risk assessment framework (Section 3.1) and a research-to-practice agenda (Section 3.2) that characterizes N_2O risk and makes recommendations for how the research community can provide actionable guidance for improved N_2O accounting. Our risk assessment framework yields a “risk score” that we argue should influence the payout of carbon credits when credits are retired (Figure 1). Our research-to-practice agenda is part of a cycle of improvement for SOC storage projects (Figure 2). Over time, our scientific understanding of how SOC storage projects affect N_2O emissions may grow so that future accounting protocols eliminate risk of induced N_2O emissions. Until then, the risk score provides a mechanism for documenting N_2O uncertainty in claimed net SOC-storage-offsets. We reiterate that improving MMRV for SOC storage itself is an active area of research (e.g., Bradford et al. 2023, Oldfield et al. 2024, Potash et al. 2025) but here we are highlighting the vulnerability of these SOC projects due specifically to their lack of accounting for N_2O emissions.

3.1 Defensible claims for SOC-building projects require evaluating the potential N_2O risk on a project-by-project basis

Our framework characterizes N_2O risk in two distinct facets of the SOC project. The first part evaluates risk from the SOC project context itself, and the second evaluates risk from the quality of N_2O MMRV in the project’s accounting (Table 2). Characterizing risk from the project context itself is vital because some project settings and practices are more likely than others to stimulate N_2O emissions that erode net GHG benefits (Li et al. 2005, Lugato et al. 2018, Kelley et al. 2024). We present a risk assessment “scorecard” that identifies specific factors (e.g., high amendment N content, high site N surplus, poor site drainage) that are likely to be associated with project-induced increases in N_2O emissions, and our scorecard penalizes projects deploying in riskier field sites and/or using riskier protocols that do not mandate sufficient N_2O MMRV. Although our scorecard currently provides a qualitative, ordinal characterization of risk, future work can develop the sets of equations for integrating this approach into protocols. Evaluating risk based on the quality of N_2O emissions accounting is vital, because it threatens credit integrity if EFs and existing process-based models (Table 1) are inaccurate (Saha et al. 2017, Gaillard et al. 2018, Saha et al. 2021, Lu et al. 2026). Consequently, in our risk scorecard, SOC projects that use direct measurement to quantify N_2O fluxes get the highest score, those that use context-specific and rigorously validated EFs or process-based models get intermediate scores, and projects that use generic EFs or region-wide models get low scores.

An important and novel feature of the scorecard is that it separates two sources of uncertainty that are often conflated: 1) risk of the project setting causing significant increase in N_2O emissions, and 2) risk arising from how well N_2O emissions are quantified. Distinguishing those risks creates a more practical basis for deciding when stronger N management vs. stronger MMRV is warranted, and consequently how either of those features of a SOC project should then warrant more conservative crediting (IPCC 2021, Brummitt et al. 2024). Importantly, this puts the impetus both on the project to improve N management, and on the protocol that evaluates the project's GHG emission offsetting. Simply put, we propose that SOC projects deployed on suitable sites with rigorous accounting protocols will have lower N_2O risk and therefore be eligible for more carbon credits retired.

Moreover, the risk framework we developed motivates all parties involved in SOC projects to have a more vested interest in how N management and MMRV rigor impacts the number of credits a project could earn. Project developers need to recognize when project settings and management regimes create elevated N_2O risk, warranting stronger N controls or more careful practice selection. Project buyers need to distinguish between projects whose net climate claims are supported by stronger evidence and projects whose claims remain more uncertain because of project setting, management, or N_2O accounting. And finally, registries and protocol developers need to determine when stronger evidence requirements (e.g., MMRV), uncertainty deductions, or more conservative crediting are warranted. We propose that each of these considerations should not only impact the potential riskiness of a SOC project, but also the amount of money a project should earn from retired credits.

