Nature-Based Climate Solutions: Current Uncertainties and Data Gaps in the Assessment of Soil Carbon Sequestration Potentials

MCSC White Paper
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Section 1: Introduction

The escalating climate crisis has accelerated the search for robust and sustainable solutions for mitigation and adaptation. Among the myriad of approaches under consideration, nature-based solutions (NBS) have garnered exceptional attention for their potential multifaceted benefits and immediate scalability. NBS strategies are not merely adjuncts to fossil fuel emissions reductions; they are increasingly perceived as critical components of comprehensive climate action plans (Amelung et al. 2020).

Land-based NBS, with an estimated global mitigation potential of 11 Gt CO_2e per year, represent carbon storage in plant biomass and soils (Seddon et al. 2021). NBS entail a wide variety of approaches that harness natural ecosystems to achieve diverse environmental objectives. Terrestrial ecosystems have the capability to act as significant carbon sinks, sequestering carbon in both plant biomass and soils (Jackson et al. 2008). Established NBS strategies include afforestation and reforestation, agroforestry, sustainable land management, and the restoration of degraded ecosystems like wetlands and peatlands (Mori 2020). This white paper will concentrate specifically on the issue of soil carbon sequestration, a subset of the broader spectrum of NBS, as soils store more carbon than the atmosphere and vegetation combined (Jackson et al. 2017), and thus even small changes have a great effect.

Soil carbon is commonly referred to as soil organic carbon (SOC) to distinguish it from inorganic forms of carbon found in the soil, such as carbonates. SOC consists of a complex mixture of decomposing plant material, microbes, and stable organic matter, and it plays a crucial role in soil health and fertility (Weil and Brady 2017). The term SOC is particularly relevant when discussing carbon sequestration strategies because the organic components of soil carbon, while transient, have the potential to be stabilized for long periods, thereby serving as a sink for atmospheric carbon dioxide. Understanding the dynamics of SOC is essential for optimizing NBS.

Due to agricultural practices such as tillage, croplands have seen a marked decline in SOC stocks, contributing to a staggering global carbon debt specifically related to agriculture, estimated at 116 Gt C for all of human history (Sanderman et al. 2017). This amount is

