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RESEARCH ARTICLE

Global suitability and spatial overlap of land-based climate mitigation strategies

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Abstract

Land-based mitigation strategies (LBMS) are critical to reducing climate change and will require large areas for their implementation. Yet few studies have considered how and where LBMS either compete for land or could be deployed jointly across the Earth's surface. To assess the opportunity costs of scaling up LBMS, we derived high-resolution estimates of the land suitable for 19 different LBMS, including ecosystem maintenance, ecosystem restoration, carbon-smart agricultural and forestry management, and converting land to novel states. Each 1 km resolution map was derived using the Earth's current geographic and biophysical features without socioeconomic constraints. By overlaying these maps, we estimated 8.56 billion hectares theoretically suitable for LBMS across the Earth. This includes 5.20 Bha where only one of the studied strategies is suitable, typically the strategy that involves maintaining the current ecosystem and the carbon it stores. The other 3.36 Bha is suitable for more than one LBMS, framing the choices society has among which LBMS to implement. The majority of these regions of overlapping LBMS include strategies that conflict with one another, such as the conflict between better management of existing land cover types and restoration-based strategies such as reforestation. At the same time, we identified several agricultural management LBMS that were geographically compatible over large areas, including for example, enhanced chemical weathering and improved plantation rotations. Our analysis presents local stakeholders, communities, and governments with the range of LBMS options, and the opportunity costs associated with scaling up any given LBMS to reduce global climate change.

KEYWORDS
climate change, climate mitigation, land-based climate mitigation, land-use change, natural climate solution, nature-based solution, net zero

1 | INTRODUCTION

Limiting global warming to 2°C requires dramatic reductions in greenhouse gas emissions paired with the widespread deployment of land-based mitigation strategies (LBMS)—a suite of land use and land management practices that harness plant and soil processes to reduce greenhouse gas emissions and increase carbon removals (Griscom et al., 2017; Robertson et al., 2022; Roe et al., 2021; Seddon, 2022;

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Seddon et al., 2020) (Table 1). While cutting emissions is the single most important component of reaching net-zero emissions, these reductions must be complemented by LBMS as they allow society to remove carbon that has already been released into the atmosphere (Griscom et al., 2017; IPCC, 2022). To meet their full potential, however, LBMS must be implemented across large spatial extents (Field & Mach, 2017; IPCC, 2022; Novick et al., 2022), requiring major shifts in the Earth's distribution of land cover. The degree to which LBMS can address climate change therefore depends on the extent of land available for, and in turn dedicated to implementing land-based climate mitigation. Accordingly, identifying the spatial distribution of opportunities for LBMS is particularly critical for actualizing national and global commitments to reduce climate change (Dooley et al., 2023; Drever et al., 2021; Fargione et al., 2018).

In recent years, approaches to land-based mitigation have expanded to include a diversity of strategies that differ greatly in their potential impact on greenhouse gas fluxes and thus their contribution to net-zero emissions targets (Griscom et al., 2017; Roe et al., 2021; Seddon et al., 2020; Slade et al., 2014; Smith & Torn, 2013). While the growing number of LBMS provides multiple options for addressing climate change, many LBMS have yet to be implemented at scale (Buma et al., 2024), and uncertainties about the efficacy and feasibility of any one solution vary substantially (Anderson & Peters, 2016; Babin et al., 2021; Bai & Cotrufo, 2022; Buma et al., 2024; Calabrese et al., 2022; Moinet et al., 2024). As a result, little is known about how scaling up the deployment of one LBMS might affect the potential of others. For example, previous work has mapped geographic suitability for a single strategy (Bunting et al., 2022; Cook-Patton et al., 2020; Leifeld & Menichetti, 2018) or estimated the maximum area available to several LBMS without considering where this land is distributed (Griscom et al., 2017; Roe et al., 2021). The few studies that map suitability for multiple LBMS in concert tend to focus on approaches to better land stewardship (e.g., habitat maintenance and restoration) (Walker et al., 2022; Zheng et al., 2022), which are often siloed from LBMS that involve novel modifications to land processes (e.g., enhanced chemical weathering) (Bellamy & Osaka, 2020; Field & Mach, 2017; Osaka et al., 2021). Regardless of this distinction, all of these strategies require land (Baruch-Mordo et al., 2019; Roe et al., 2021; Zheng et al., 2022) and must be scaled up collectively—and rapidly—to achieve net-zero emissions (Rogelj et al., 2018). Thus, an approach that quantifies how the suitable area for all LBMS overlaps is ultimately needed.

Such a holistic approach is particularly important to avoid overestimating the joint contribution of different LBMS to climate mitigation. For example, agricultural lands are candidate areas for expanding carbon smart management methods as well as for restoring forest (Albanito et al., 2016; Gvein et al., 2023). However, since these strategies are incompatible on the same landscape, independently considering land available to each LBMS risks overestimating their combined mitigation potential. Similarly, only by overlaying the land suitable for each strategy, can we properly estimate the opportunity cost associated with deploying one alternative versus another. Conversely, if mitigation strategies with overlapping land requirements are compatible with one another (e.g., enhanced chemical weathering can supplement bioenergy crop production and other sustainable crop management actions, Kantola et al., 2017), these areas may provide opportunities for amplifying carbon removals and emission reductions. In either case, considering which and how many LBMS are possible across different landscapes can inform society's choices when using land to meet climate targets.

