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Pellegrini, A., Georgiou, K., Powell, R. et al. (2026) Persistence and potential of soil organic carbon in nature-based climate solutions: a review of managed disturbances. Plants, People, Planet, 8 (3). pp. 811-830. ISSN: 2572-2611

https://doi.org/10.1002/ppp3.70186

Received: 19 May 2025 | Accepted: 8 February 2026

DOI: 10.1002/ppp3.70186

Plants People Planet PPP
Open Access

THOMAS REVIEW

Persistence and potential of soil organic carbon in nature-based climate solutions: A review of managed disturbances

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Funding information
UKRI, Grant/Award Numbers: G1165725, G115385; DOE, Grant/Award Number: DE-AC52-07NA27344

Societal Impact Statement

Implementing nature-based climate solutions is important for mitigating climate change, which is a global issue, but requires local adjustments in management practices. Using the association between soil carbon and minerals as a proxy for carbon persistence, we evaluated the effect of different management regimes on soil carbon sequestration and loss. We identified areas where management practices that increase carbon inputs should be prioritized and areas where management should focus on avoiding severe disturbances. Using this storage-potential-and-persistence framework to identify how to increase or maintain soil organic carbon storage locally will increase the effectiveness of nature-based climate solutions globally.

Summary

Increasing soil organic carbon storage could reduce the pace of climate change, but the longevity of this nature-based climate solution depends on the persistence of carbon in soils, not just the input rates into soils. We apply a framework for considering how soil carbon persistence—namely, via the association with minerals—sheds light on soil carbon sequestration. We review how management of disturbances, such as prescribed burning, forestry, and grazing, can change soil carbon storage, persistence, and potential. Past work demonstrated that management of disturbances can sequester soil carbon, but it remains unclear how the potential stabilization of that accrual and vulnerability to loss varies across disturbance types and geographies. We found that there is substantial geographical heterogeneity in the overlap among estimates of carbon accrual, disturbance occurrence, and potential stabilization: Fire-prone grasslands and intensively grazed rangelands occur in areas estimated to have high potential to store mineral-associated organic carbon, and studies also find that adjusted fire and grazing can promote mineral-associated organic carbon. Plantation forestry and burned area span large regions where particulate organic matter is the dominant form, and studies find that particulate organic carbon is disproportionately

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Adam Pellegrini and Katerina Georgiou contributed equally.

lost following intense wildfires and forest harvests. Thus, areas with high mineral-associated organic carbon deficits should be prioritized for practices that increase carbon inputs; whereas areas with high proportions of particulate organic carbon should be prioritized for practices that help to avoid severe disturbances. Taken together, the distribution of and changes in persistence mechanisms shed light on the durability of nature-based climate solutions.

KEYWORDS
fire, grazing, mineral-associated organic matter, nature-based climate solutions, soil organic carbon

1 | CONSIDERING PERSISTENCE IN THE CLIMATE MITIGATION POTENTIAL OF SOILS

Management of ecosystems to sequester CO_2 is one pathway to slow global warming (IPCC, 2023; Roe et al., 2019) through reducing degradation and promoting restoration. The nature-based climate solution framework seeks to quantify potential CO_2 sequestration while also reducing tradeoffs with humans and nature (Griscom et al., 2017). Estimated changes in soil organic carbon (SOC) still rely on simple extrapolations using syntheses to calculate global means, climate-specific means, or process-based models not independently validated across the range of conditions being evaluated (Bossio et al., 2020; Henderson et al., 2015; Lal, 2004; Smith et al., 2008). These limitations contribute to the uncertainty of potential CO_2 removal estimates, which vary by an order of magnitude even within the same management pathway (Roe et al., 2019). The uncertainty in potential CO_2 removal partly arises from diverse assumptions around (i) the persistence of newly stored carbon (C) and (ii) the constraints on maximum C storage and implications on the attenuation of fluxes as the maximum is approached. The constraints can be informed by the concept of soil carbon persistence.

This review will discuss how a soil carbon potential and persistence framework can help inform utilizing SOC as a nature-based climate solution (NbCS)—both the capacity to store more carbon and the opportunities to avoid losses. We then use a comparison among fire, grazing, and forestry pathways to illustrate the complexities in applying the framework at global scales.

2 | ASSESSING POTENTIAL FOR SOIL ORGANIC MATTER STORAGE IN NATURE-BASED SOLUTIONS

Many of the global estimates of NbCS and CO_2 removal more broadly assume a per-area absolute change in SOC or a change expressed as a percentage of starting stock, multiplied over the area where solutions could be implemented (Bossio et al., 2020; Lal, 2010; Zomer et al., 2017) (Table 1). However, some studies have sought to constrain estimates of potential SOC storage by either using process-based models that often impose theoretical limits set by biophysical properties (Henderson et al., 2015; Poeplau & Don, 2015) or fitting a sigmoidal function for SOC gains as a function of current SOC concentrations (Sommer & Bossio, 2014) (Table 1). More mechanistic and precise approaches are necessary that consider how the distribution of SOC between functionally distinct underlying forms (e.g., formations of aggregates, association with minerals, and chemical recalcitrance) can regulate the accrual, persistence, and limits to carbon storage (Breure et al., 2025; Stanley et al., 2024).

There is a multitude of empirical evidence that soil carbon accrual can be limited. Beyond limitations driven by productivity or climate (Poeplau et al., 2024; Viscarra Rossel et al., 2024), the maximum carbon storage capacity can be predicted by underlying physicochemical properties of soils (Georgiou et al., 2022; Hassink, 1997; Six et al., 2002). Likewise, frameworks for predicting the vulnerability of soils to lose carbon have proposed the same physicochemical properties that determine accrual can also be used to infer vulnerability (Sanderman et al., 2021; Viscarra Rossel et al., 2019). Although the importance of stabilization pathways in defining SOC storage limits and persistence has been experimentally explored in the context of many NbCS pathways, it has yet to be integrated into any of the recent global estimates to our knowledge. In fact, the recent estimates of NbCS removal on land did not consider soil pools when they assessed "risk" of sequestration (Walker et al., 2022).

3 | BIOPHYSICAL MECHANISMS THAT DRIVE FLOW AND STOCK PERSISTENCE

Studies quantifying CO_2 removal at the global scale generally treat SOC as a single homogeneous entity. Yet it is known that distinct functionally and operationally defined components of SOC are important for determining overall SOC turnover and persistence (Kleber et al., 2015; Sollins et al., 1996; Trumbore, 2000). Furthermore, SOC components can differ in their formation pathways and efficiencies and limits to accrual (Cotrufo et al., 2019; Lavallee et al., 2020). Consequently, understanding the distribution of SOC among distinct components can shed light on potential C storage in soils, both in terms of amount and duration.

For instance, organic carbon that is physicochemically associated with soil minerals (hereafter referred to as mineral-associated

TABLE 1 Studies used to estimate CO_2 removal potential from croplands and rangelands and the methods employed that are relevant for maximum storage and spatial extent.

Reference	Fluxes	Spatial extrapolation
Zomer et al. (2017)	Linear function of percentage change under different scenarios over a 20-year time horizon.	Homogenous accumulation in top 30 cm and multiplied across croplands extent. Built upon underlying data from Sommer and Bossio (2014).
Sommer and Bossio (2014)	Sigmoidal function (four parameters) of SOC stocks parameterized for three land classes.	Assumed homogeneous accumulation in top 25 cm and a fixed bulk density.
Smith et al. (2008)	Compilation of empirical data from reviews and prior studies on per-area fluxes summed over a fixed time period.	Climatically constrained distributions based on agro-ecological zones.
Smith et al. (2016)	Statistical extrapolation from a mixed-effects model trained on long-term experiments from 126 studies Ogle et al. (2005)	Climatically constrained distributions based on agro-ecological zones sensu Smith et al. (2008)
Henderson et al. (2015)	Used Daycent and Century models to calculate changes in soil stocks, identified grazing area boundaries and linked forage consumption, animal production and GHG emissions.	Simulations across environmental conditions constrained to agricultural areas.
Herrero et al. (2016)	Used estimates based on Henderson et al. (2015).	Gains mostly in areas where primary production rises from grazing alteration.
Conant et al. (2001, 2017)	Explored covariates controlling rates of SOC sequestration by type of improvement in grasslands across the suite of processes that are relevant to NbCS. Evaluated timescale to discuss constraints on duration of sequestration.	Not applicable.
Powlson et al. (2014)	Focused on no tillage and used a fixed coefficient.	Multiplied fluxes by the area of cropland with constraints based on the distribution of crops and areas where no tillage is not already occurring and can have the largest benefit.
Poeplau and Don (2015)	Cover cropping meta-analysis that leveraged the model RothC to estimate accumulation. Integrated covariates from the studies and forcing with a fixed empirically derived input.	Calculated the extrapolation area by masking out cropland that biophysically cannot have a cover crop for example, areas with winter planting
Hooijer et al. (2010)	Focusing on organic soils in peatlands. Mapped peat depth, water table depth to establish drainage class, and then CO_2 fluxes that scaled linearly with groundwater depth.	Map of the distribution of peatlands.
Frank et al. (2017)	Values from Smith et al. (2008) that were constrained by agro-ecological zone.	Integrated Assessment Model of GLOBIOM to map area of applicability.
Lal (2010)	A compilation of reviews and other studies but original calculations for several fluxes. For example, no till was calculated using West and Post (2002). Grassland avoided conversion/restoration was calculated using Conant et al. (2001).	Assessed technical potential when available

Note: Many studies implicitly accounted for reaching a new steady state of soil organic carbon (SOC) storage (i.e., accounting for new inputs coming into equilibrium with losses) by using a constrained timescale, but only a few studies used empirical models with nonlinear carbon (C) accrual functions or process-based models with nonlinear accrual responses.
Abbreviations: GHG, greenhouse gas emissions; NbCS, nature-based climate solutions.

organic carbon; MAOC) or that is freely available in soil (hereafter particulate organic carbon; POC) exhibits differences in its responsiveness to management or other disturbances (Cotrufo et al., 2019; Lavallee et al., 2020). MAOC is typically less vulnerable and slower to respond than POC to disturbances such as warming or changes in biomass inputs (Georgiou et al., 2024; Rocci et al., 2024). Furthermore, the finite nature of mineral surfaces may impose a maximum physicochemical capacity of C storage as MAOC that is defined by a soil's mineral content and composition (Georgiou et al., 2022; Hassink, 1997; Six et al., 2002). Although this maximum capacity may not always be feasible in practice for a given system, the proximity of a soil to its respective capacity may impact its C accrual efficiency. That is, soils further from their capacity (i.e., further from C saturation) may accrue more SOC following an increase in C inputs or improved management (Georgiou et al., 2022). Box 1 outlines definitions of the used terminology. However, microbial feedbacks and priming responses can complicate observed SOC accrual in some cases, especially in highly degraded soils (Wu et al., 2024).