To illustrate the tradeoffs between project risk and project payout, we present this relationship as a retirement-risk payout curve (Figure 1), where credit retirement is negatively impacted by higher N_2O risk scores. Projects with lower risk scores should be able to retire more credits upon project completion because they have better constrained the project site, intervention, and accounting risks to a demonstrable net climate benefit. However, registries may differ in their risk tolerance, and so different curves may emerge. To reflect a range of potential risk tolerances, we illustrate three types of curves for potential credit retirement payouts: conservative (low risk tolerance), moderate (moderate risk tolerance), and permissive (high risk tolerance). The nature of these curves reflects the probability and magnitude of project-induced N_2O emissions based on project risk. Whether a protocol is conservative, moderate, or permissive, when projects are deemed low risk, they will withhold or discount the fewest carbon credits, and when projects are deemed high risk, they will withhold or discount the most carbon credits. Under intermediate-risk scenarios, conservative protocols will still withhold or discount most to all credits, whereas permissive protocols will credit SOC projects generously despite intermediate N_2O risk scores. We anticipate that the specific shape of this retirement-risk payout curve will become refined with further research, especially depending on how actual N_2O emissions responses vary with SOC project practices.

3.2. A research-to-practice agenda for translating biogeochemical understanding into practical guidance for SOC projects

The research community has a responsibility to translate its mechanistic expertise in soil carbon and N cycling into practical guidance that SOC project developers, buyers, and registries can implement. In recognition of this, we used our risk assessment framework as a guide to propose an iterative research-to-practice agenda (Figure 2) that creates a clear set of opportunities for the research community to better partner with project developers, buyers, and registries and improve SOC project N_2O accounting. Our proposed research-to-practice agenda is comprised of two complementary priorities that will bring together field measurements and protocol evaluations to improve project guidance both over time and, critically, in the immediate-term. First, the research community should test SOC project accounting protocols under field conditions to evaluate how effectively they quantify the N_2O emissions that may offset SOC storage climate benefits. Second, because these protocol performance trials will take time to establish and analyze across diverse project settings, the research community should simultaneously draw on existing SOC projects, datasets, and monitoring infrastructure to develop guidelines for what "minimum viable N_2O MMRV" can look like for SOC projects that are happening right now. Together, these efforts would allow researchers to move beyond general calls for more data and instead provide project developers, buyers, and registries with empirically grounded guidance on where additional evidence, stronger accounting, or more conservative crediting is warranted.

3.2.1 Protocol performance trials to evaluate SOC project protocols under real field conditions

The first facet of our research-to-practice agenda is to evaluate how existing SOC protocols perform when their accounting workflows are compared against intensive field-based measurements. There are a variety of different SOC storage protocols (see Table 1), and they are all distinct operational tools with specific monitoring rules and quantification pathways that may succeed in some contexts and fail in others (Lugato et al. 2018, Brummitt et al. 2024). Rather than continue to debate abstractly which SOC protocols are "good enough," for managing N_2O risk, we instead propose a class of experiments at research sites. These experiments will perform hypothesis-driven "protocol performance trials" that run protocol workflows in parallel with intensive MMRV to directly quantify protocol bias, uncertainty, and failure modes. Results of these experiments can help determine how effectively different protocols quantify net CO_2e offsetting under SOC storage and associated N_2O emissions, and help directly improve process-level understanding, leading to improved risk characterization and protocols (Figure 2; Barton et al. 2015, Brummitt et al. 2024). Through these evaluations, the research community will draw on its mechanistic understanding of the biogeochemistry governing carbon and N cycles to help provide project developers, buyers, and registries with empirically supported thresholds for when additional accounting, additional evidence, or stronger conservativeness is needed (Zelikova et al. 2021, Oldfield et al. 2021, Brummitt et al. 2024). Although the Protocol Intercomparison Project has identified how different SOC storage protocols can issue non-equivalent carbon credits for the same project scenarios (Eash et al. 2025), its sole reliance on existing simulation models underscores this need for in-field protocol tests using direct measurements of N_2O emissions.

Supersites, as proposed by Yang et al. (2026), are defined as a global network of long-term monitoring ($\geq$ 3 years) field sites that measure N_2O fluxes and critical covariates across spatiotemporal scales, and they are a promising platform for conducting these protocols performance trials. Supersites will be able to leverage high-quality N_2O MMRV infrastructure with the research community's mechanistic expertise to develop experiments of varying complexity that evaluate the efficacy of different SOC protocols for N_2O quantification. Usefully, these supersites will be outfitted with diverse instrumentation including automated flux chambers, flux-gradient towers, and tall towers, all of which can support intensive MMRV as appropriate. Moreover, long-term monitoring sites like these bring the capacity and resources to do repeated soil sampling and intensive environmental benchmarking measurements to then compare against values determined from SOC protocol approaches.