Ultimately, the decision to implement a climate mitigation strategy will be based on local factors such as land-use rights and current land-use practices. These factors are rarely considered in national climate pledges for implementing LBMS, pledges often made without a clear pathway for where these land conversions will take place (Dooley et al., 2023). A spatial synthesis of the geographic potential of LBMS is, therefore, needed to provide the foundation for informing the choices society has across local, national, and global scales. In particular, situating local decisions within the broader spatial context for where LBMS could alternatively be deployed can provide a better understanding of (1) how to strategically scale up multiple approaches to climate mitigation and (2) how policies that incentive one mitigation strategy influence the area that is available to others (Drever et al., 2021; Novick et al., 2022). Indeed, coordinating the local deployment of the various strategies is essential to meeting national and global climate targets (Eckert et al., 2023; Petzold et al., 2023), and thus, national and global syntheses of LBMS opportunity costs are needed to later inform optimal outcomes for climate, people, and biodiversity (Walker et al., 2022).

To meet this need, we synthesized the literature to identify the extent and overlap of land suitable for 19 different LBMS. These strategies (Table 1) help stabilize the climate by (1) maintaining the carbon in today's ecosystems, (2) restoring ecosystems that accumulate carbon, (3) modifying agricultural and forestry management practices to reduce emissions and increase carbon sequestration, or (4) converting habitat to store additional carbon in aboveground biomass (e.g., afforestation). For each LBMS, we compiled data on their geographic constraints and derived global, binary, high-resolution (~1 km) maps of the area suitable for each mitigation strategy. We then compared these estimates of geographic suitability to identify the number of LBMS that are compatible with the environment of any one location across the Earth's surface, highlighting when overlapping land potentials could result in hotspots of climate mitigation opportunities or potential conflicts in the space use of LBMS.

Specifically, we asked (1) how much area is suitable for each climate mitigation strategy given its global geographic and biophysical requirements? (2) How many mitigation strategies are suitable in any one location, and where are overlaps most pronounced? and (3) Which mitigation strategies could compete for space, and which are mutually compatible with one another?

2 | METHODS

We compiled a list of 24 land-based climate mitigation strategies (LBMS) from the literature, defined as approaches that harness

TABLE 1 Land-based climate mitigation strategies, a brief description of their geographic requirements, and a rounded estimate of the intensity of greenhouse gas emissions avoided or atmospheric carbon sequestered per hectare per year, measured in terms of carbon (C) or carbon equivalents (Ce).

Approach to mitigation	Mitigation strategy	Geographic and biophysical requirements	Carbon flux (per hectare per year)
Maintain ecosystems/avoid conversion to avoid emissions	Maintain forests	Unprotected forests without signs of management	>100 Mg C avoided
	Maintain grasslands	Unprotected grasslands, shrublands, and savannas in historically open biomes of temperate, subtropical, and tropical zones (excludes pastures but includes other grazing lands)	10–20 Mg C avoided
	Maintain wetlands	Unprotected global wetlands, including salt marshes and mangroves; primarily coastal but includes some inland wetlands	>100 Mg C avoided
	Maintain peatlands	Unprotected global peatlands	>200 Mg C avoided
Modify forestry & agricultural management to reduce emissions or sequester carbon	Natural forest management (e.g., deferred timber harvest)	Naturally regenerating forests with signs of management (e.g., logging) and planted forests with a long rotation time (>15 years)	<1 Mg C sequestered
	Improved plantations (e.g., biologically optimal rotation lengths)	Even-aged intensively managed timber production forests typically defined by a short rotation time (≤15 years)	<1 Mg C sequestered
	Cropland nutrient management (e.g., reducing over-application of fertilizer)	Global croplands	<1 Mg Ce sequestered
	Regenerative annual cropping* (e.g., applying compost, reducing tillage)	Most annual croplands (excludes ricelands)	<1 Mg C sequestered (Schlesinger, 2022)
	Conservation agriculture* (e.g., cover crops)	Most annual croplands (excludes ricelands, areas that already have winter cover crops, areas with a fallow period, and areas with a late harvest)	<1 Mg C sequestered (Schlesinger, 2022)
	Improved rice cultivation (e.g., periodic draining)	Global ricelands	<1 Mg Ce sequestered
	Integrating trees in croplands	Unforested croplands with high predicted potential for tree cover; excludes silvopastoral systems and ricelands	<1 Mg C sequestered
	Silvopasture	Unforested planted pastures with high predicted potential for tree cover	1–10 Mg C sequestered (Dold et al., 2019; Dube et al., 2011)
	Sowing legumes in pastures	Global planted pastures	<1 Mg C sequestered
	Optimal grazing* (e.g., avoid overgrazing)	Global rangelands and planted pastures	<1 Mg C sequestered
	Improved animal feed* (e.g., energy dense feed to reduce fermentation)	Global rangelands	<1 Mg Ce avoided
	Improved animal management* (e.g., livestock breeding)	Global rangelands	<1 Mg Ce avoided
	Biochar	Global croplands with sufficient crop residue for sustainable biochar production	<1 Mg Ce sequestered
	Enhanced chemical weathering	Croplands, pastures, and plantation forests in wet and warm biomes	1–10 Mg C sequestered (Beerling et al., 2020)

(Continues)

TABLE 1 (Continued)