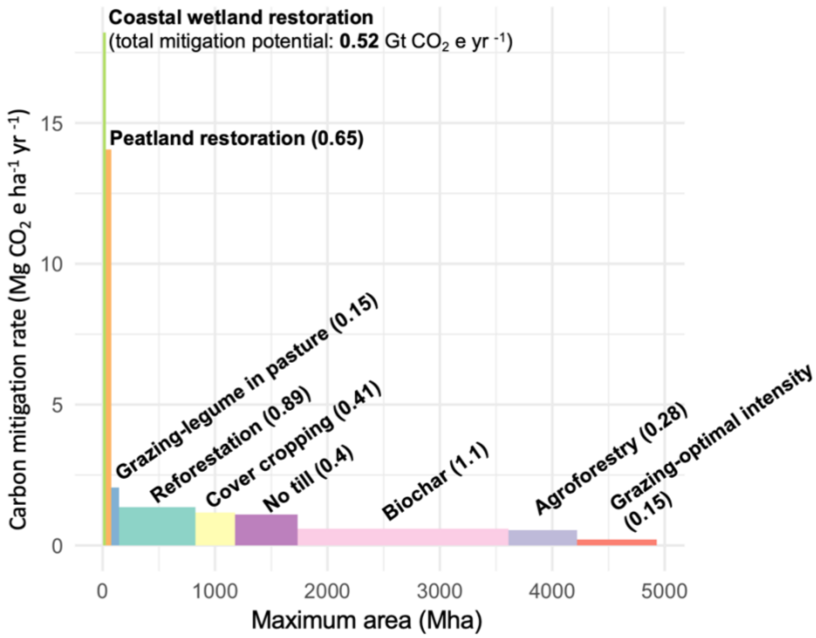

Figure 1. *Carbon sequestration potentials for interventions that actively increase soil carbon storage apart from coastal wetland and peatland restoration, which both include avoided loss of carbon in addition to soil carbon sequestration (modified from Powlson et al. 2014, Griscom et al. 2017, and Bossio et al. 2020). The y-axis shows the potential mitigation effect of a given intervention per unit area of implementation. The width of each bar shows the global maximum applicable area for that intervention type. The area of each bar is the total mitigation potential for soil carbon sequestration within each intervention class. For a baseline comparison, anthropogenic emissions amounted to 59 ± 6.6 Gt* CO_2e *yr* $^{-1}$ *in 2019 (Calvin et al. 2023).*

equivalent to the total CO_2 emissions from the United States over the past century. Among the reasons for the considerable sequestration potential of soils is that SOC pools that have been heavily depleted tend to absorb carbon more rapidly and in greater quantities when favorable conditions are restored. Moreover, specific strategies such as regenerative agriculture practices and the restoration of grasslands and peatlands are almost exclusively geared towards SOC sequestration, as most of the stored carbon in these scenarios is found belowground (Chausson et al. 2020).

On a per-hectare basis, coastal wetland restoration and peatland restoration yield the highest SOC sequestration potentials, albeit in limited areas of intervention (Fig. 1). In contrast, biochar application, reforestation, and regenerative agriculture approaches—like cover cropping, no-till farming, and agroforestry—exhibit lower sequestration rates per unit area but broader global applicability (Fig. 1). When these SOC accrual rates—sourced from existing literature—are multiplied by the respective potential areas for each intervention, the landscape of efficacy shifts (Fig. 2). Specifically, biochar stands out as the NBS with the most substantial overall sequestration potential, followed in sequence by reforestation, peatland restoration, coastal wetland restoration, and cover cropping.

However, there remains significant uncertainty in these estimates. Uncertainty ranges for the mitigation potential of certain NBS pathways are wide; for example, growing nitrogen-fixing