We emphasize that the intention of these protocol performance trials should be to analyze the strengths and weaknesses of existing SOC protocols so that they can lead to updated N_2O risk assessment scoring and updated credit retirement-risk payout curves (Table 2, Figure 1). Therefore, it will be important to design experiments for evaluations that accurately emulate real SOC projects. For example, most SOC projects deploy multiple SOC-building practices ("bundles"), like no-till and cover cropping on the same field, rather than just one practice at time (Lugato et al. 2018, Guenet et al. 2020, Eash et al. 2025). As a result, protocol performance trials should evaluate practice bundles that resemble how SOC projects are actually implemented. At the same time, trials will also need experimental designs that can distinguish the marginal effects of individual practices from the combined effects of practice bundles on SOC storage, N_2O fluxes, and net CO_2e outcomes. In addition, trials should be stratified across risk gradients that are already identified as potentially consequential for N_2O fluxes, including sites with variation in drainage, precipitation, and irrigation regimes, N surplus, OC input chemistry and N content, freeze–thaw exposure, residue management, and tillage history

(Groffman et al. 2009, Guenet et al. 2020, Wagner-Riddle et al. 2020, Elberling et al. 2023, Stuchiner et al. 2025, Yang et al. 2026).

We recognize that rigorously evaluating protocols across diverse project settings, practice bundles, and environmental gradients will take time. As those trials progress, parallel efforts within the research community can focus on a second facet of our research-to-practice agenda which helps clarify what "minimum viable N_2O MMRV" could look like.

3.2.2 Defining minimum-viable N_2O MMRV for projects operating right now

We define minimum viable N_2O MMRV to be the smallest number of direct measurements and smallest amount of contextual data needed to support defensible net CO_2e claims for a given project at a particular N_2O risk tier (Table 2). The intention is not to encourage lower-quality or less rigorous datasets, but to distinguish what evidence is needed to prevent overclaiming, and consequently over-crediting, the net climate benefit of a SOC project. In this way, minimum viable N_2O MMRV can become a practical bridge between ideal measurement infrastructure and GHG accounting decisions that must be made while MMRV infrastructure is still being developed. To make this framework operational, we propose a set of research-to-practice priorities for the research community: optimizing event-triggered sampling, identifying which additional data streams will reduce uncertainty most efficiently, and improving analytical pipelines that translate project data into practical MMRV guidance.

Our first research-to-practice priority aims to optimize event-triggered N2O emissions sampling. Annual N_2O budgets are often dominated by hot spots and hot moments, so low-frequency sampling can be systematically biased (Groffman et al. 2009, Barton et al. 2015, Ashiq et al. 2021, Lammirato et al. 2021, Stuchiner et al. 2025). To account for these spatiotemporally variable events under minimum viable N_2O MMRV, we must perform N_2O flux sampling during periods when risk of high N_2O emissions is expected. These include periods following fertilization, first major wetting events, irrigation shifts, management events (e.g., tillage), freeze–thaw events, and periods following crop residue or other OC inputs (Wagner-Riddle et al. 2020, Zhang et al. 2024, Stuchiner et al. 2025). By performing flux measurements around periods of anticipated high N_2O risk, we can better quantify how much uncertainty is reduced per unit effort compared to sampling schedules where flux measurements are taken at fixed intervals. Moreover, we can better determine which events contribute to higher N_2O risk across different soils, climates, and management regimes (Barton et al. 2015, Lawrence et al. 2021). To do this, we propose leveraging the infrastructure of supersites (Yang et al. 2026) by establishing "sentinel fields." We envision these sentinel fields as a subset of fields that receive higher-frequency N_2O monitoring (ideally automated flux chambers and flux gradient measurements where feasible) to constrain event dynamics, identify high-risk event windows, and test the efficacy of different monitoring strategies to adequately capture important N_2O fluxes. These sentinel fields would help define when lower vs. higher-intensity N_2O sampling methods were needed, when event-based sampling intensity needed to be more intensive, and when direct measurement really should be prioritized over modeled or EF-based flux estimates (Barton et al. 2015, Venterea et al. 2020, Lu et al. 2026).