Approach to mitigation	Mitigation strategy	Geographic and biophysical requirements	Carbon flux (per hectare per year)
Restore ecosystems to historical state to reduce emissions or sequester carbon	Coastal wetland restoration	Degraded/converted mangroves and salt marshes	1–10 Mg Ce avoided, sequestered
	Peatland restoration	Degraded/converted peatlands	1–10 Mg Ce avoided
	Grassland restoration	Croplands and pastures in grassland biomes (excludes the boreal zone)	<1 Mg Ce sequestered (Bai & Cotrufo, 2022)
	Reforestation	Unforested areas in forested biomes with high predicted potential for tree cover (excludes areas with negative effects on albedo)	1–10 Mg C sequestered
Convert land to increase biomass to sequester carbon and/or avoid emissions from fossil fuels	Afforestation	Unforested areas outside of forested biomes with high predicted potential for tree cover (excludes areas with negative effects on albedo)	1–10 Mg C sequestered (Cook-Patton et al., 2020)
	Bioenergy with carbon capture and storage (BECCS)	Areas with a predicted yield of a common bioenergy crop that overlap with or occur within 40 km of a sedimentary basin identified as high priority for carbon capture and storage	1–10 Mg C avoided, sequestered (Gelfand et al., 2020)

Notes: Carbon flux estimates are intended as a means of comparison across the strategies, but large uncertainties remain in the magnitude, temporal, and spatial variation in these estimates. Flux estimates were adapted from Griscom et al. (2017), unless otherwise noted. Nineteen of the strategies listed here were mapped in our analysis (all but those with an asterix). Additional details are provided in Supporting Methods.

*Not mapped.

the processes that occur in vegetation, soils, and ecosystems to reduce greenhouse gas emissions and/or increase negative emissions (Table 1, Supporting Methods). This includes 18 of the 20 ‘natural climate solutions’ as defined and described by Griscom et al. (2017). From the list provided by Griscom et al. (2017), we excluded two strategies that were not mappable: (1) “fire management” due to uncertainties in the spatial extent and long-term carbon benefits of this as a management practice (Buma et al., 2024), and (2) ‘avoided wood fuel harvest’ for cooking and heating because the climate benefits are estimated as a function of the number of people who abandon this practice, not the area where it applies. We also included seven climate mitigation strategies which are not discussed by Griscom et al. (2017) but could be deployed across large spatial extents to help reach net-zero emissions, including regenerative annual cropping (Newton et al., 2020), silvopasture (Jose & Dollinger, 2019), grassland restoration (Bai & Cotrufo, 2022), afforestation (Doelman et al., 2020), enhanced chemical weathering (Beerling et al., 2020), and bioenergy crop production paired with carbon capture and storage (BECCS) (Babin et al., 2021).

Five of the mitigation strategies could not be mapped due to insufficient spatial resolution of their potential distributions (Supporting Methods): regenerative annual cropping, conservation agriculture, optimal grazing, improved animal feed, and improved animal management. We nonetheless retained these LBMS in Table 1 because previous studies have reported the maximum global extent suitable for each strategy (Griscom et al., 2017), and most of these are complementary to those which we were able to map (e.g., optimal grazing and improved animal feed/management complements other grassland conservation and management strategies, Supporting Methods).

For the remaining 19 LBMS, we mapped each strategy's binary global suitability at a 1 km resolution. Suitability is defined using reasonable, strategy specific rules applied to the Earth's current climate system and distribution of land cover (Table 1, Supporting Methods). Given uncertainties in the environmental and socioeconomic factors that may influence the feasibility and efficacy of mitigation (Babin et al., 2021; Bai & Cotrufo, 2022; Calabrese et al., 2022; Moinet et al., 2024; Seddon, 2022; Seddon et al., 2020), we map LBMS opportunities given present-day conditions in the absence of socioeconomic constraints, and with only minor technical constraints on LBMS that have yet to be tested at scale (e.g., BECCS, enhanced weathering, and biochar). We take this approach because the feasibility of and demand for LBMS varies substantially given different climate, technological, and socioeconomic scenarios (Chen et al., 2022; IPCC, 2022), as well as different model assumptions for predicting future outcomes (O'Neill et al., 2016). For example, future demand for LBMS can be predicted, and to some degree mapped, using coupled climate, economic activity, and land-use models, known as integrated assessment models (IAMs). IAMs are valuable tools for exploring potential futures, but IAMs predict land use/land cover change at coarse spatial resolution (10–50 km) and for only a small number of simplified land cover types (Chen et al., 2022). IAMs are thus most useful for mapping particular LBMS in the context of broad-scale drivers of land-use change (Zheng et al., 2022), such as changes to forest cover (Chen et al., 2022) or demand for bioenergy (Daioglou et al., 2019). IAMs are less useful for allocating land to more novel and/or spatially constrained LBMS, for which the high resolution of present-day spatial data provides the opportunity to map their near-term potential. Furthermore, regardless of what socioeconomic assumptions define the feasibility of implementing a mitigation strategy, implementation is first and foremost contingent on the area that is currently geographically and biophysically suitable. We therefore focus on this geographic and biophysical suitability question, acknowledging that many additional feasibility constraints, and ongoing climate change, affect the extent to which LBMS are implemented within the area of suitability we map.

2.1 | Map derivation overview

All spatial data were compiled or derived from existing datasets, which included remotely sensed products of land cover type (Buchhorn et al., 2020) and land use intensity (Lesiv et al., 2022), historical land cover changes (Bunting et al., 2022; Campbell et al., 2022), and predictions of suitability based on contemporary geographic and climatic conditions (Bertagni & Porporato, 2022; Li et al., 2020). To define suitability for individual mitigation strategies as well as the degree of land conversion that would result from implementing a strategy, we first derived a basemap of discrete land cover types using the International Union for Conservation of Nature (IUCN) habitat classification scheme (Jung et al., 2020) applied to Copernicus land cover data (Buchhorn et al., 2020). We assigned pixels with >50% of a land cover type as one of cropland, grassland (including shrubland and savanna), pasture, forest, plantation, wetland, peatland, or mosaic vegetation (>50% of some combination of the former land cover types). Areas outside of these land cover types are small fractions of mosaic vegetation, deserts, rocky areas, urban areas, or part of the built environment (Jung et al., 2020); we included mosaic vegetation but considered the other surfaces unsuitable for LBMS (Supporting Methods) given both their geography and as a safeguard for human habitation in built environments (Walker et al., 2022).