Thus, in addition to understanding the physicochemical C storage capacity of a soil, predicting the potential C storage that can be achieved under a particular set of environmental conditions requires an understanding of how changes in inputs impact, and ultimately balance, changes in losses. For instance, a rise in plant NPP can be offset by increased microbial decomposition as well as erosional and hydrological losses. When inputs balance outputs, a new steady state is reached, but its proximity to the maximum physicochemical capacity (i.e., C saturation) for a given soil requires additional information on mineral content and properties. Although saturating

Box 1 **Key definitions and functional interpretability.**

- *Unrealized SOC*: The potential total SOC gains from NbCS. This is estimated by Walker et al. (2022) and quantifies how much SOC would increase by reverting land cover back to intact natural vegetation. The predicted SOC is based on a machine learning model, which includes land use (e.g., cropland and pasture) alongside biophysical variables (Sanderman et al., 2017). The calculation is based on the difference between two model runs: with and without land use.
- *Vulnerability index*: The vulnerability of SOC is approximated via the ratio of POC:MAOC. This is based on the expectation that, on average, POC turns over more quickly and is more prone to decomposition than MAOC, making it more sensitive to changes in input and loss pathways.
- *MAOC deficit*: The difference between the MAOC capacity of a soil (based on silt and clay content and mineral type) and the actual MAOC content (i.e., by subtraction). A synthesis of 103 carbon accrual measurements demonstrated that new biomass inputs led to greater C gainsin soils further from their maximum MAOC capacity (i.e., soils with greater MAOC deficit or lower percent C saturation).
- *Percent C saturation*: The amount of MAOC relative to the MAOC capacity of a soil (i.e., calculated by ratio as a percentage).

behavior could be estimated heuristically by imposing a maximum potential via observed maximum gains from empirical observations or forcing a saturating function, a mechanistic understanding is critical for constraining process-based soil models—for example, the Millennial, COMISSION, and MEMS models that explicitly represent a MAOC capacity (Abramoff et al., 2022; Ahrens et al., 2020; Zhang et al., 2021)—and projecting how potential C storage may change into the future. As process-based soil models continue to represent and predict measurable SOC components (e.g., dissolved OC, MAOC, POC, and microbial biomass) that better capture flow and stock durations, corresponding measurements of SOC components and stabilization mechanisms are needed across experiments to overcome existing data limitations that hinder validation of model responses, especially at larger spatial scales. A recent review provided an overview of how different stabilization mechanisms can be used to explain the efficacy of different CO_2 removal pathways (van Noordwijk et al., 2023).

4 | SATURATION OF POTENTIAL SOC ACCRUAL INFORMED BY MINERAL CAPACITY

To highlight the potential for stabilization processes to constrain NbCS, we compared recent global estimates of unrealized SOC accrual potential with those that partition SOC into components either associated with minerals or in a particulate form (Figure 1).

Recent studies have advanced our understanding of the geospatial distribution of (i) SOC fractions that vary in their persistence—for example, MAOC is on average more persistent than POC—and (ii) the maximum storage capacity of MAOC, from which the MAOC deficit and %C saturation have been estimated (Cotrufo et al., 2019; Georgiou et al., 2022). Ideally, these advances should be combined with global estimates of the NbCS potential to sequester C in soils to improve understanding of the persistence of SOC gains. As a first pass, we present a geographical analysis of potential SOC gains (referred to as "unrealized SOC") from NbCS (Walker et al., 2022). The unrealized SOC uses land cover change scenarios to assess potential changes. Briefly, they utilize results from Sanderman et al. (2017) mapping soil carbon stocks to current (2010) land use and abiotic conditions using a machine learning model. The potential SOC is predicted based on assuming a scenario of no land use (i.e., all gridcells are natural vegetation). Spatial resolution was 10 km but reprojected to match 500-m MODIS via nearest-neighbor resampling. Walker et al. (2022) removed areas where transition to agriculture increased SOC. Potential SOC gains are overlain here onto estimates of the distribution of SOC between fractions (using the ratio of POC:MAOC as a vulnerability index) (Sanderman et al., 2021; Viscarra Rossel et al., 2019) as well as the MAOC deficit (Georgiou et al., 2022). The maps of POC and MAOC are based on a machine learning model trained on 1144 soil profiles and gridded at 0.5° × 0.5° resolution (Georgiou et al., 2022). Although spatial scales differed amongst the datasets, we reprojected all maps to 0.25° × 0.25° resolution by aggregating finer resolutions (taking the mean) and resampling coarser resolutions (using bilinear interpolation). We map the bivariate distributions of these datasets spatially in Figure 1a,b and summarize the lowest and highest quartile combinations globally in Figure 1c,d and by biome in Figure 2.

We found that there are areas with high MAOC deficit (low % C saturation) and high unrealized SOC potential, but also with low unrealized SOC potential. Areas with high MAOC deficit and low unrealized SOC—that is, where MAOC deficit exists but SOC gains are unlikely—are mostly found in regions that have other limitations (especially aridity) that are predicted to hinder any significant SOC gains despite mineralogical potential (Figure 1a,c; shown in yellow). However, there are also large areas of high unrealized SOC potential that coincide with high MAOC deficits, such as in the Central Plains and Western United States, and the steppe of Asia (shown in green, totalling 1018 Mha globally with 28.7 Pg C of unrealized SOC potential). Given that these regions tend to have extensive agricultural cultivation—and thus are one reason why they have high potential (Bossio et al., 2020; Zomer et al., 2017)—improving

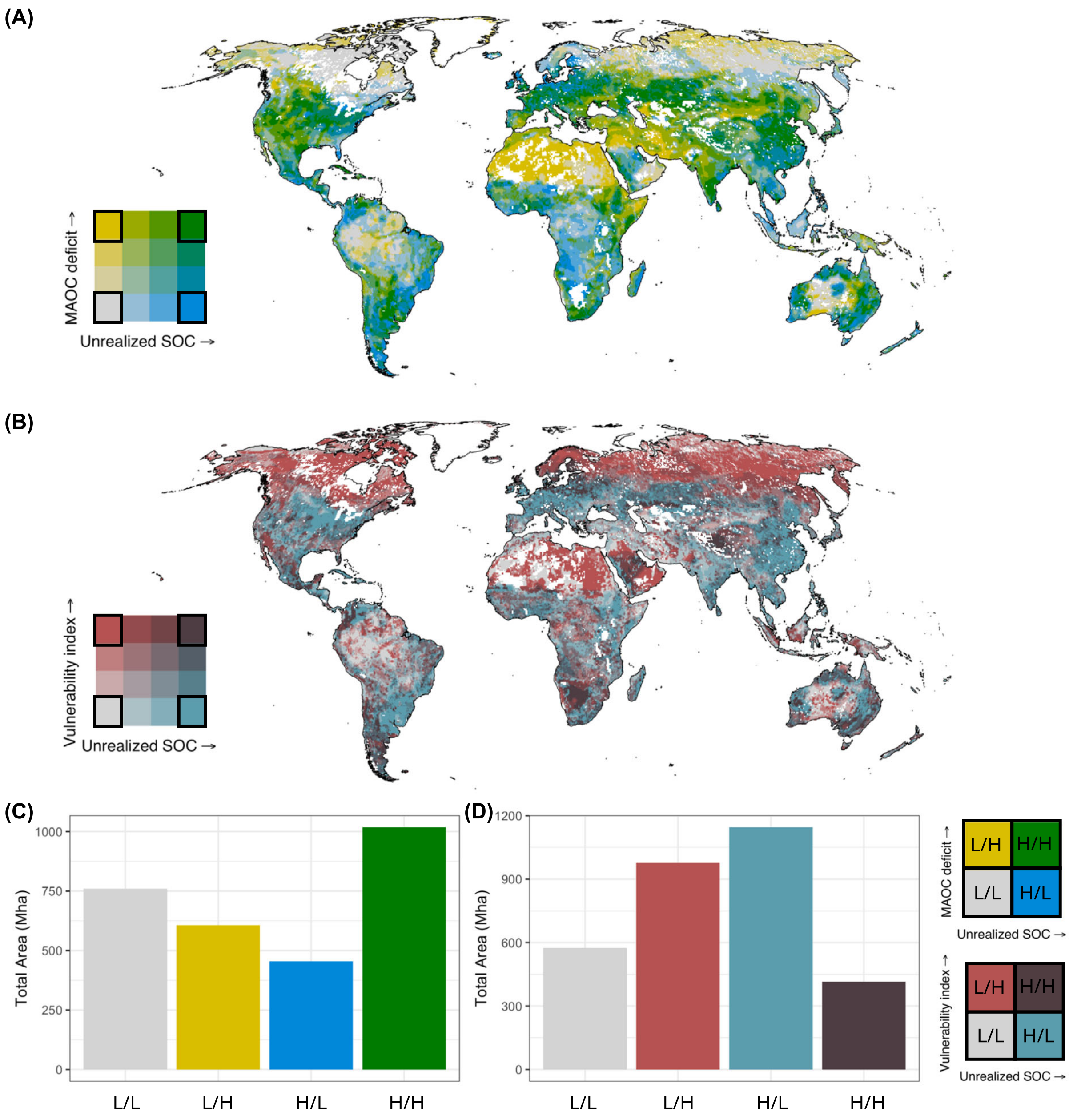

FIGURE 1 Persistence and vulnerability of soil organic carbon (SOC) accrual. Maps overlaying categories of unrealized SOC potential and (a) mineral-associated organic carbon (MAOC) deficit (as the proximity of a soil to its maximum MAOC capacity) and (b) soil carbon vulnerability (based on the ratio of underlying particulate organic carbon [POC] and MAOC fractions). The maps illustrate a combination of 16 categories corresponding to four quartiles for each, but the bar charts summarize the land area covered by the four extremes (i.e., "low" [L] and "high" [H] indicate the first and fourth quartiles of each global distribution). Unrealized SOC potentials in each of the four extreme categories (from left to right) total (c) 0.1, 0, 13.0, 28.7 Pg C and (d) 0, 0.1, 34.1, 11.5 Pg C. Data on unrealized SOC potential from Walker et al. (2022) and MAOC deficit and vulnerability from Georgiou et al. (2022).