In that vein, our second research-to-practice priority should be identifying what information reduces N_2O uncertainty most efficiently. The research community can investigate how event-triggered flux sampling, stratifying fields by wetness-zone, or improving N balance tracking and OC inputs have the potential to guide SOC project protocol upgrades, depending on project context (Barton et al. 2015, Eagle et al. 2020, Brummitt et al. 2024). For example, projects with high wetness or drainage risk may benefit most from terrain-informed wetness zone stratification, whereas projects with high N surplus may require stronger N balance tracking or more targeted monitoring following fertilization, irrigation, or rainfall events.

Finally, minimum viable N_2O MMRV will require analytical pipelines that effectively translate available project data into useable guidelines for project developers (Dorich et al. 2020). Thus, our third research-to-practice priority emphasizes utilizing methods to support SOC project data infrastructure to optimize MMRV designs that maximize net GHG abatement. Remote sensing approaches are gaining traction for making accurate estimations of SOC (Dangal et al. 2019, Angelopoulou et al. 2019, Wijewardane et al. 2020, Xu et al. 2026), while also making efficient measurements of site-level information about project fields, like topography and soil moisture (Zappa et al. 2019, Celik et al. 2022, Lamichhane et al. 2025). This information can help identify wetness-prone zones or other landscape positions in fields where additional surveying could indicate where N_2O production or consumption is likely to dominate, depending on soil moisture and NO_3^- retention (Stuchiner et al. 2024, Zhang et al. 2024). Such information could then guide project decisions about where to intensify monitoring, where to apply more conservative credit discounting, or where to consider applying alternative management strategies to reduce N_2O risk while still optimizing SOC gains. In practice, this could mean targeting known wet depressions or poorly drained zones for heightened N_2O monitoring (Groffman et al. 2009, Elberling et al. 2023) and similarly decreasing fertilization or application of N-rich amendments (e.g., legume residues or manure) in those higher N_2O risk areas (Ding et al. 2013, Wang et al. 2019, Kelley et al. 2024). For example, redirecting chronically wet areas or regions of fields where NO_3^--leaching is a greater concern towards cover crops, perennial vegetation, or pollinator habitat could support sustainable agricultural practice that reduce NO_3^- loss, decrease

N_2O emission risk, and avoid the potential for low-yielding crop production (Zhou et al. 2010, Brandes et al. 2016, Schulte et al. 2017). Moreover, these management shifts may also align with farmer economic goals because these practices can generate value through carbon crediting or other incentive programs, such as the USDA Natural Resources Conservation Service's Environmental Quality Incentive Program, which can support cover crop implementation, or the USDA Farm Service Agency's Conservation Reserve Program, which supports pollinator habitat practices such as CP42 (USDA NRCS, USDA FSA[a], USDA FSA[b]). In this way, by focusing on translating current SOC project data pipelines into field-specific guidance, researchers can drive minimum viable N_2O MMRV that reduces N_2O risk, optimizes SOC gains, and supports farmer goals.

3.3 Geographic considerations for N_2O accounting remain unresolved

Our N_2O risk assessment framework focuses on N_2O emissions generated within a SOC project's field, or set of fields, and notably does not address offsite N_2O emissions. This is an important limitation to our work, because offsite N_2O emissions associated with NO_3^- leaching into drainage canals and downstream aquatic systems are recognized as indirect sources of agricultural N_2O emissions and are included in GHG inventories (IPCC 2019). However, we chose to not include offsite N_2O emissions in our risk assessment framework because two fundamental questions emerged from this limitation that undoubtedly need resolving, but are beyond the scope of this work: *where* does a SOC project's boundaries lie with respect to N_2O emissions, and how far beyond a project's geographic boundaries *should* a project be accounting for N_2O emissions? A project's geographic boundary and it's GHG accounting boundary are not necessarily the same. The geographic boundary typically refers to enrolled fields where SOC-building practices are implemented, whereas the GHG accounting boundary can be more diffuse. The GHG accounting boundary will depend on which GHG sources, sinks, and potential leakage pathways a SOC project protocol includes in a project's net climate claim. In many SOC protocols, it is not explicitly stated where, spatially, N_2O emissions will stop being included as sources of leakage from a project (Table 1). Indeed, SOC projects vary in how far "offsite" they will account for NO_3^- runoff-driven N_2O leakage. This begs the question: how far beyond a project's fields' edges is reasonable to expect for indirect N_2O emissions accounting?