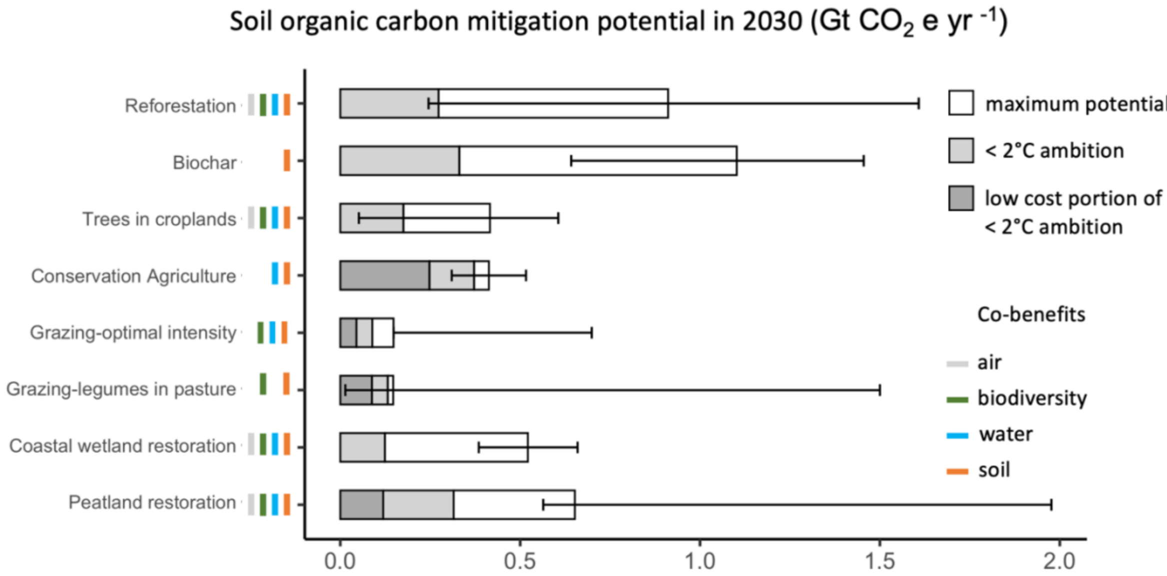

Figure 2. *Estimated soil organic carbon mitigation potentials and co-benefits of NBS for a 2030 outlook, revealing high uncertainties (modified from Bossio et al. 2020 and Griscom et al. 2017). Intensive scientific data collection efforts are required in order to reduce the uncertainty in the impacts of NBS, especially as we shift paradigms from performing global estimates to understanding local effects. Light gray portions of bars represent cost-effective mitigation levels assuming a global ambition to hold warming to <2°C (<100 USD Mg CO_2e yr^{-1}). Dark gray portions of bars indicate low cost (<10 USD Mg CO_2e yr^{-1}) portions of <2 °C levels. Error bars represent 95% confidence intervals, except for Trees in croplands, Grazing-legumes in pasture, and peatland restoration, for which they represent uncertainties based on expert interviews.*

plants in managed pastures as an NBS (abbreviated as "Grazing-legumes in pasture") could sequester anywhere between 14 and 1,500 Gt CO_2e per year, based on existing research (Fig. 2). Understanding the sources of these large uncertainties—and then methodically reducing them—is an important prerequisite for prioritizing and implementing NBS.

To that end, this white paper describes the key uncertainties in estimating the mitigation potentials of soil-based NBS (Section 2), our proposed approach to reducing some of these uncertainties (Section 3), and a collection of case studies demonstrating how our research can help refine estimates of NBS mitigation potentials (Section 4).

Section 2: Uncertainties in Soil Carbon Sequestration Estimates

As illustrated in Fig. 2, existing estimates of the potential for land-based NBS to store SOC vary greatly, depending on their underlying assumptions (Seddon et al. 2021; Beillouin et al. 2023). Here we enumerate some of the key sources of uncertainty.

2.1 Spatial Extent and Variability

The total mitigation potential of each NBS pathway depends on the areal extent over which that pathway can be applied. As a result, uncertainty in the feasible application area gives rise to unclear estimates of total mitigation potential. For example, biochar addition has often been highlighted as one of the most promising avenues for soil carbon sequestration, with recent estimates indicating a potential sequestration rate of 1,102 Tg CO_2e/yr (Bossio et al. 2020). The uncertainty of this potential, however, is incredibly high, as evidenced by a 95% confidence interval ranging from 642 to 1,455 Tg CO_2e/yr. This uncertainty derives in part from open questions about the estimated area of applicability. Additionally, Schlesinger (2022) points out that the efficacy of biochar in capturing carbon in soil can vary by a nearly tenfold difference across studies as it depends on the biochar material that is used, and notes that most carbon sequestration estimates of biochar are overly optimistic because they do not consider ancillary and off-site emissions associated with its production and transport.

The efficiency of carbon storage in soils can also differ based on a myriad of spatially varying factors, including soil type, existing land management techniques, and local climatic influences (Alidoust et al. 2018; Cotrufo 2019). For example, within sustainable agriculture it remains unclear which nitrogen fertilization levels result in highest SOC accrual when cover cropping (Bai et al. 2019). Additionally, the effects of biochar application, cover cropping, and no-till farming on SOC are modified by aridity and temperature and thus vary greatly. This variability complicates the accurate estimation of SOC storage and introduces uncertainty in formulating effective carbon sequestration strategies (Panda et al. 2008; Rabotyagov 2010).