agricultural management practices, or restoring them to their original ecosystems (namely grasslands and savannas) when possible, would be beneficial for SOC sequestration and persistence. In grassland ecosystems, belowground plant traits can be particularly important for the formation of MAOC, including rhizodeposition, symbioses with arbuscular mycorrhizal fungi, and deep roots (Bai & Cotrufo, 2022; Villarino et al., 2021). Finally, some regions with high unrealized SOC may be better suited to accumulating POC given a lower MAOC deficit (i.e., high % C saturation) (shown in blue, totaling 455 Mha with 13.0 Pg C of unrealized SOC potential), for instance, in soils with a lower MAOC capacity, such as in sandy soils or in tropical regions that are dominated by low-activity clay minerals (Georgiou et al., 2022). While it is important not to overlook the unrealized SOC potential in these (or any) regions, more care may be needed to maintain accrued POC, and thus, insights on carbon persistence can be useful for informing management decisions.

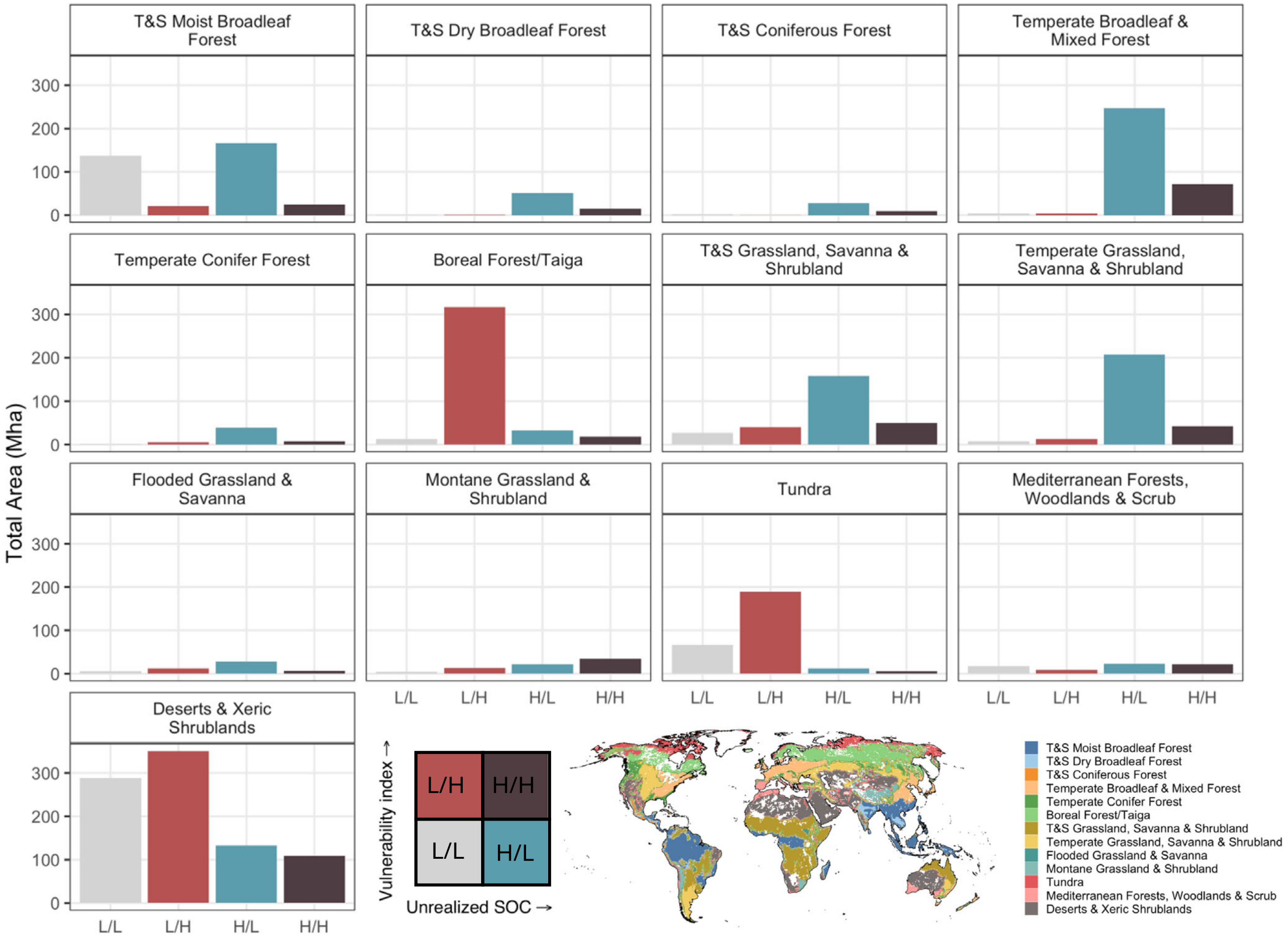

FIGURE 2 Partitioning the total land surface area with different degrees of soil organic carbon (SOC) vulnerability (inferred via the POC:MAOC ratio) and unrealized SOC potential (estimated via NbCS). We summarize the land area covered by the four extremes (i.e., "low" [L] and "high" [H] indicate the first and fourth quartiles of each global distribution) of 16 total categories, following on the maps of Figure 1. Light blue bars show the optimal areas for SOC storage with both large unrealized potential and relatively low vulnerability. The darker bars highlight areas where there is high vulnerability, with the red bars depicting regions with low unrealized potential and the dark purple bars highlighting regions with high unrealized potential. For the low vulnerability areas, the gray bars illustrate low unrealized potential and the light blue bars depict high unrealized potential. MAOC = mineral-associated organic carbon; POC = particulate organic carbon; T&S = tropical and sub-tropical. Larger map of ecoregions presented in Figure S1.

This analysis showcases the importance of understanding the destination of new biomass inputs that may arise from implementation of NbCS. If increased plant NPP is stored in soil as POC, it may be shorter lived and/or vulnerable to loss if the NbCS is discontinued or other abiotic stressors occur. Similarly, stimulated decomposition could result in more rapid SOC losses because of declines in POC.

5 | PERSISTENCE OF POTENTIAL SOC ACCRUAL INFORMED BY PHYSICOCHEMICAL SOIL FRACTIONS

Another way to assess the potential persistence of SOC accrued from NbCS, or the susceptibility of existing SOC to loss, is to evaluate how it is distributed between soil fractions—specifically, using a vulnerability index represented by the POC:MAOC ratio (Sanderman et al., 2021; Viscarra Rossel et al., 2019). The underlying hypothesis in using this index is that higher ratios signify that a greater proportion of SOC is in a form more susceptible to decomposition. Here, we used this index to identify geographic regions that may be advantageous for both gains and persistence (i.e., high unrealized SOC in areas with low POC:MAOC ratios) versus regions that may gain SOC that is more vulnerable to loss (i.e., high unrealized SOC and high POC:MAOC ratios). We find large areas with high potential to accrue SOC that coincide with low vulnerability (high persistence), including in the Brazilian Cerrado, the Eastern and Central United States, much of Europe and Eurasian grasslands as well as China (Figure 1b,d; shown in light blue, totaling 1144 Mha with 34.1 Pg C of unrealized SOC potential). These savanna-grassland systems can be dominated by deep rooting grasses with high allocation to fine root biomass, which could favor the formation of MAOC. We also identify large areas with low unrealized SOC potential and high vulnerability, primarily in boreal forests (Figure 2; shown in red), which highlights the need to preserve and protect these ecosystems from both human and climate pressures.

We do note, however, that a key uncertainty here is whether SOC accrued from implementing NbCS leads to the formation of MAOC, POC, or both and thereby changes the POC:MAOC ratio over time. A recent meta-analysis found that degradation from land use change results in losses of both POC and MAOC, but especially POC (Zhao et al., 2025). During restoration, the accrual was mainly in POC over short timescales but MAOC over long timescales (Zhao et al., 2025). Our analyses assume that the likelihood of new inputs forming MAOC is higher in soils with higher MAOC deficits, but in practice, this can depend on the types of inputs and management practices. Furthermore, our use of the vulnerability index ultimately assumes that historical conditions which favored the tendency of a region to have high MAOC will also favor new inputs to form MAOC with limited losses of existing SOC. Prior studies on carbon accrual have found that greater inputs into soils with higher mineral deficits tend to result in greater accrual of MAOC (Georgiou et al., 2022). Ultimately, changes in the unrealized SOC potential, MAOC deficit, and SOC vulnerability index will occur over time following NbCS or disturbances, but these quantities can provide present-day metrics to help inform regions that are more predisposed to gain or lose carbon.