This boundary issue is especially important in the context of SOC projects because SOC-building practices may alter the magnitude and location of N losses. Increasing OC in soils can stimulate denitrification under wet or anaerobic conditions, which can both increase direct N_2O emissions and decrease soil NO_3^- availability for crops (Stuchiner and von Fischer 2022, Lazcano et al. 2021). In the same vein, adding OC to soils can also promote microbial N immobilization, which may also reduce NO_3^- availability (Cao et al. 2021). While denitrification and N immobilization can decrease NO_3^- leaching in some contexts (Abdalla et al. 2019), it also could decrease soil N enough to decrease crop yield in other contexts, which could then lead to compensatory N fertilization additions. Consequently, changing cropland SOC-balance can affect both onsite and offsite N_2O emissions potential. Future work must clarify how SOC protocols define responsibility for downstream N losses and where indirect N2O emissions should and should not be treated as sources of SOC project leakage. More broadly, these outstanding questions about project boundaries and N_2O leakage highlight that the biogeochemical consequences of SOC projects can extend far beyond a project's field's edges.

4. Conclusion

Soil carbon markets are scaling faster than the science and accountability that are vital for ensuring their integrity. A core problem is not that SOC-building practices lack merit, but that net climate benefit cannot be assumed when N_2O emissions remain poorly constrained. The risk is structural: episodic N_2O flux dynamics, context-dependent responses to OC inputs, and measurement approaches that systematically miss N_2O hot spots and hot moments mean that current protocols can issue credits for SOC climate benefits that were never fully realized. Our risk scorecard and retirement-risk payoff curve offer a practical path forward that does not require waiting for perfect science. By separately evaluating the probability of project-induced N_2O increases and the adequacy of N_2O quantification, the scorecard creates accountability for both project developers who must recognize when site conditions and management choices elevate risk, and for registries and protocol developers who must determine when stronger MMRV requirements or more conservative crediting are warranted. Protocol performance trials, conducted alongside the supersite infrastructure being called for, will generate the empirical foundation needed to update both the scorecard and crediting thresholds over time, and the research-to-practice priorities we propose provide a useful roadmap for advancing N_2O MMRV forward as the research evolves. The research community has the mechanistic expertise to lead this effort, but what is needed now is the collective commitment to translate that expertise into tools that markets can actually use.

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Figures and tables:

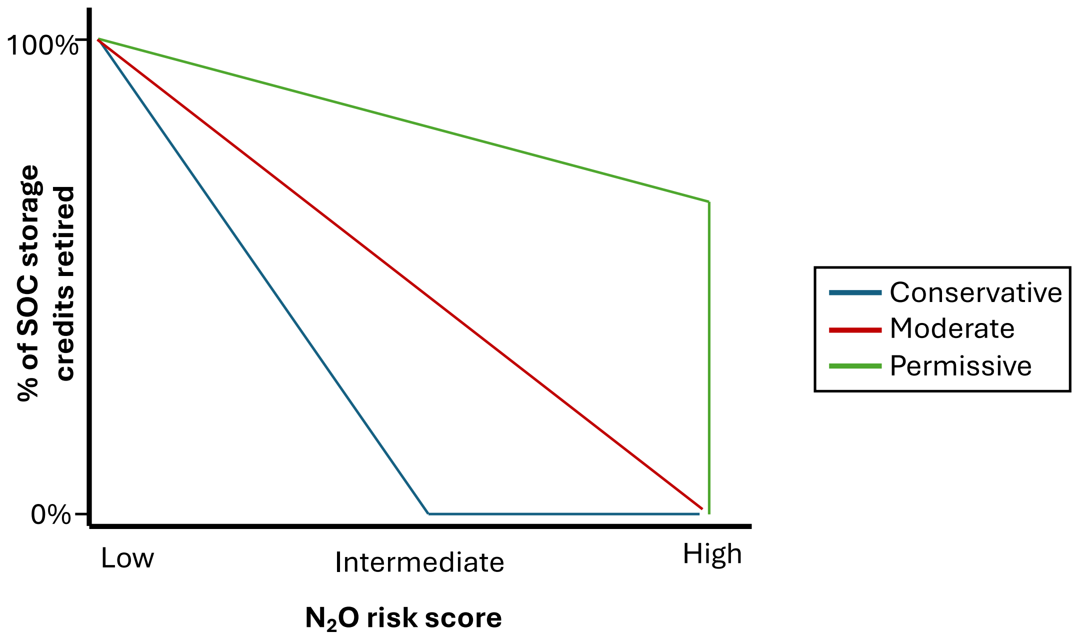

Figure 1. Retirement-risk payoff curve relates the N_2O risk assessment score to the fraction of credits for retirement upon project completion. Projects with lower risk scores should be able to retire more credits upon project completion because they have better constrained the field, intervention, and accounting risks to a demonstrable net climate benefit. The three curves presented here represent a conservative (low risk tolerance), moderate (moderate risk tolerance), and permissive (high risk tolerance) crediting payout upon project completion. The payout curve is considered conservative if it withholds or discounts credits at intermediate risk, while the payout is considered permissive if it credits a project generously despite intermediate N_2O risk scores. The specific shape of this curve will become refined with further research, and the choice of curves may differ among registries.

Figure 2. A conceptual schematic of our research-to-practice agenda. There is an "on-ramp" where the research community agrees upon minimum viable N_2O MMRV that uses direct measurements of N_2O emissions to improve SOC protocols. This iterative agenda creates a clear set of opportunities for the research community to support improving quantification and reporting of N_2O risk in SOC projects.

Table 1. A summary of the N_2O evaluation practices from publicly available SOC storage protocols (at the time of this publication) for agricultural systems.

Protocol (active version; version year)	Protocol scope and accounting boundary	N_2O in GHG ledger?	N_2O estimation method	Project data used to estimate N_2O	Verification evidence that gets reviewed	Primary public source
Verra VCS VM0042 Improved Agricultural Land Management (v2.2; 2025)	Improved agricultural land management	Yes (estimated)	Approved pathways: model-based accounting with calibration/validation requirements, IPCC-style EF equations for direct and indirect N_2O emissions.	Field area/boundaries, fertilizer N (rate/form/timing/placement), manure/organic amendments (amount and N content if known), legumes/N-fixing crops, residue management, grazing/excreta where applicable	Activity records (invoices/logs), field boundaries, calculation workbook/model report (inputs/outputs), boundary completeness checks, uncertainty deductions	https://verra.org/methodologies/vm0042-improved-agricultural-land-management-v2-2/
Climate Action Reserve Soil Enrichment Protocol (SEP) (v1.1; 2022)	Cropland SOC projects	Yes (estimated)	Modeled or default equations/EF accounting for direct and indirect N_2O emissions from fertilizer (and other N sources as applicable)	Synthetic and organic fertilizer amounts (amount and N content), biomass burning, application dates/methods, crop/area, residue/organic inputs where relevant	Fertilizer/amendment records (invoices, applicator logs), stratification/area records, calculation sheets, boundary completeness	https://www.climateactionreserve.org/wp-content/uploads/2022/06/Soil-Enrichment-Protocol-V_1.1-final.pdf
Gold Standard Soil Organic Carbon Framework Methodology (v1.0; 2019/2020)	Agricultural SOC (emissions/leakage handled via module rules)	Conditional (module-triggered; estimated)	Module-specific: Depends on activity module and sources (e.g., synthetic fertilizer applied); exclusions allowed only if 'insignificant' or conservatively treated	Module-specific (typically fertilizer/amendment/grazing activity data if those sources are within accounting boundary)	Module-specific MRV evidence, documented justification for inclusions/exclusions, activity records and calculation/model outputs and QA/QC per module	https://globalgoals.goldstandard.org/standards/402_V1.0_LUF_AGR_FM_Soil-Organic-Carbon-Framework-Methodolgy.pdf
Plan Vivo PV Climate PM001 Agriculture & Forestry Carbon Benefit Assessment (v3.0; 2023)	Community-led land management projects (approved methodologies, modules, and tools)	Conditional (module-triggered; estimated)	Module-and tool-based accounting (includes quantification of relevant GHG emissions from N fertilizers, N-fixing bacteria, and manure additions)	Project activity data (land management, N inputs where relevant), practice adoption	Monitoring reports, activity records, model run outputs, QA/QC and validation requirements per module/tool	https://www.planvivo.org/projects/certify-a-project/pvclimate/methodologies
Regen Registry Ecometric 'GHG Benefits in Managed Crop & Grassland Systems' (v1.5.2; 2025)	SOC credit class for managed cropland and grassland systems	No for credit quantity (co-benefits may be measured separately)	Not used to determine credit quantity: primary crediting indicator is SOC CO_2e	Not required for crediting; SOC samples and remote sensing/model inputs for SOC, practice evidence	SOC sampling/analysis documentation, remote sensing/model documentation, practice evidence per protocol	https://www.registry.regen.network/crediting-protocols/ecometric---ghg-benefits-in-managed-crop-and-grassland-systems-credit-class
BCarbon Soil Carbon Protocol (v2.0; 2022) (v3.0 issued 2026, not fully reflected here)	Measurement-based SOC crediting (soil carbon accrual only) in eligible lands	No (SOC-only for credit quantity; project GHG emissions handled separately)	N_2O not required as a quantified debit/credit line item for SOC credits	Not required for crediting; SOC sampling inputs and project activity documentation	SOC sampling/analysis documentation, project records and QA/QC, verification audit trail	https://bcarbon.org/soil-carbon
Australia ACCU Soil Carbon Method (measurement & models) (2021 method; updated 2026)	National compliance SOC method (credits SOC increases and deducts project emissions)	Partial (via project emissions deductions using EFs/Inventory approach)	Activity data and inventory-aligned EFs for project emissions (e.g., fertilizer-related emissions expressed as CO_2e)	Fertilizer inputs, lime, fuel/operations and other required project emissions parameters	Input records (fertilizer/lime/fuel), method calculations, reporting and audit documentation per scheme	https://cer.gov.au/schemes/australian-carbon-credit-unit-scheme/accu-scheme-methods/estimating-soil-organic-carbon-sequestration-using-measurement-and-models-method