All subsequent mapping was harmonized to the extent, resolution, and native coordinate system of the basemap, following Jung et al. (2020): ~1 km World Geodetic System 1984. Any dataset that was not provided at this resolution or coordinate system was resampled and projected using bilinear interpolation (Supporting Methods). All maps were then discretized (Supporting Methods) and masked to terrestrial Earth using ESRI's World Countries shapefile (Table S1).

We handled potential conflicts between LBMS and biodiversity and food security as follows. We excluded protected areas (UNEP_WCMC and IUCN, 2019) from maintenance LBMS and from any LBMS that would cause a change in land cover type (e.g., afforestation, BECCS) although we included protected areas when mapping ecosystem restoration. We determined protected areas using categories I–IV in the World Database on Protected Areas (UNEP_WCMC and IUCN, 2019), which encompass geographic units designated for the long-term conservation of species and which are protected from human disturbance and associated land-use change. Categories V and VI allow for development and resource extraction, and thus, we consider these areas suitable for LBMS, as we do for all other unprotected ecosystem types. The exclusion of protected areas serves as a biodiversity safeguard and excludes areas which are least likely to undergo anthropogenic land-use change. Safeguarding food production is critical for protecting human livelihoods; however, we do map suitability for certain LBMS in croplands and pastures (e.g., reforestation, afforestation), because the rates and causes of cropland abandonment are uncertain and spatially heterogeneous (Potapov et al., 2022), and abandonment could be incentivized under future climate policies and programs. Due to a lack of adequate spatial data (Erb et al., 2016), we were not able to delineate rangelands from global grasslands in our basemap. We are therefore not able to consider conflicts with livestock management. In our analysis, we focus on potential conflicts among LBMS, but we acknowledge that conflicts with food, timber, and other products needed for human livelihoods are important considerations when deploying LBMS.

Map derivations and analyses were done using the “terra” package in R (Hijmans et al., 2023). Individual data sources, map derivation, and validation are described briefly below and in detail in Table S1 and Supporting Methods. Output maps for each mitigation strategy are openly available on figshare at https://doi.org/10.6084/m9.figshare.24933312 (Beaury, 2024b), as is the code for processing all input layers, generating strategy maps, and testing sensitivity: https://doi.org/10.6084/m9.figshare.26980447 (Beaury, 2024a). We discuss the accuracy and uncertainty associated with each of the input datasets in Supporting Methods.

2.2 | Individual maps

2.2.1 | Maintaining forest, grassland, wetland, and peatland habitat

To map strategies that reduce business-as-usual greenhouse gas emissions by avoiding ecosystem conversion/maintaining the current ecosystem type (and its continued uptake of CO_2) (Table 1), we used current distributions of unprotected forest, grassland, and wetland habitat types (Jung et al., 2020; UNEP_WCMC and IUCN, 2019). To map forest maintenance, we focused on forested pixels without signs of management (Lesiv et al., 2022) (managed forests are considered suitable for natural forest management or improved plantations, described below). For grassland maintenance, we mapped grassland, shrubland, and savanna pixels in non-forested biomes (Dinerstein et al., 2017), assuming these represent historically intact natural grasslands (we assume grasslands in forested biomes reflect the loss of forest due to human land use (Hansen et al., 2013), and would therefore be suitable for reforestation, described below). To map peatland maintenance, we overlaid a recent study of peatland extent (Leifeld & Menichetti, 2018) onto the Jung et al.'s (2020) distribution of wetland habitat types, with remaining wetlands and mangroves mapped as wetland maintenance. For all habitat types except peatlands, which cover large parts of the boreal zone, we focus on habitat maintenance in temperate, subtropical, and tropical climate zones, where loss from human activity is most likely (Griscom et al., 2017; Tyukavina et al., 2015).

2.2.2 | Cropland nutrient management, sowing legumes in pastures, improved rice cultivation, and biochar

To identify croplands and pastures suitable for the aforelisted strategies, we used distributions of arable croplands (Jung et al., 2020), crop type (Monfreda et al., 2008), and planted pastures (Jung et al., 2020). Following Griscom et al. (2017), we assumed each of the LBMS could theoretically apply to the full extent of the focal crop type. Ideally, we would exclude areas already devoted to these cropland LBMS, but these LBMS cannot be detected using satellite land cover data (Supporting Methods). Thus, it is possible that we map some croplands/pastures that are already being utilized for mitigation. To map suitability for biochar, we used a recent study that mapped agricultural areas with enough crop residues to sustainably produce biochar with minimal biomass transport, without reducing soil fertility, and without diverting crop residues from the livestock industry (Karan et al., 2023).