6 | MANAGEMENT OF DISTURBANCES—NOT EXCLUSIONS—TO INCREASE SOC

Determining the responses of soils in many of the NbCS pathways depends on their sensitivity to disturbances. Often, soils-focused NbCS involve modifying ecosystems in ways to change biomass inputs into soils (e.g., cover cropping, improved grazing, residue management) or reduce the rate of decomposition of soil organic matter (e.g., tillage management). Given many disturbances are fundamental ecological processes, influencing the evolution of organisms, ecological biodiversity, and biogeochemical cycling (Chapin et al., 1994; Odum, 1969; Staver et al., 2011), it is key to manage them—adjusting their frequencies and intensities but not excluding them is a more sustainable path. A large portion of potential greenhouse gas mitigation from changing the intensity and frequency of disturbances occurs belowground via storage of carbon as soil organic matter (Minasny et al., 2017; Paustian et al., 2016; Vermeulen et al., 2019). However, much of the past work considers soil organic matter as a single pool, overlooking the considerable changes in the physicochemical properties of soil organic matter that provide insight into potential and persistence of storage.

Here, we review the literature on the potential and persistence of carbon storage in SOM under management of disturbances—namely, fire management, forestry, and rangeland grazing—to highlight how knowledge of soil carbon stabilization pathways can inform assessments of CO_2 removal in soils. We focused on these disturbances because of their large spatial extent (quantified below) and their variability in the soil conditions that reflect different mineral deficits and POC:MAOC ratios. Furthermore, several disturbances have not been well quantified for SOC (e.g., prescribed burning and avoided wildfire emissions), and many overlap (e.g., burning is an effective practice in rangeland management, Anderies et al., 2002a; Limb et al., 2016a; Wang, Li, & Ravi, 2019, and wildfires are a large threat to industrial forestry, Bousfield et al., 2025).

7 | PERCENT SATURATION AND THE VULNERABILITY INDEX APPLIED TO NbCS-RELEVANT MANAGEMENT PRACTICES

The SOC potential and persistence framework outlined above can be applied to understanding the impact of changing disturbance regimes on total SOC stocks (Figure 3). In the case of a high mineral deficit (i.e., low MAOC saturation) management to increase inputs can lead to greater storage of SOC via the sorption of C to minerals (Figure 3 blue points). These gains are likely to be larger in systems with higher net-primary productivity or under conditions that promote greater inputs because more C is flowing into soils. Alternatively, when thinking about intensifying the severity of disturbances, which might happen from the abandonment of NbCS projects, losses should be low when the deficit is low because relatively more SOC is in the MAOC pool and thus less sensitive to changes in inputs (Figure 3a red points). Variability within the degrees of bulk SOC change may instead depend on the total POC in the soil, which could rapidly decrease with a drop in inputs.

8 | DISTURBANCE TYPES AND THEIR OVERLAP WITH SOC SEQUESTRATION POTENTIAL

To highlight the scope of disturbances and their relevance for SOC accrual (Walker et al., 2022), we overlaid unrealized SOC potential with historical disturbance pressure: frequency of fires, both wild and prescribed (Chen et al., 2023), grazing intensity (ratio of forage demand relative to total forage production), primarily by livestock (Herrero et al., 2016), and forestry split by plantations and natural forestry (Lesiv et al., 2022). Data on unrealized SOC potential—the difference between potential and current SOC—are from Walker et al. (2022) with the methods described above (500 m × 500 m resolution). Rangeland extent from Herrero et al. (2013) and Robinson et al. (2011) (5 arcmin resolution). Grazing intensity was the ratio of livestock forage demand relative to total forage production. Demand was calculated using GLW4.0 (Gilbert et al., 2018) using species- and region-specific livestock characteristics under an IPCC Tier 2 approach (IPCC, 2019). Production was assumed to be mostly herbaceous forage productivity (derived from the MODIS satellite

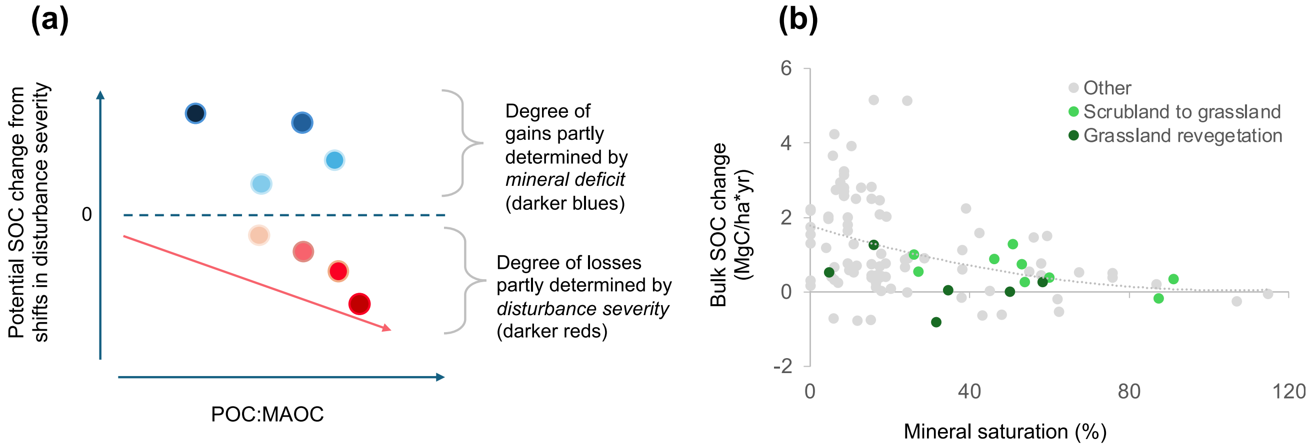

FIGURE 3 (a) Conceptual relationship between the change in bulk soil organic carbon (SOC) following changes in disturbance severity (e.g., degree of losses of organic matter inputs to soils and/or decomposition losses of residual soil organic matter) as a function of the POC:MAOC ratio (vulnerability index) and then how that links with the mineral saturation in a soil. The POC:MAOC ratio is most important for determining the potential losses if disturbance severity is increased (relevant for NbCS that involve protection of an ecosystem from increased disturbance than is historically present). (b) Gains in SOC as a function of the mineral saturation in the soil. The negative exponential relationship is because the mineral deficit influences the potential for new organic matter inputs to remain in the soil. MAOC = mineral-associated organic carbon; POC = particulate organic carbon. Mineral saturation is calculated from Georgiou et al. (2022) and defined as the amount of MAOC relative to the MAOC capacity of a soil (i.e., calculated by ratio as a percentage).

following; Piipponen et al., 2022). Fire occurrence is based on 2001–2020 from the Global Fire Emissions database v5 (Chen et al., 2023) (0.25° × 0.25° resolution). We partitioned the burned area data such that fires on croplands and peatlands are not included. Forestry data are from Lesiv et al. (2022). We used the scenarios of (i) naturally regenerating forest with some sign of management as well as (ii) planted forests and plantations. Datasets were plotted on a spatial scale of 1° × 1°.

We then calculated the areas with the highest disturbance pressure and highest unrealized SOC potential to identify global hotspots using the upper quartiles. We defined grid cells as being "high pressure" based on occupying the upper quartile of the global distribution of grazing intensities (for grazing) and fire frequencies (for fire). This clearly does not account for the fact that low-frequency but high-severity wildfires are also "high pressure," and thus, we discuss examples from the ecosystems that tend to experience these regimes (e.g., North American boreal forests). Our approach integrates the spatial overlap in both datasets and relativizes their distributions (Figures 4 and 5; Table 2). These spatial overlaps are intended to provide insight into qualitative patterns, as a full quantitative analysis would be out of the scope of a review.

8.1 | Contrasting disturbance types and their overlap with SOC sequestration potential

Grazing—although tending to span a lower total area globally—had a higher proportion of area containing both high pressure and high SOC sequestration potential than other disturbances. For example, in Asia, 32% of all grazed lands are both under high intensity management and have high unrealized SOC potential. The second largest potential is in Africa (21%) closely followed by North America (19%). This highlights the potential opportunity for managing grazing in a smaller area to have an outsized impact on SOC accrual. Ultimately, whether SOC changes from altered grazing can depend on several factors and is not always achieved via a reduction in stocking density (i.e., increasing intensity in a low intensity system can raise plant NPP and potential inputs to SOC) (see below and Conant et al., 2001, 2017).

Fire has the greatest overlap between frequent burning and high unrealized SOC potential in Africa (24%) and Asia (26%). This is likely because areas with frequent burning are estimated to transition into forest with fire exclusion in underlying datasets for estimating NbCS potential (Griscom et al., 2017). Given uncertainties in SOC accrual in forests relative to grasslands (Berthrong et al., 2009; Jackson et al., 2002; Smith, 2014), we hesitate to conclude that these are areas with high potential sequestration under fire management. However, management of fire in ecosystems within these regions—such as burning at intermediate fire frequencies or during cooler seasons in savannas and grasslands—can be beneficial. For example, a study in a South African savanna with a 70-year fire frequency and season manipulation experiment found little difference in SOC sequestration between the fire suppression plots and those with "cooler burns," which were burned during the wet season (Coetsee et al., 2023). In the South African study, SOC gains were also positively related to the clay content, with greater gains in clay-rich soils. Studies have produced diverse estimates of what factors drive SOC gains—some propose that trees are the dominant variable determining relative changes in SOC across sites (Pellegrini