Table 2. Scorecard for quantifying the risk that N_2O emissions may diminish the demonstrable net GHG benefit for a SOC project. The scorecard is organized into two domains. Table 2a addresses field and intervention risk (Q1-Q4) by evaluating how the project setting or management practices impact potential N_2O emissions, and Table 2b addresses accounting quality risk (Q5-Q9) by characterizing if the N_2O MMRV is sufficient to accurately detect and quantify N_2O emissions from the project. For each question, users select the lower risk (-1), moderate risk (0), or higher risk (+1) category that best matches the project. To qualify for a given risk category within a grid square, the project should satisfy at least n – 1 bullet points listed in that square, unless only one bullet is provided, in which case that bullet must be fulfilled. Within each domain, points are then summed across questions to generate separate field and intervention risk and accounting quality risk scores. Then, the scores for each domain are summed for a total project risk score. The most successful program has a field intervention risk score ≤ 0 and an accounting risk score ≤ 0 because while a program can have a composite negative score, that does not necessarily mean that the risk is low in both domains. Projects with a total score ≤ 0 are classified as lower risk, 1 – 2 are classified as moderate risk, and ≥ 3 are classified as higher risk. A lower score indicates a project has better-constrained N_2O risk, whereas a higher score indicates a project is at a greater risk of uncharacterized N_2O emissions offsetting net GHG benefits. The scorecard is intended to be used as a practical diagnostic tool for assessing project vulnerability and identifying where stronger field controls or stronger MMRV is needed to guide more conservative crediting, especially when N_2O risk is high. Although our scorecard currently provides a qualitative, ordinal characterization of risk, future work can develop the sets of equations for integrating this approach into protocols.

(a)

Field and intervention risk evaluation				
	Lower risk (-1)	**Moderate risk (0)**	**Higher risk (+1)**	**Points**
Q1) Are the fields prone to wetness, poor drainage, or localized saturated areas?	▪ The site is well-drained ▪ Limited irrigation practices are used	▪ The site has moderate drainage ▪ The site is well-watered for the given crop and management strategy relative to the region	▪ The site has poor drainage ▪ The site is intensively irrigated for the given crop and management strategy relative to the region ▪ Uncharacterized drainage/wetness	
Q2) Is the fertilizer N surplus likely to be high?	▪ Fertilization rates are constrained for a given crop and management strategy relative to the region	▪ Fertilization rates are typical for a given crop and management strategy relative to the region	▪ Fertilization rates for a given crop and management strategy are intensive relative to the region	
Q3) Is the project using any N_2O risk controls?	▪ Project uses 4Rs (right source, rate, time, and placement) for fertilizer or OC applications ▪ Project uses nitrification inhibitors ▪ Project manages wet areas and times ▪ Project anticipates and manages hot spots and moments ▪ An N_2O risk plan is documented, approved by a credentialed expert, and implemented.	▪ At least two N_2O risk controls from lower risk grid are in place. ▪ An N_2O risk plan is documented and approved by an accredited expert but not yet implemented.	▪ 0-1 N_2O risk controls from lower risk grid are in place. ▪ No N_2O risk plan is documented, and/or project crediting relies on SOC benefits solely.	
Q4) Have the project fields been evaluated sufficiently to justify a claimed risk tier?	▪ Well mapped wet spots or depressions ▪ N fertilizer needs for profitable crop yields are clearly documented. ▪ Land management history is clearly documented. ▪ Fields are evaluated frequently (every ~5 years) and are up to date	▪ Depressions or wet spots partly/non-robustly mapped ▪ N fertilizer needs are documented but poorly justified or not fully documented. ▪ Land management history is partial but incomplete.	▪ Depressions or wet spots are poorly mapped, or there are no plans to map these landscape features. ▪ N fertilizer needs are poorly documented or poorly justified. ▪ Land management history is not documented or poorly documented.	
SUBTOTAL SCORE				