2.2.3 | Natural forest management, improved plantations, integrating trees in croplands, silvopasture, reforestation, afforestation

To map natural forest management and improved plantations, we used global forest management data to classify different intensities of forest management (Lesiv et al., 2022). We classified natural forest management as applicable to naturally regenerating forests with signs of management and planted forests with long rotation times (>15 years). We assumed improved plantation management applies to forests intensively managed for timber production (rotation times <15 years). For integrating trees in croplands and silvopasture, we combined Jung et al. (2020) with a predicted layer of global tree potential (Bastin et al., 2019), identifying croplands and pastures with high potential for added forest cover. We also used global tree potential (Bastin et al., 2019) and a global map of biome types (Dinerstein et al., 2017) to identify areas suitable for reforestation (restoring tree cover in forested biomes) and afforestation (adding tree cover to historically open biomes). For both reforestation and afforestation, we excluded areas where added tree cover would negatively affect albedo to an extent that reforestation/afforestation would have a net warming effect (further described in Supporting Methods) (Hasler et al., 2024).

2.2.4 | Grassland, peatland, and coastal restoration

To map grassland restoration, we assumed croplands and pastures in historically open biomes could be restored back to grassland. Maps of peatland and coastal wetland restoration were derived from global products on remotely sensed land cover change (Bunting et al., 2022; Campbell et al., 2022; Leifeld & Menichetti, 2018).

2.2.5 | Enhanced weathering and BECCS

Maps of enhanced weathering and BECCS are based on theoretical environmental potentials and some infrastructure constraints, but we acknowledge that additional technical limitations will play a significant role in where each of these strategies will ultimately be placed (Slade et al., 2014). We mapped enhanced weathering in areas with a theoretical potential for carbon capture given temperature and aridity (Bertagni & Porporato, 2022), and restricted these areas to land cover types where the habitat structure and management is suitable for mechanically spreading the minerals (croplands, pastures, planted forests).

To map BECCS, we integrated data on predicted yields of common purpose-grown bioenergy crops (Li et al., 2020) and maps of onshore and offshore sedimentary basins identified as high priority for carbon capture and storage (CCS) (Bradshaw & Dance, 2005; Turner et al., 2018). It is possible that bioenergy crop production is implemented without CCS (Gelfand et al., 2020; IPCC, 2022) or that new transmission pipelines could transport CO_2 over long distances to reach an injection site (Turner et al., 2018). However, without CCS, the mitigation potential of bioenergy drops substantially (Gelfand et al., 2020), and we currently lack the infrastructure for cost-effective, long-distance CO_2 transport (Turner et al., 2018). We therefore restrict bioenergy potential to areas that are (1) suitable for purpose-grown bioenergy crops and (2) located within 40 km of a sedimentary basin suitable for CCS (Albanito et al., 2019). Keeping with previous work (Albanito et al., 2019; Hastings et al., 2017; Turner et al., 2018), we assume that, within this buffer, the biomass or captured CO_2 from bioenergy could be sustainably transported for geological storage.

To estimate spatial overlap, all maps were discretized. For most maps, suitable areas were classified based on the discrete basemap and land cover classes described above (e.g., maintaining grassland ecosystems applies only to the discrete grassland pixels). Several maps required thresholding to convert continuous values into a binary classification. Thresholds followed conventional rules for classifying remotely sensed data (e.g., classifying forests as areas with >30% canopy cover) (Hansen et al., 2013) or were selected to align with the total expected global area given the input dataset (Yuan et al., 2021). For example, the extent of rice cultivation on Earth is estimated at 165 Mha (Griscom et al., 2017; Yuan et al., 2021). To identify areas under rice cultivation, we discretized continuous data on crop harvest (Monfreda et al., 2008), selecting pixels where >25% of the harvested area was rice. This resulted in a global extent matching the expected area provided by other sources. At finer spatial scales, the few maps that required thresholding (see Supporting Methods) are inherently sensitive to the threshold rules used to derive them (e.g., a lower tree cover threshold for reforestation increases the area for this LBMS); however, the basemap dictating the LBMS distributions is well resolved (Jung et al., 2020), and thus, we expect the large-scale patterns to hold regardless of the details of individual datasets. We explore sensitivity to thresholds in the Supporting Methods (Figures S1–S4).

2.3 | Spatial data analysis

We estimated the total spatial extent (in millions of hectares, Mha) and distribution of the area suitable for each strategy. We also estimated the spatial overlap in suitable area among all, and between each pair of LBMS. For the first overlap analysis, we stacked the 19 maps of mitigation strategies to estimate the total number of strategies suited to the geography of each 1 km grid cell across the globe, highlighting areas where there are multiple choices for which LBMS to deploy. We conditioned the number of LBMS possible in each location depending on whether the strategy applies to what is currently classified as cropland, forest (including natural, managed, and plantation forests), wetland, peatland, pasture, or grassland (including shrublands and savannas).

To quantify the opportunity cost associated with scaling up a mitigation strategy, we estimated the area of intersection between pairs of LBMS. We identified both the absolute and percent overlap between each pair of mitigation strategies. The absolute overlap is equal to the total land area that is geographically suitable for both members of the pair. To then estimate percent overlap for a given LBMS, we divided the absolute area of its overlap with another strategy by the total area over which the focal strategy could be applied. Doing so allowed us to assess how much an intersecting solution overlaps the total area suitable for a focal solution.

As a first approximation of trade-offs that could ensue from LBMS, we classified each pair of overlapping strategies as mutually compatible (both can be applied to the same landscape, assuming each would maintain climate mitigation benefits) or conflicting (mitigation strategies cannot be applied to the same area due to incompatible infrastructure or management needs).