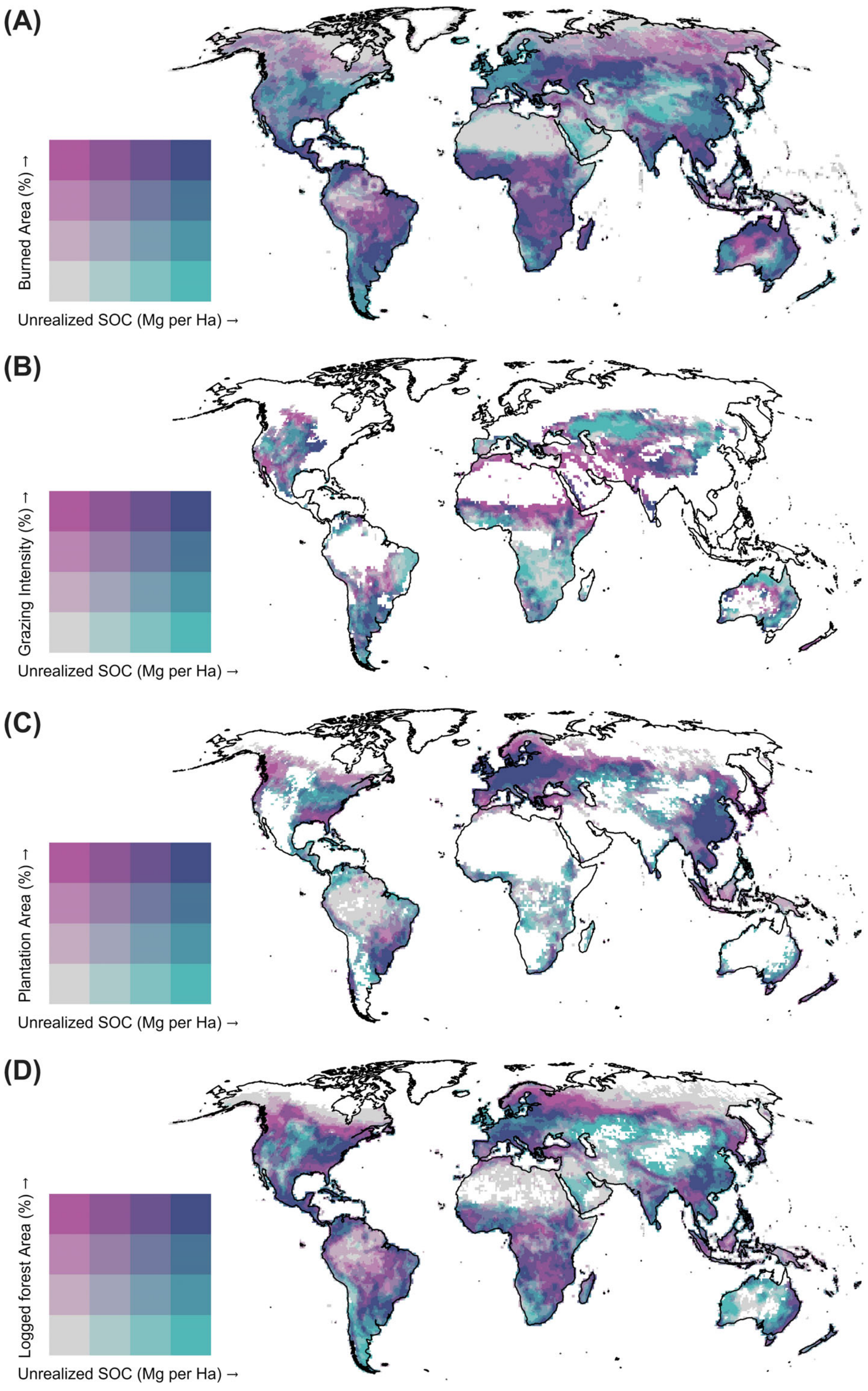

FIGURE 4 Global distribution of unrealized soil organic carbon (SOC) potential distributed across disturbance regimes. In all panels, unrealized SOC is expressed as a per-area stock to illustrate hot spots of potential sequestration. The four facets panel different disturbances. (a) Burned area expressed as a percentage of the grid cell. (b) Grazing intensity is calculated is the percentage of total forage production that is demanded by livestock. (c) Plantation and planted forest area expressed as a percentage of the grid cell. (d) Logged forest area that is the naturally regenerating forest with some sign of management. Maps illustrating where potential SOC gains are most intensively threatened by high disturbance. The colors split the distribution of the focal variable into quartiles based on its global distribution. Our methodology for calculating disturbance intensity is detailed in Section 8.

et al., 2020), but others highlight the important role of grasses (e.g., especially in dry sites across a soil moisture gradient in Botswana; Bird et al., 2004).

Forestry has the largest total overlap in Europe and Asia, with plantations covering 370.9 and 363.5 Mha, which amounts to 43% and 42% of the total area with high potential and high intensity in plantations, respectively. Forest harvest changes—such as changing timber harvesting from a plantation to a naturally regenerating forest, or forest thinning—can have large impacts on SOC (Mayer et al., 2024). A recent meta-analysis found that timber harvesting reduced organic horizons by 22.7% (−6.3 MgC ha^{-1}) but had no effect on mineral soil C (Mayer et al., 2024). When we investigated the proportion of a forestry practice that existed in areas with high potential accrual and high disturbance pressure, we found that some of the highest values are in plantations—35.7% in Europe, 42.7% when Russia is considered, and 41.8% in Asia. This highlights that

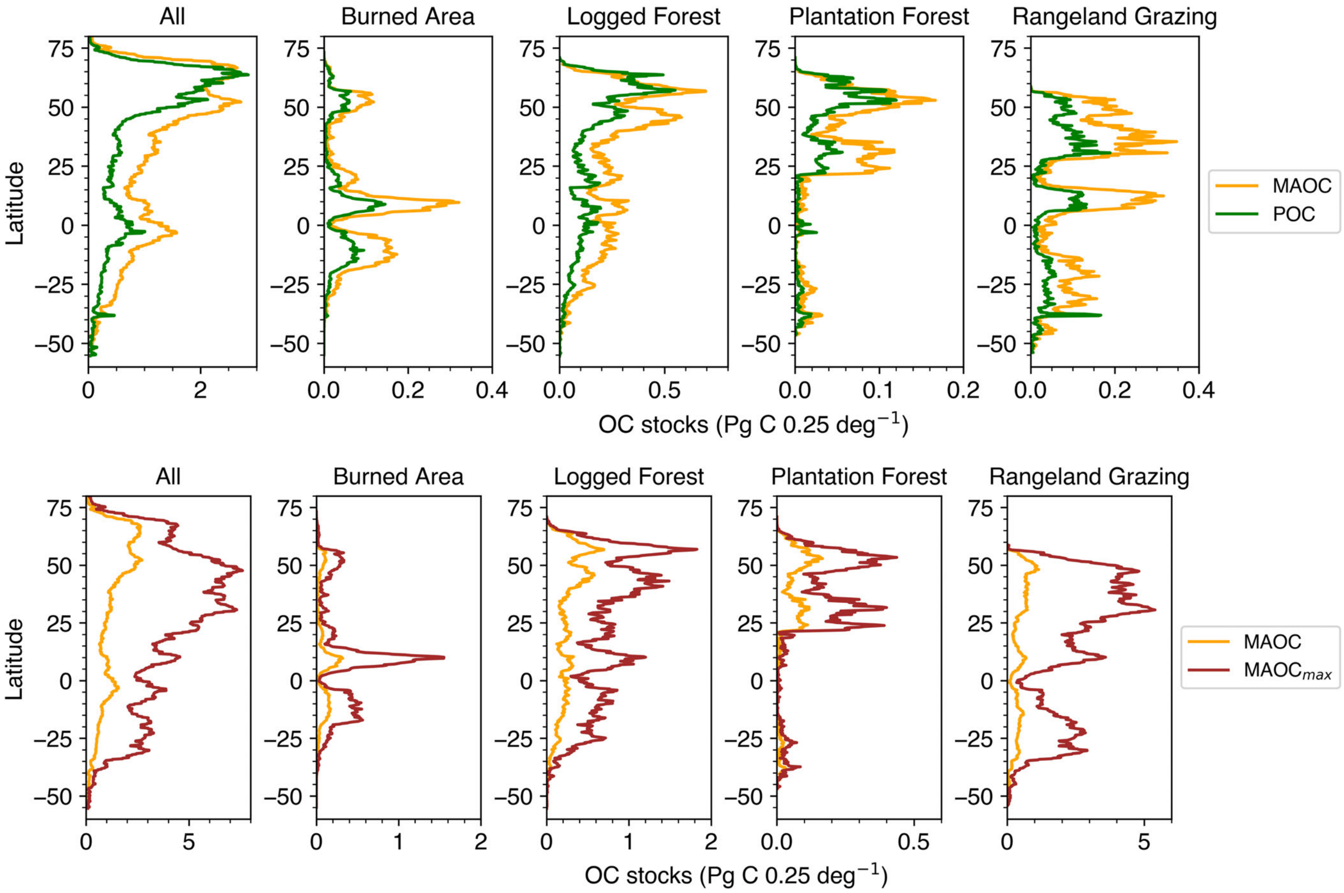

FIGURE 5 Latitudinal distribution of mineral-associated organic carbon (MAOC), particulate organic carbon (POC), and the maximum MAOC capacity (MAOC$_{max}$) from Georgiou et al. (2022). Organic carbon (OC) stocks in each panel are calculated by weighting disturbance pressures, represented as the proportion of a grid cell that is exposed to that disturbance. The column "All" denotes the entire global extent of the dataset, not just the areas covered by disturbances.

TABLE 2 Areas with the highest disturbance pressure and highest soil organic carbon (SOC) accrual potential across space.