2.2 Temporal Variability

Although SOC can build up after restoration practices take place, information about the timing of the recovery and limits in how much SOC can be restored is lacking, complicating estimation of sequestration potential (Grogan and Matthews 2002). In the context of regenerative agriculture practices such as no-till farming or cover crops, the timing of SOC build-up and potential reversals after the cessation of these practices are of primary concern. Furthermore, it remains unknown when a soil will be saturated with SOC. Simulations for sustainable agricultural practices have ranged from 80 to 155 years, but specific site characteristics influence this SOC saturation as well as the permanence of the SOC storage (Lessmann et al. 2020).

2.3 Pathway-Specific Uncertainties

Measurement techniques, and thus measurement uncertainties, of SOC accrual following restoration vary across NBS pathways. These techniques rely on a basic understanding of how and where specifically SOC accumulates. For instance, ignoring the subsoil carbon dynamics in deeper layers of soil fails to recognize potential opportunities for soil C sequestration and may lead to false conclusions about the impact of management practices on C sequestration (Tautges et al. 2019).

Griscom et al. (2017) and Bossio et al. (2020) highlighted the uncertainties in quantifying the potential of SOC sequestration, emphasizing the need for more studies on specific NBS pathways. Indeed, the small number of studies focused on certain NBS pathways (e.g., peatland restoration) makes uncertainty quantification, let alone mitigation potential estimation, difficult. Griscom et al. (2017) have used empirical estimates to compute uncertainty ranges for just 12 of the 20 NBS pathways—the remaining eight uncertainty ranges are derived from expert elicitation. More pathway-specific research is needed to turn “unknown unknowns” into “known unknowns,” which can then be critically studied.

Section 3: A Path Forward

Research on soil-based NBS remains in an early state and “unknown unknowns” may abound. As indicated in Section 2, more pathway-specific studies are needed to understand context-specific challenges of different NBS strategies. At the same time, “known unknowns” relating to spatial and temporal variability can be addressed now. Here we propose a data collection, synthesis, and analysis pipeline to resolve issues that may arise with global upscaling of spatially and temporally heterogenous NBS data.

To reduce the uncertainty in global predictions of soil-related NBS, we will systematically collect published soil carbon measurements of field experiments to compile the largest to-date database of SOC measurements after implementation of NBS. These measurements are series of sampled plots that share key characteristics but differ in time since land use change, allowing us to robustly model SOC changes on the scale of years, decades, or centuries. Our database will include global studies of *changes* in SOC and variables known to influence SOC such as soil texture (i.e., data before and after the introduction of an NBS over a known time period) through data-mining scientific literature databases. We will funnel collected data through a rigorous quality assurance and control process.

Using this comprehensive database, we will leverage state-of-the-art machine learning methods to predict global and US-specific potentials for soil carbon sequestration (in CO_2 equivalents per year) following the implementation of the most promising NBS. We will first train a suite of machine learning models and evaluate their performance against a benchmark model. Our final, refined model will be applied on a grid to geographically (i.e., on a map) establish the most efficient NBS to accrue SOC at a given location based on environmental characteristics, crop type, and other biogeochemical and climatic considerations. Artificial intelligence models, leveraging real-world field experimental data, unlike biogeochemical models which are based on theoretical assumptions, make spatially explicit predictions which are consistent with available observations (Li et al. 2011).

Through partnership with organizations performing NBS interventions around the globe, we can systematically expand the pool of available chronosequence observations, which will in turn