Given the 1 km scale of the data, we focus on trade-offs in the context of land cover change. Pairs are assumed to be compatible if both LBMS modify management without changing the existing land cover type, such as applying enhanced chemical weathering to soils in plantation forests (Larkin et al., 2022) or the joint deployment of biochar and enhanced chemical weathering in croplands (Honvault et al., 2024). Pairs are also considered compatible if the management strategies apply to different pools of greenhouse gases (e.g., one LBMS increases soil carbon sequestration while the other increases aboveground carbon storage). Pairs are assumed to be conflicting if the LBMS would result in different trajectories of land use change, such as the conflict between restoring the land to a more natural state versus continuing to manage the land for agriculture. At finer resolutions, additional environmental trade-offs could limit compatibility or result in other LBMS opportunity costs (e.g., lower water availability or reduced yield when tree cover is added to croplands), but these are highly context specific as well as spatially and temporally variable, and thus untenable to include given the current scope of the study. Future studies should further explore the extent to which LBMS have additive, antagonistic, or synergistic climate benefits. Our process for defining pairs as non-overlapping, compatible, or conflicting is more thoroughly described in Supporting Methods.

3 | RESULTS

The global area suitable for each of the 19 LBMS varies substantially (Figure 1), with some of the mitigation strategies with the greatest impacts on greenhouse gas fluxes constrained to small geographic areas (e.g., maintaining peatland habitat and peatland restoration). Due to their biophysical requirements, LBMS are non-randomly distributed across land cover types, continents, and climate zones (Figures S5–23). For example, enhanced chemical weathering could occur throughout temperate and tropical zones but is concentrated in biomes with high precipitation (Figure 1a,e,g, tropical China and India). Bioenergy with carbon capture and storage (CCS) is determined by the location of sedimentary basins for CO_2 storage. This includes onshore basins throughout South America, Indonesia, and the temperate zone and offshore basins that could allow for bioenergy cropping along the western coasts of Africa and small regions of Australia (Figure 1b). In croplands, integrating tree cover while maintaining food production is environmentally suitable in many regions of the Earth (Figure 1c), with the highest density of potential in the midwestern United States and temperate Europe.

3.1 | Global overlaps

After overlaying the spatial potential for each LBMS, we estimate a maximum global area suitable for mitigation strategies equal to 8.56 billion ha of the Earth, or ~57% of the global land area (Figure 2). This includes 3.36 billion ha of overlapping LBMS (i.e., suitable for more than one mitigation strategy, indicating a choice among which to deploy) and 5.20 billion ha of non-overlapping LBMS (i.e., suitable for only one of the analyzed LBMS). In the overlapping region, 17% of the area is only suitable for compatible LBMS, whereas the other 83% includes at least one conflicting pair of strategies. In the non-overlapping region, the majority of the area corresponds to the maintenance of the current ecosystem (61%), where habitat protection can avoid future emissions and no other LBMS are suitable.

Given the non-random and differing distributions of individual LBMS, overlaps are also non-randomly distributed (Figure 2). For example, due to the large number of LBMS that can be implemented in agricultural settings (Table 1), croplands and pastures were most commonly identified as areas with multiple choices for which LBMS to deploy. This includes, for example, the Great Lakes region of North America, croplands in China, and pastures in Madagascar, where up to six or seven LBMS overlap (Figure 2). This high degree of overlap includes multiple compatible management strategies that