Region	Fire area in high-highMha (% of total)	Grazing area in high-highMha (% in high-high)	Logged forest area in high-highMha (% in high-high)	Plantation area in high-highMha (% in high-high)
Europe	79.7 (3.8%)	2.7 (0.9%)	150.0 (15.0%)	310.4 (35.7%)
Europe (incl. Russia)	257.1 (12.1%)	12.3 (4.1%)	189.0 (18.9%)	370.9 (42.7%)
Asia	546.0 (25.8%)	95.8 (32.2%)	169.7 (17.0%)	363.5 (41.8%)
Africa	513.6 (24.2%)	61.8 (20.7%)	179.0 (17.9%)	8.8 (1.0%)
North America	203.5 (9.6%)	57.3 (19.2%)	254.6 (25.5%)	27.2 (3.1%)
South America	385.8 (18.2%)	42.3 (14.4%)	176.1 (17.6%)	90.3 (10.4%)
Oceania	214.2 (10.1%)	27.9 (9.4%)	30.6 (3%)	9.8 (1.1%)
Total	2199.9	300.1	1149	1180.9

Note: Area where the disturbance pressure is high and unrealized SOC potential is high ("high" is calculated as the fourth quartile of the global distribution of either the SOC potential or disturbance data). The total area (millions of hectares [Mha]) allows for comparability across practices because it quantifies the amount of area with high SOC sequestration potential that also experiences the highest disturbance pressure. The percentage allows for comparison within practices showing the proportion of overlap that exists in the high-high quartile. One caveat is that fire frequency here does not account for severity, and thus, forest fires are likely underrepresented in their importance because they are less frequent but more impactful.

intensive plantation practices tend to occupy high potential SOC accrual. This is a key observation given that some of the highest losses of soil carbon occur during conversion of tropical forest to plantations (Guillaume et al., 2015). In Africa, North America and Oceania, forestry is extensive but tends to be in areas with low potential SOC accrual.

9 | DISTURBANCE EFFECTS ON SOC POTENTIAL AND PERSISTENCE

9.1 | Overview

The expanse of fire, grazing, and forestry across SOC sequestration potential, vulnerability, and mineral deficits points to the relevance for integrating the potential and persistence framework. The variability in how disturbances cover areas with different SOC properties can be visualized in Figure 5, which illustrates the latitudinal distribution of the overlap between these disturbances and the different forms of SOC, as well as the maximum capacity to store MAOC defined by the soil mineral content and composition. High-latitude ecosystems tend to have high proportions of POC relative to MAOC (Figure 5a) and hence greater SOC vulnerability (Figures 1b and 3). These ecosystems are also relatively closer to their MAOC capacity (Figures 1a and 5b). As such, high-latitude ecosystems remain vulnerable to disturbance pressure and may not be as effective for gaining SOC, especially in more stable forms. In contrast, temperate and tropical ecosystems tend to have higher proportions of MAOC relative to POC, but many regions are still far from their maximum MAOC capacity. This signifies a large potential for more stable SOC gains, in agreement with the high unrealized SOC potential (Figures 3 and 4).

9.2 | Evidence for the relevance of mineral-association and vulnerability concepts

Two observations provide indirect evidence for the mineral deficit and vulnerability concepts being applicable to management of disturbances. First is that disturbance management can shift biomass inputs into soils by altering the net primary productivity of plants and decomposition rates in soils. This is likely to lead to changes in both POC and MAOC. A recent meta-analysis across 17 studies found that inputs can lead to greater POC and MAOC (Zhang et al., 2022). Thus, if the management of fire, grazing, and forestry increases inputs, then SOC in both pools should change. Given MAOC is a large part of this change, the mineral deficit is likely relevant.

Second is the negative relationship between SOC changes under disturbance management and total SOC stocks in the control plots. Frequently, these studies did not track changes through time in a single plot but rather looked across plots with different treatments. Although the propensity for lower SOC soils to gain SOC is partly influenced by a statistical artifact (Slessarev et al., 2023), there is also biogeochemical theory behind the expectation that lower SOC soils experience greater gains (Georgiou et al., 2025).

9.3 | Evidence for potential gains in MAOC

There are few studies that have looked at the impact of fire management on different soil fractions. Within forests, prescribed burning can be an NbCS for avoided wildfire emissions because forests with a history of prescribed burning tend to burn less severely in a wildfire. Prescribed burns in a longleaf pine system increased MAOC and POC relative to another forest that had been raked (Moss et al., 2025). These soils were relatively sandy, but low in SOC, consistent with the expectation that soils low in SOC could sequester more. Implementing prescribed burning for 5 years in a wetland also increased MAOC but resulted in greater gains in POC (Wang, Xu, et al., 2019). The authors inferred this to be due to an increase in C inputs because of greater dissolved organic carbon (DOC) and the correlation between SOC changes and plant biomass inputs (Wang, Xu, et al., 2019). Finally, reintroduction of fires—burning every decade for 30 years—into a coniferous forest that has experienced fire exclusion for >100 years reduced POC but left MAOC unchanged (Pellegrini et al., 2021). To our knowledge, there has been no study to quantify mineral deficits across plots, implement prescribed burns (or alter their frequency) and then sample the different fractions.

For grazing, a study in Northern US grasslands comparing 12 ranches with adaptive multi-paddock (AMP) grazing to 12 ranches with conventional grazing found increased MAOC stocks and the proportion of SOC in a MAOC form, inferred to be a result of the greater plant productivity (Khatri-Chhetri et al., 2024). Another study on AMP grazing within farms in the Southeastern United States found 25% more C in the MAOC pool under AMP grazing, but no change in the POC pool (Mosier et al., 2021). In Western US pastures, a survey of four sites found 17% more topsoil SOC in AMP pastures at half the sites—this was related to greater live plant cover and 82% greater perennial grass cover, pointing to higher inputs as a contributor (Stanley et al., 2025). Thus, improvements in grazing (like rotational grazing and/or reducing intensity) can increase MAOC stocks (e.g., Carrascosa et al., 2025), especially when plant biomass inputs rise. Grazing lands tend to be far below soil C saturation; for example, 80% of European grasslands are below C saturation based on their physicochemical properties and environmental conditions (Cotrufo et al., 2019, and Figures 4 and 5). Thus, managing grazing in a way to promote MAOC could be a promising pathway to obtaining durable NbCS.

Comparing grazing exclosure experiments provides a mixed picture. A study on 34 years of sheep grazing exclusion in Mongolia found 2.7-fold greater POC when compared to fields that were continuously grazed (Cao et al., 2013), a similar finding to a manipulation lasting several decades (Wiesmeier et al., 2012). Contrastingly, a 6-year study in a steppe found that exclosures had higher MAOC but lower POC (Wu et al., 2022). A survey of 108 pairs of long-term grazed versus ungrazed pastures across Canada found that grazing increased total SOC in the topsoil but had no general effect on the distribution of SOC between MAOC and POC fractions (Hewins et al., 2018). The large cross-site studies tend to observe that pedogenic controls on MAOC exceed the impacts of grazing exclusion but that POC more consistently rises.

For forestry, retaining residues can promote sequestration in POC and MAOC, with POC gains exceeding MAOC, in shallow topsoils (<5 cm) in a Eucalyptus plantation in Brazil (Ferreira et al., 2021). Another study found higher POC, especially with bark retention, in the top 1 cm (Oliveira et al., 2021). Plantations reduced savanna-derived SOM suggestive of continued decomposition, but residue removal reduced accretion of C in all fractions in the top 5 cm (Epron et al., 2015). However, aboveground inputs do not always result in gains, as residue retention under salvage logging after a wildfire did not increase POC (Avera et al., 2020). In Germany, a survey across 82 beech forests found that MAOC changed little with management (e.g., selection cutting), but tracked clay and iron oxide content (Grüneberg et al., 2013).

Taken together, MAOC is slow to change with management over years–decades, and it tracks mineral surfaces and pedogenic oxides, not just inputs. But some management practices can stimulate its formation and warrant further study.

9.4 | Evidence for the vulnerability concept predicting losses

NbCS also involve avoided disturbance of ecosystems (e.g., cultivation for agriculture, intensively grazed rangelands, slash and burn, short-rotation plantations). Indirectly, there is evidence that disturbances can have larger effects on SOC in systems with higher POC:MAOC proportions. For example, a meta-analysis demonstrated that harvesting in forests with very high SOC stocks had the largest negative effects on SOC (Mayer et al., 2024). These forests tend to have large organic horizons where SOC is primarily in the POC pool and thus accessible to decomposition following a reduction in inputs or stimulation of decomposition.

Overgrazing, which reduces plant biomass inputs into soils, can impact POC more than MAOC, suggesting that soils with greater POC:MAOC ratios would be more vulnerable to losses. In a study that increased grazing intensity for 5 years on a moderately grazed steppe, MAOC remained relatively unchanged with more frequent grazing, while POC tended to decline (He et al., 2011). Notably, the changes were starker when grazing intensity was decreased relative to background levels compared to being increased (He et al., 2011). A study that modified cattle density for >10 years to increase grazing relative to the control found no detectable difference in MAOC, but the fraction POC declined (Guo et al., 2025). A comparison of grazing (predominantly cattle) between two ranches in an African rangeland found that less intensive grazing (continuous vs. controlled), not exclusion, resulted in 24% greater POC and 2.6% greater MAOC in topsoil (Gitau et al., 2025). Taken together, moving from ungrazed to light/moderate grazing can increase POC without MAOC loss, but heavy and long-term grazing generally reduces MAOC, consistent with lower plant inputs, trampling-induced aggregate disruption, and texture shifts that occur.

For forestry, intensive harvesting and plantations more consistently reduce POC, especially in systems with large organic horizons. For example, in Germany, beech forests undergoing management (e.g., selective harvesting) that reduced the organic horizon tended to reduce the POC fraction but not change the MAOC (Grüneberg et al., 2013). However, in the Northeastern United States, there were no clear effects of a whole tree harvest after 17 years on either soil fraction (Parker et al., 2002). Furthermore, severe disturbances can cause losses of MAOC. For example, in a red spruce forest, a recovery-from-harvest chronosequence found large losses of the MAOC in subsoils (Diochon & Kellman, 2009). Thus, POC responds first and most strongly to harvest intensity (whole-tree vs bole-only, slash removal) often increasing or decreasing quickly while MAOC stays buffered.