(b)

Accounting quality risk evaluation				
Q5) Is N_2O directly measured at the project-field level? ***If you are in the lower risk tier for this question, skip down to Q8**	▪ Direct measurements, repeated periodically, project design captures hot spots and moments	▪ Direct measurements, but only on a subset of fields or for limited periods	▪ No direct measurements, or measurements too limited to constrain emissions	
Q6) If not measured, or not measured well enough, is N_2O **estimated with a robust site model?** ***If you are in the lower risk tier for this question, skip down to Q8**	▪ Model is informed by site-specific data, appropriate for crops and management intervention; key inputs are field-specific ▪ Model is well-fit and captures N_2O peaks. ▪ Model has been trained, and, at least initially, run by a credentialed expert. ▪ Model assumptions are transparent	▪ Model is partly informed by site or field-specific data (some generic inputs) ▪ Model fit is decent and there is some uncertainty capturing N_2O peaks. ▪ Model has not been run by a credentialed expert, although input has been provided. ▪ Model assumptions are vague.	▪ Model weakly constrained or not transparent, no site-informed inputs, inputs too sparse for robust output	
Q7) Is N_2O estimated only from default emission factors (EFs)?	▪ EFs are derived from direct flux measurements ▪ EFs are derived from a validated site-specific process-based model	▪ EFs are derived from a combination of Tier 2 and locally-informed data ▪ EFs are derived from a model with limited site-specific validation	▪ N_2O is estimated from default or Tier 1 EFs only with no site-specific refinement	
Q8) Are there pre-specified consequences applied (e.g., credit withholding) when uncertainty is high?	▪ Uncertainty deductions or credit withholdings are pre-specified and tied to the magnitude of uncertainty ▪ Explicit credit-reduction rules are used when project data is weak or missing ▪ High uncertainty triggers clear consequences and an enforceable response (e.g., reduced issuance, stronger evidence requirements/MMRV)	▪ Some conservative features are specified but they are not linked to project-specific uncertainty magnitude ▪ Credit reduction rules are applied inconsistently or not tailored to N_2O risk ▪ The protocol acknowledges uncertainty but does not explicitly define consequences or the response	▪ No deductions or withholdings are triggered in response to N_2O uncertainty ▪ The protocol issues credits as usual even if N_2O uncertainty is poorly constrained or not constrained ▪ Default conservative assumptions, stronger evidence requirements, or enhanced MMRV are either absent from the protocol or optional	
Q9) Does the accounting approach iteratively improve MMRV effort to manage project risk?	▪ The protocol is reviewed or tested periodically (every ~5 years) by a credentialed expert to identify MMRV weaknesses or areas for improvement ▪ Deadline-driven plans to improve N_2O MMRV are documented, approved by a credentialed expert, and implemented.	▪ Some protocol-testing or expert review has been conducted, but concrete plans have not been made to improve MMRV ▪ Deadline-driven plans to improve N_2O MMRV are documented and approved by a credentialed expert but not yet implemented.	▪ No protocol-testing or expert review is planned or has been conducted to evaluate N_2O accounting robustness ▪ No plans to improve N_2O MMRV have been documented and MMRV focuses solely on SOC accrual.	
SUBTOTAL SCORE				

TOTAL SCORE		