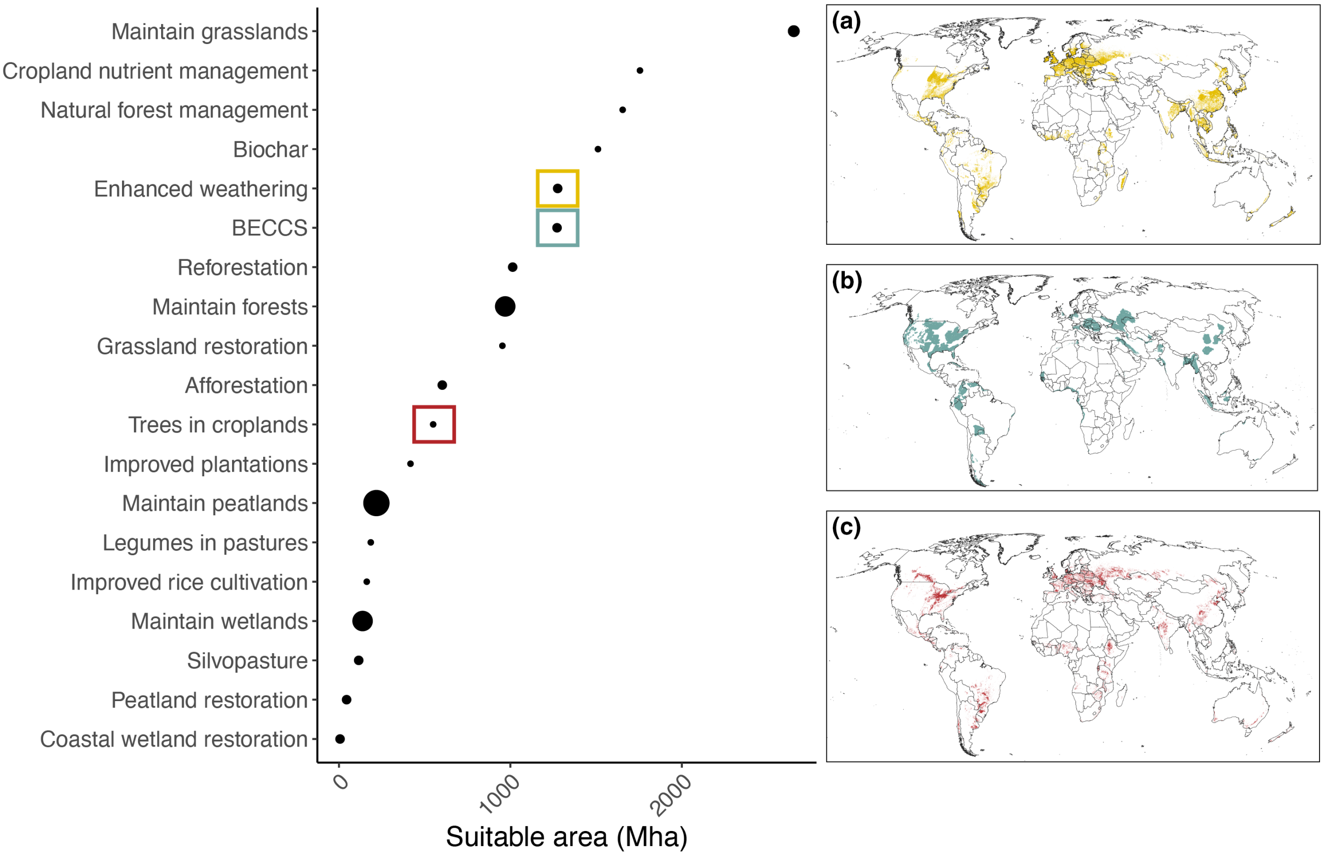

FIGURE 1 The global land area geographically suitable for each mitigation strategy, in millions of hectares. Area estimates do not account for spatial overlaps among LBMS or socioeconomic feasibility constraints. Example distributions are shown by the inset maps for (a) enhanced chemical weathering, depicting croplands, pastures, and plantation forests within suitable environmental conditions; (b) bioenergy with carbon capture and storage (BECCS), depicting areas suitable for one of five common purpose-grown bioenergy crops that occur within 40 km of a saline sedimentary basin for CO_2 storage; and (c) integrating trees in croplands, depicting croplands that have a high predicted potential for added tree cover. Points are scaled to highlight variation in mean greenhouse gas flux estimates, measured in units of carbon or carbon equivalents (Table 1). Map lines delineate study areas and do not necessarily depict accepted national boundaries.

could potentially be added to the same landscape. For example, up to 19% of croplands are suitable for increased tree cover, enhanced weathering, and biochar (Figure S24). Up to 42% of pastures are suitable for silvopasture, enhanced weathering, optimal grazing, and sowing legumes as cover crops (Figure S25). Many of these croplands and pastures could also be converted to BECCS, afforestation, or restored to grassland.

Locations with three or more mitigation strategies are less common in forests, grasslands, wetlands, and peatlands (Figure 2 barplot). In forests, the maximum number of LBMS occurs in plantations suitable for enhanced weathering and bioenergy with carbon capture and storage (BECCS). This occurs, for example, in the southeastern United States, coastal Nigeria, and Europe (Figure 2). In grasslands excluding pastures, the areas with three or more strategies most often involve overlap between maintaining extant grasslands, BECCS, and afforestation (e.g., western United States, parts of Brazil, Africa south of the Congo Basin).

As noted above, excluding areas of overlap, we estimate 5.20 billion ha where only one of the analyzed LBMS is suitable. This area is dominated by an opportunity to maintain the carbon that is already stored in grasslands (i.e., avoiding emissions from historical rates of habitat conversion), followed by suitability for natural forest management (Figure 3). Eleven additional LBMS are suitable in portions of land that do not overlap with the other strategies, including a large area of suitability for reforestation in the tropics and subtropics and maintaining wetlands and peatlands in northern latitudes. In total, 3.18 billion ha of the non-overlapping region is suitable for emissions avoided from habitat maintenance (Figure 3 Maintain Ecosystems), whereas 2.02 billion ha are suitable for LBMS that contribute to emissions reductions or carbon sequestration (Figure 3 blue, green, and purple regions).

3.2 | Opportunity costs of land-based mitigation

The absolute and percent overlap between each pair of mitigation strategies varies depending on whether the mitigation strategy involves maintaining, managing, converting, or restoring land (Figure 4), the total extent available to each strategy in the pair, and their geographic co-variation. Many pairs of mitigation strategies do