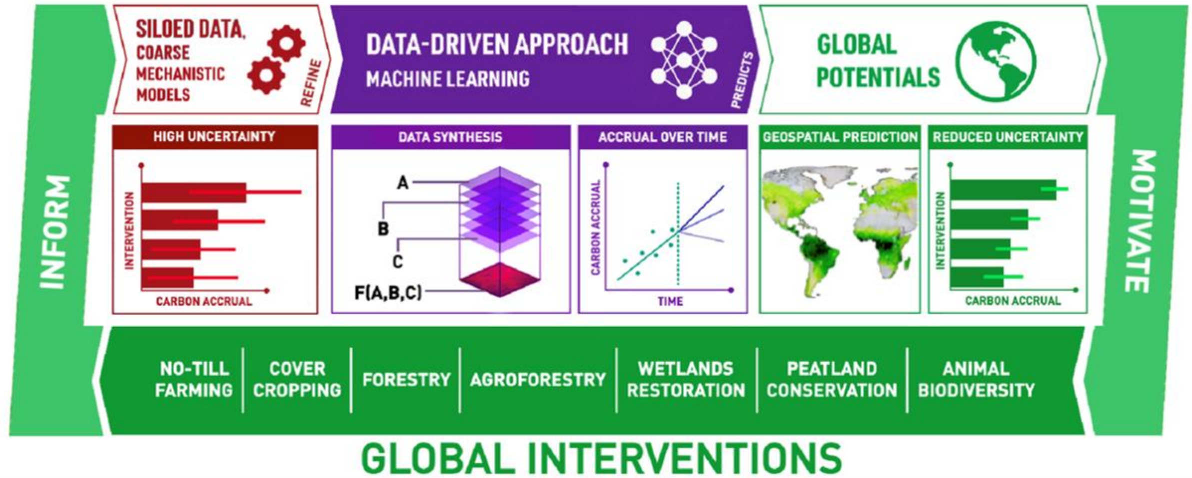

Figure 3. *A path forward for nature-based climate change mitigation strategies. Uncertainties in mechanistic models, as well as the costs of continuous measurement, can be reduced with the assistance of machine learning and data-driven models. These tools permit the estimation and optimization of global intervention potentials, which are holistic assessments of the true climate benefits of interventions, based on local data which will become increasingly granular over time. At any given moment in time, this knowledge enables and motivates both private and public sector entities to deploy NBS interventions at a global scale to protect the natural carbon sink, and scientists can continue to learn from the outcomes of those interventions to inform the next cycle of interventions. (Image credit: Kevin Huang, Evan Coleman)*

help to further reduce the uncertainties described in Section 2. The schematic in Fig. 3 illustrates this uncertainty-reduction process.

Section 4: Case Studies

This section of the white paper focuses on case studies that explore the most promising NBS for SOC sequestration, applying the data-driven approach described in Section 3. These case studies serve as focused investigations, allowing us to examine the effectiveness, limitations, and context-dependent factors that influence SOC sequestration.

Through these real-world examples, we aim to identify the most promising areas for future research and deployment, thereby reducing the existing uncertainties that currently limit the broader application of NBS. Each case study delves into the specifics of the selected NBS, exploring its potential for SOC sequestration, the open questions that remain, and the challenges that must be addressed for these strategies to be both feasible and effective. This targeted approach will not only offer a detailed understanding of each NBS but also highlight where further research is most urgently needed. In doing so, we aim to build a diversified portfolio of reliable and effective NBS for SOC sequestration, contributing to the larger goal of climate change mitigation.

4.1 Baseline: SOC sequestration in undisturbed systems

Traditionally, carbon budget studies have operated under the assumption that soil carbon stocks in undisturbed ecosystems remain stable unless subjected to extreme events such as land-use change, logging, cultivation, or grazing. However, emerging evidence suggests that increased atmospheric CO_2 levels and global warming can influence plant growth, potentially augmenting plant carbon inputs to soil (Yan et al. 2020; Dietzen et al. 2019). Consequently, whether soils in undisturbed environments are static, sequestering, or losing carbon under the influence of climate change remains an open question. Furthermore, if these soils are either storing or releasing carbon, the specific ecosystems that are more effective in SOC sequestration and the underlying reasons for such effectiveness are not yet fully understood (Jones and Donnelly 2004; Wang et al. 2021). These knowledge gaps hinder our ability to establish accurate baseline scenarios and to devise effective NBS.