Prescribed burning can be an NbCS via avoided emissions from severe wildfires. Prescribed burning to reduce wildfire severity is empirically robust (Boer et al., 2009; Davis et al., 2024; Fernandes & Botelho, 2003; Pollet & Omi, 2002; Stephens et al., 2014; van Wagtendonk et al., 2012). For example, a recent meta-analysis of 40 studies and 172 sites in the Western United States highlighted that thinning and repeated burning combined reduced wildfire severity by 72% (Davis et al., 2024). Severe wildfires reduce SOC, but often these losses are less severe in the MAOC pools. For example, 1-year post wildfire in a North American temperate forest where much of the organic horizon was removed, MAOC was little changed (Peter-Contesse et al., 2024). Similarly, in a humid Mediterranean forest, wildfires reduced POC by 50%–70% and MAOC by 7%–10% across a fire severity gradient (Merino et al., 2021). In a Chaparral ecosystem, high-severity fire reduced POC by 50%, but also MAOC by 33%—thus even when MAOC is lost, generally the magnitude is less than POC (Krichels et al., 2025). In forests, the driver of greater POM vulnerability in wildfires is likely the accumulated SOM in long-unburned forests mostly being in an organic horizon that is readily combustible. In systems with a less pronounced organic horizon, and thus lower POM:MAOM ratios, fire severity is likely a key driver of whether soils reach high enough temperatures to combust SOC sorbed to minerals. We propose that there is enough evidence for the POC:MAOC ratio to provide insight on SOC losses, such that integrating these fractions into analyses of how disturbances change ecosystem C storage is key.

10 | RELEVANCE FOR CARBON PROJECTS

To provide further context and illustrate the relevance of considering soil persistence and saturation for informing policy, we consider their overlap with existing carbon projects. Soil carbon saturation status and/or the persistence of sequestered soil carbon via management are directly relevant to the requirements of carbon projects, which need to demonstrate additionality and potential as well as durability of sequestered carbon. We overlaid our mineral deficit maps with 56 grazing-related carbon projects in the Verified Carbon Standard Registry ("Verra Search Page") to shed light on the diversity of edaphic conditions across projects (Figure 6). Most of the projects exist in areas with relatively low MAOC saturation, pointing to good

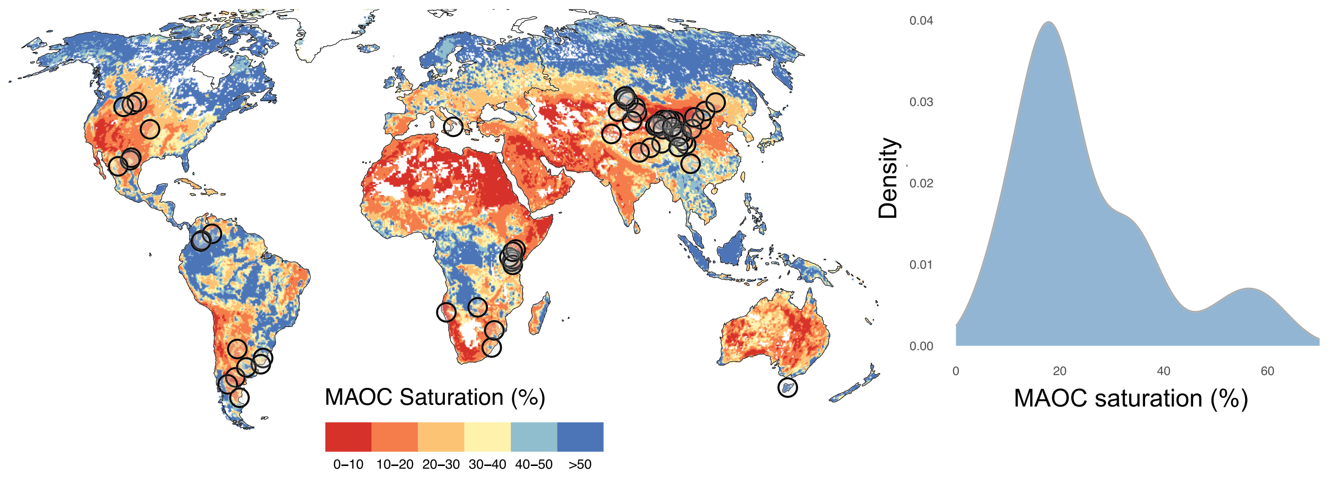

FIGURE 6 Distribution of carbon credit projects in Verra registry (2025) overlaid with mineral-associated organic carbon (MAOC) saturation expressed as a percentage. The adjacent density plot is of the distribution of MAOC saturation across projects.

alignment of project location and the potential gains in MAOC. Realizing this potential, however, will depend on how the implemented management changes biomass inputs into soils and the formation of MAOC.

11 | INTERACTIONS BETWEEN DISTURBANCES

Many disturbances do not occur in isolation, even when they are implemented intentionally (Figure 7). For example, prescribed fire can be used to stimulate plant productivity in rangelands in some regions, but is suppressed in others because of the concern that it removes forage and leads to nitrogen losses. This directly couples the implementation of one type of NbCS (prescribed burning) with another (grazing management). In some cases, disturbances are complementary: prescribed fire is used to reduce wildfire risk in the same areas where timber harvesting occurs (Hiers et al., 2020). Prescribed burning can also help to maintain a healthy open savanna or grassland (e.g., reducing shrub encroachment) which can sustain grazing mammals (Anderies et al., 2002b); although this can be context specific (Limb et al., 2016b). Avoided wildfires is another benefit of combining prescribed burning and grazing, as illustrated via a modeling study that found the combination of fire and grazing reduced wildfire intensity three-fold relative to plots with prescribed burning alone (Starns et al., 2019). Thus, implementing NbCS that leverage multiple processes—such as prescribed burning in areas where it can improve plant NPP combined with rangeland management practices that might also improve NPP (e.g., sowing legumes or rotational grazing)—could create win-wins.

In other cases, disturbances that co-occur can be unintentional and deleterious. For example, changing fire regimes in timber producing regions (e.g., Western United States and Eurasia), which often result in stand-clearing wildfires (Bousfield et al., 2023). However, prescribed burning can be used concurrently with forestry in other regions such as the Southeastern United States to reduce fuel loads (Kobziar et al., 2015) and subsequently dampen carbon losses should a wildfire occur.

We assessed the potential for using one disturbance to manage another by combining data on the extent of fire, grazing and forestry practices (Figure 6). There are clear geographic differences in the overlap. The largest overlap of high frequency areas is in logged forests that burn, especially in the tropics. Thus, managing both logging practices and fire—which is often used as a pathway for deforestation or rotational cultivation (Curtis et al., 2018)—is relevant. For plantations, overlap is largely along central Eurasia and southeastern South America, pinpointing fire management as key for forestry (Bousfield et al., 2023). The overlap between grazing and fire is most extensive in the Sahel. This region is also a hotspot of unrealized SOC and relatively high grazing intensity (Figure 1) with high potential to store more C as MAOC. Thus, considering the positive impact of prescribed burning on grass biomass and allocation to roots, and the formation of pyrogenic C, add to the potential total NbCS in this area.

12 | FEASIBILITY, IMPLEMENTATION, AND ENVIRONMENTAL CHANGE

There have been very few assessments of economic feasibility of implementing NbCS of fire and grazing management at the global scale, with assessments of forest management largely focusing on reforestation (e.g., afforestation and reforestation: $65–$108 per-tC in 2100) (Smith et al., 2016). Land area tradeoffs can be high when changing practices requires clearing of new land (e.g., increasing bioenergy production), but our focus is on the management of disturbances on existing land, thus it is not relevant. More local studies have elucidated the potential economic tradeoffs. For example, grazing management can also involve costs (e.g., fencing, labor, water access) (Che et al., 2023) while also resulting in potentially divergent impacts on livestock productivity. Where grazing intensity is altered, the impact on livestock production depends on the responses of plant productivity. Even where improved grazing results in productivity-driven financial benefits, implementation costs (Tang et al., 2024), social norms (Tesfaye & Tessema, 2023), uncertainty of SOC monitoring and carbon payments (Messner et al., 2025), and access to extension services can limit adoption (Ayal & Mamo, 2024). In well-resourced regions like the United States, improved grazing practices have seen wider adoption (40% in a recent survey of cow-calf operators; Whitt & Wallander, 2022) while in less well-resourced regions, adoption can be significantly lower (22%) (Ayal & Mamo, 2024). Therefore, there remain cultural and economic barriers to implementing improved grazing management across global contexts.

Climate change will have uncertain effects on SOC stocks and potential changes; however, the vulnerability index can provide insight. A recent modeling analysis highlighted the tendency for Earth system models to have larger amounts of faster-cycling soil carbon pools, which are analogous to POC (Georgiou et al., 2024). Given that these models predict a large response of these fast-cycling pools to perturbations (e.g., temperature), it is likely that areas with a higher POC:MAOC ratio are more likely to lose SOC with warming. Warming experiments also tend to show larger losses of POC than MAOC (Rocci et al., 2021), especially in deeper soil layers (Soong et al., 2021). However, a recent study found that 3 years of warming did not change POC yet increased MAOC in abandoned croplands (Zhang et al., 2025). The mechanisms behind variable responses across studies are largely unclear, with changes in decomposition dynamics and plant productivity likely playing out in tandem.

In our analysis, we used a dataset on unrealized SOC potential that already applied several societal constraints to mapping the suitable areas. Areas essential for food production (currently used, not projected) and human habitation were removed. These included croplands, delineated by the Global Food Security Support Analysis Data, permanent pastures, delineated by (Ramankutty et al., 2008) (centered on the year 2000), and areas with human densities of >300 people per-km^2 all being removed. For comparability with published estimates on SOC accrual from NbCS, we used these same underlying maps. However, we acknowledge that more nuanced assessments of the feasibility of implementing NbCS are needed.