To address these uncertainties, we have compiled a dataset comprising long-term, repeated soil carbon sampling across hundreds of undisturbed sites. Through statistical analyses, we aim to elucidate the temporal trends of soil carbon storage in various undisturbed ecosystems and identify the drivers behind observed trends. This research endeavor is designed to reduce uncertainty in estimating the mitigation impact of strategies that aim to protect undisturbed ecosystems from degradation and conversion, and to project counterfactual baseline SOC for more accurate estimation of SOC accrual with different NBS strategies.

4.2 Optimal grazing management

The global demand for livestock products has more than doubled over the past few decades, driven by factors such as population growth, rising incomes, and shifts in dietary preferences (Herrero et al. 2016). This surge in demand has led to approximately 37% of the world's soils being allocated for livestock grazing (Ritchie and Roser 2013). The implications for soil carbon dynamics are profound, as these soils serve as significant reservoirs of stored carbon. Grazing activities can induce soil compaction, reduce plant cover, and alter plant community composition, all of which can potentially influence soil carbon storage (McSherry and Ritchie 2013). Contrarily, field experiments have indicated that under certain conditions, moderate intensities of grazing can actually lead to increased SOC sequestration. This counterintuitive outcome can be attributed to the stimulation of plant growth and root development, which in turn enhances soil structure and microbial activity, facilitating greater carbon storage. The research goal is to map optimum grazing intensity for SOC sequestration at a high spatial resolution, taking into account variables such as climate and soil properties. Once the optimum grazing intensity is estimated, projections can be made regarding the potential carbon sequestration over time by adjusting grazing intensity—either decreasing it in most cases or increasing it in low-intensity pastures. Our initial estimates (Ren et al., in review) suggest that optimizing grazing management on a global scale has the potential to result in a carbon sequestration rate of approximately 0.8 Gt C yr^{-1}. This optimization strategy could serve as a significant lever in global efforts to mitigate climate change through enhanced SOC sequestration.

4.3 Natural forest regrowth

Natural regrowth refers to the process by which forests recover naturally without human intervention, often following disturbances such as logging or land clearance. This approach has been highlighted in some studies as one of the most promising NBS, potentially storing between 1.60 and 2.43 Pg C yr^{-1} (Griscom et al. 2017; Chazdon et al. 2016; Cook-Patton et al. 2020), due in part to its cost effectiveness and co-benefits for biodiversity (Poorter et al. 2021; Gilroy et al. 2014). However, these studies also show tremendous variation in the effectiveness of forest regrowth as an NBS. While some areas experience large increases in carbon uptake, other areas are unable to regrow naturally. The causes of this are likely many, but we hypothesize that animal seed dispersal, so far an understudied factor, may play a significant role. In some ecosystems, such as tropical forests, up to 90% of seed dispersal occurs through animals. Human activities that cause habitat loss and landscape fragmentation impede animal seed dispersal, thereby obstructing the establishment of new forests in previously disturbed systems like croplands. In essence, the loss of animal biodiversity precludes the regrowth of forests, creating a direct link between biodiversity loss and climate mitigation—arguably the two most significant challenges humanity has ever faced. The central question this research aims to address is: Can we reduce uncertainty in natural forest regrowth's carbon sequestration potential by including the role of animal biodiversity in facilitating the establishment of forests naturally through ecological succession? This will allow us to determine in which locations carbon sequestration through natural regrowth is a feasible and effective NBS, and where actively planting trees may be necessary. By analyzing the drivers of aboveground carbon accrual with natural forest regrowth, we can better understand SOC accrual and ecosystem-level carbon storage, which link is described in more detail in the following case study.

4.4 Forest Restoration Through Tree-Planting

Afforestation, reforestation, and revegetation (ARR) is distinct from natural forest regrowth and is estimated to provide carbon storage between 71.7 and 75.7 Gt C globally, including carbon stored in plant biomass and soil (Taylor and Marconi 2020). While natural regrowth allows forests to recover naturally from a perturbation or a land-use change without human intervention, ARR is an active strategy that often involves the planting of monocultures with the primary goal of sequestering carbon. However, the increase in aboveground biomass resulting from ARR does not necessarily lead to an increase in the total carbon stock. One of the most significant caveats we aim to address is the impact of tree-planting on soil carbon stocks. Observational evidence suggests that, in some contexts, tree-planting may lead to a loss of soil carbon, potentially offsetting increases in biomass and resulting in no net carbon sequestration at the landscape level. For example, afforestation—planting trees in grasslands—may result in carbon moving from soils to plant biomass, with no increase in carbon content at the ecosystem level (Friggens et al. 2020; Hong et al. 2020; Rytter and Rytter 2020). Furthermore, reallocating carbon from soils to biomass can have important consequences for the fate and persistence of that carbon as biomass carbon is considered to be shorter-lived than SOC (Thuille et al. 2000). By collecting data on aboveground biomass carbon and SOC before and after ARR, we aim to identify the drivers and map the locations where afforestation and reforestation lead to win-wins in both aboveground plant biomass and SOC stocks. Moreover, we hope to create maps to determine where either natural regrowth or tree-planting are the most effective solutions for total carbon sequestration.

4.5 Regenerative agriculture: Cover cropping

Sustainable farming practices (e.g., cover crops and no-till farming) have gained significant attention over the last decade, promising carbon sequestration as well as co-benefits such as improved nutrient retention (e.g., Bai et al. 2019; Paustian 2019; Amelung et al. 2020; Bossio et al. 2020; Lessmann et al. 2022). However, field measurements have produced contradictory results, with some studies reporting an increase in SOC and others finding no change—or even a decline—in SOC. Recent studies have estimated a total mitigation potential of 0.41 Gt CO_2e per year for cover crops, thus making it the most effective measure among regenerative agricultural practices (Bossio et al. 2020). However, these estimates do not account for potential nitrous oxide (N_2O) emissions if leguminous cover crops are used. Abdalla et al. (2019) is one of the few meta-analyses that has investigated this issue. However, their analysis relied on a limited dataset, a major caveat for achieving reliable predictions. Furthermore, uncertainties remain as to whether these practices increase or decrease crop yield, which is obviously a crucial factor for farmers (Vendig et al. 2023). Our goal is to reduce these uncertainties and provide spatially explicit predictions for SOC, N_2O emissions, and crop yield after cover cropping to better understand the potential of this NBS in mitigating climate change.

As the climate crisis intensifies, actionable and readily deployable solutions are becoming increasingly urgent. NBS, particularly those focused on SOC sequestration, offer a promising pathway for mitigating climate change. However, the effectiveness of these strategies is mired in uncertainties and data gaps. Through a comprehensive review of existing literature, the introduction of a data-driven approach, and the discussion of case studies, we aim to reduce these uncertainties and provide a clearer picture of the potentials and limitations of SOC sequestration as a climate mitigation strategy.

The case studies presented herein serve as examples of the broader challenges and opportunities in the field of soil-based NBS. They underscore the need for both context-specific research and the integration of advanced computational methods to refine our understanding of ecosystem- and global-scale SOC dynamics. Machine learning and data analytics are crucial for translating these scientific insights into actionable policies and practices, reducing uncertainties, and optimizing NBS strategies for a more resilient and sustainable future. To realize this vision, interdisciplinary collaboration among researchers, policymakers, and stakeholders is essential. Notably, the MIT Climate & Sustainability Consortium (MCSC), in partnership with industry leaders like Apple, Cargill, and PepsiCo, is actively involved in tracking and measuring ecosystem variability in areas with NBS interventions. The Terrer Lab at MIT is conducting granular, data-driven research as described in Section 3 to quantify the efficacy of soil carbon interventions. By curating extensive and quality-controlled datasets, developing machine learning models based on field data, and providing local predictions, we can reduce spatial and temporal uncertainties, supporting the successful global-scale deployment of NBS interventions. Only through such concerted efforts can we hope to leverage the full potential of NBS in the fight against climate change.

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