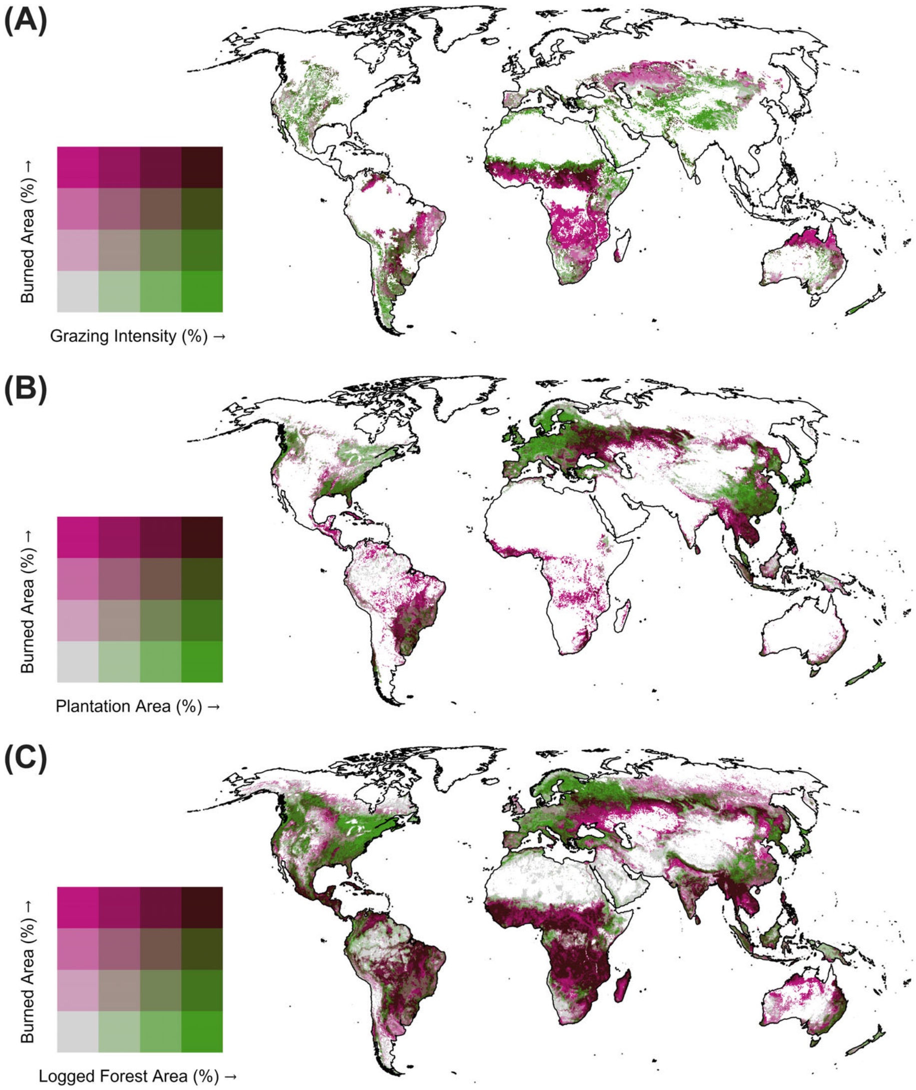

FIGURE 7 Overlap between fire activity, grazing intensity (a), plantation area (b), and logged forest area (c). Color bins are calculated based on quartiles of the distributions for each disturbance. Rangeland extent and grazing intensity from Herrero et al. (2013) and Robinson et al. (2011). Fire occurrence is based on 2001–2020 from the Global Fire Emissions database v5 (Chen et al., 2023). We partitioned the burned area data such that fires on croplands and peatlands are not included. Forestry data are from Lesiv et al. (2022). We used the scenarios of (i) naturally regenerating forest with some sign of management and (ii) planted forests and plantations.

13 | ASSOCIATED EMISSIONS FROM IMPLEMENTING MANAGEMENT

Changing the management of ecosystems can shift net-emissions through pathways other than the C stored in plant biomass and soil organic carbon. This can arise through on-field shifts in emissions (e.g., N_2O from N applications in improved grassland management; Huth et al., 2010) or CH_4 from enteric fermentation under dietary shifts (Herrero et al., 2013), as well as emissions from the implementation of management change (e.g., CO_2 from fuel used or machinery produced), which can be illustrated using life cycle assessments. Moreover, changes in emissions from machinery as well as transport and processing of products that arise from shifts in regenerative agricultural practices need to be considered (Lal, 2010). We review examples of potential pathways that NbCS may impact in a life cycle analysis framework.

13.1 | Fire management and CO_2 emissions

Fire fuel removal—either mechanically or via prescribed burns—requires a number of inputs (Ryan et al., 2013). For example, ignition methods can vary from drip torches, which are relatively low fuel consumption, to aerial ignitions, requiring emissions-intensive aircraft. Unmanned aerial vehicles offer a more cost- and emissions-efficient pathway (e.g., estimated to be \$2.66 ha^{-1}; Lawrence et al., 2023) but also carry manufacturing emissions (e.g., Figliozzi, 2017). Given prescribed burning can be focused in the urban-wildland interface (Dombeck et al., 2004), emissions from accessibility are likely low. Machinery and supplies to suppress the fire and control the prescribed burn also impact emissions—either using water trucks or aerial deposition. Mechanical fuel treatment such as fuel piling, fuel break creation and mastication are all strategies that would similarly require machinery production and fuel consumption. These are rarely assessed when determining avoided emissions benefits.

For avoided wildfire emissions, the potential rise in emission pathways from preventative methods needs to be placed in the perspective of similar emission pathways during wildfire suppression. Wildfire suppression can be much more intensive, leveraging aircraft for fire suppression, trucks for evacuation, and mobilization of personnel. Airtanker deployment is high in large fires (22.8% of all flights were for fires >8 k ha) (Thompson et al., 2012). Given planes consume high amounts of fuel, these emissions alone likely exceed any fuel emissions from the machinery used for prescribed burns and mechanical thinning.

13.2 | Pasture improvement and improved grazing CO_2, CH_4, and N_2O emissions

One option for improving rangeland productivity is to increase grass biomass without reducing stocking rates. While applying N fertilizer to stimulate NPP is one option, it both embodies substantial CO_2 emissions during the production process if it is synthetic and causes significant N_2O emissions regardless of the form (Huth et al., 2010). Alternatively, sowing legumes tends to reduce total N_2O emissions because sowing legumes helps reduce the reliance on N fertilization (Boddey et al., 2020). For example, N_2O emissions per hectare were 16%–19% lower in production systems that combined legumes and fertilizer relative to fertilizer alone (Li et al., 2011). Although legumes increase N in the system, N_2O tends to not scale with N from legumes in the same way it scales with N via fertilizers (Rochette & Janzen, 2005). Aside from direct N emissions, because of greater digestibility, cattle growth efficiency rises and CH_4 emissions can decline (Lüscher et al., 2014). Whether CH_4 emissions decline depends on the relative digestibility of legumes vs. grass, however (Phelan et al., 2015). Thus, considering supply chain emissions from the implementation of NbCS makes legume planting very favorable and fertilization of grasslands unfavorable.

Another option to enhance soil C sequestration is via reducing grazing intensity, but this either decreases the amount of forage available to livestock or else requires more land. Maintaining the same scale of livestock production without land expansion requires supplemental feed from croplands. While livestock methane emission intensities can decline by up to 22% when they switch to high-quality feed (Arndt et al., 2022), feed production can result in land-use emissions (Garnett et al., 2017; Herrero et al., 2013). Thus, for interventions to be effective, they would need to consider feed emission intensities globally. Because feed production emissions are highly geographically variable (~0.3 $kgCO_2$-eq per-megajoule in Brazil vs. 0.04 $kgCO_2$-eq per-megajoule in the United States), the emissions arising from supplementing diets with feed are mediated by global trade (where feed sources are coming from and the associated emissions of that feed) (Hong et al., 2021).

14 | CONCLUSIONS

Integrating estimates of SOC storage potential with information on the persistence of SOC is a key next step for predicting the sustainability of NbCS in soils; our own analysis illustrates the potential for SOC gains to be stored in a more persistent form in many ecoregions, especially savanna grasslands and under grazing management. It can also help to separate areas with high unrealized SOC potential but relatively high vulnerability from those with high unrealized SOC potential but relatively low vulnerability. Areas with high MAOC deficit and low unrealized SOC—that is, where MAOC deficit exists but SOC gains are unlikely—are mostly found in regions that have other limitations (especially aridity) that are predicted to hinder any significant SOC gains despite mineralogical potential. Considering high disturbance and high unrealized SOC potential, our analysis identifies global hotspots, with fire management being particularly critical in Africa, South America, and Oceania, grazing in Asia and North America, and forestry in Europe and Asia. Managing disturbances like prescribed burns can reduce wildfire severity, preserve SOC, and promote the creation of more stable pyrogenic carbon. Forestry practices, especially plantations, often degrade SOC, whereas native forests tend to maintain more stable carbon stocks, thus we should prioritize avoiding disturbances in forests with high POC:MAOC ratios. Grazing management shows promise in boosting SOC through practices like rotational grazing and promoting deep rooted grasses, especially in degraded rangelands, which can promote the formation of MAOC. However, reducing grazing intensity generally leads to gains in POC, which can be short-lived—thus the need to focus on areas with high mineral deficits such as the tropics. Finally, disturbance interactions are important: Combining fire management with grazing or forestry practices can amplify benefits. However, strategies must be region- and context-specific, balancing carbon sequestration with ecosystem health.

AUTHOR CONTRIBUTIONS

Adam Pellegrini and Katerina Georgiou designed and planned the research. Katerina Georgiou, Robert Powell, and Christopher Bousfield collected and analyzed data. Adam Pellegrini wrote the first draft of the manuscript, and all co-authors provided comments.

ACKNOWLEDGMENTS

AFAP acknowledges support by UKRI Grants G1165725 and G115385. KG was supported by LLNL-LDRD Project 24-SI-002 under the auspices of DOE Contract DE-AC52-07NA27344.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

All data are freely available from the cited studies and datasets included in the text.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Pellegrini, A., Georgiou, K., Powell, R., & Bousfield, C. (2026). Persistence and potential of soil organic carbon in nature-based climate solutions: A review of managed disturbances. *Plants, People, Planet*, 1–20. https://doi.org/10.1002/ppp3.70186