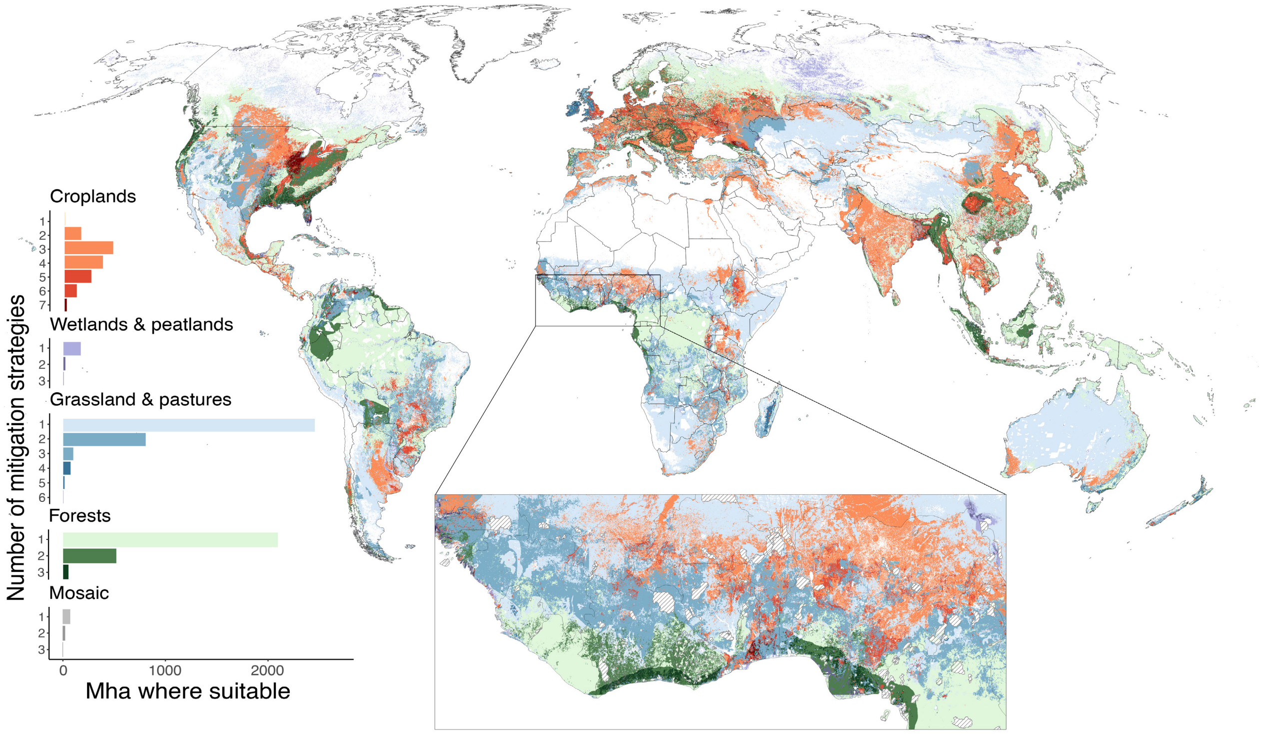

FIGURE 2 The number of land-based mitigation strategies (LBMS) that are suitable in any one area, delineated by the current land cover type. Land cover types include croplands, wetlands and peatlands, grasslands (including shrublands and savannas) and planted pastures, forests (including natural, managed, and plantation forests), and mosaic vegetation. Darker colors indicate that a higher number of strategies overlap in that region, and these can include compatible and/or conflicting strategies. Legend bars represent the total area (in millions of hectares) suitable for that number of LBMS, highlighting the large area of overlapping LBMS in croplands and pastures, and the non-overlapping area in forests, grasslands, wetlands, and peatlands. The inset map highlights the spatial variation and fine resolution (~1 km) of suitability for climate mitigation in West Africa. Protected areas are denoted by hashed polygons and were excluded from most maps of LBMS. Map lines delineate study areas and do not necessarily depict accepted national boundaries.

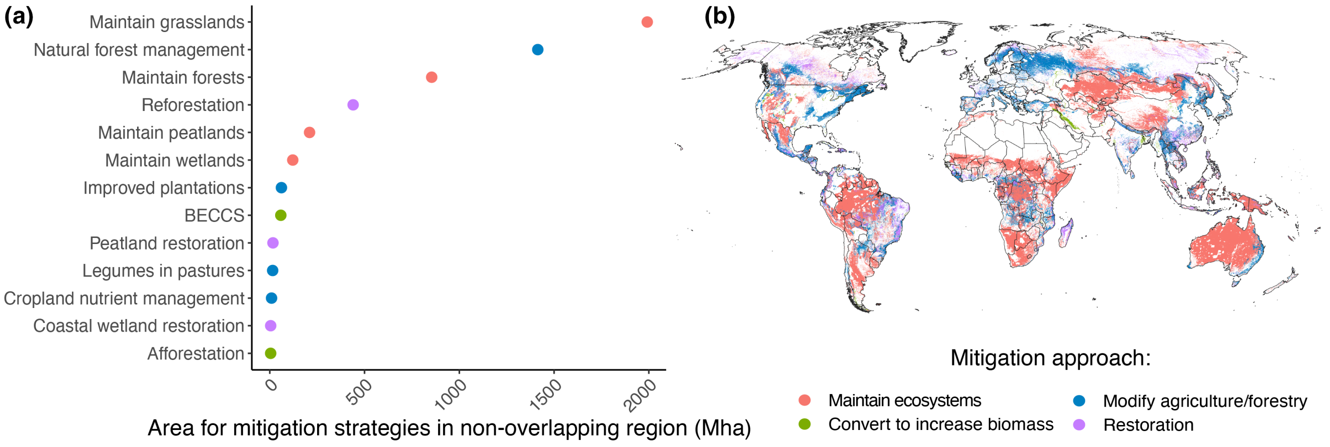

FIGURE 3 The global area (a) and distribution (b) of the 13 land-based mitigation strategies that occur in the non-overlapping region of suitability for LBMS (i.e., where only that strategy is suitable). Colors denote which approach to climate mitigation is suitable. Map lines delineate study areas and do not necessarily depict accepted national boundaries.

not overlap by definition, given that current habitat types are defined as mutually exclusive at the 1 km scale and we assume these habitat types are static in the short term (e.g., we do not allow for cropland LBMS to be deployed outside of existing agricultural areas).

Conflicting LBMS account for the majority of intersections between strategies. The major conflict is between applying LBMS to existing agricultural lands ('Modify' in Figure 4, i.e., maintaining this land as agriculture but modifying its management) or converting these lands for restoration ("Restore" in Figure 4). If biochar, for example, is to be deployed across its full extent, these lands would be maintained as agriculture, and thus, opportunities for restoration would be reduced by up to 42% for peatlands, 80% for grasslands,

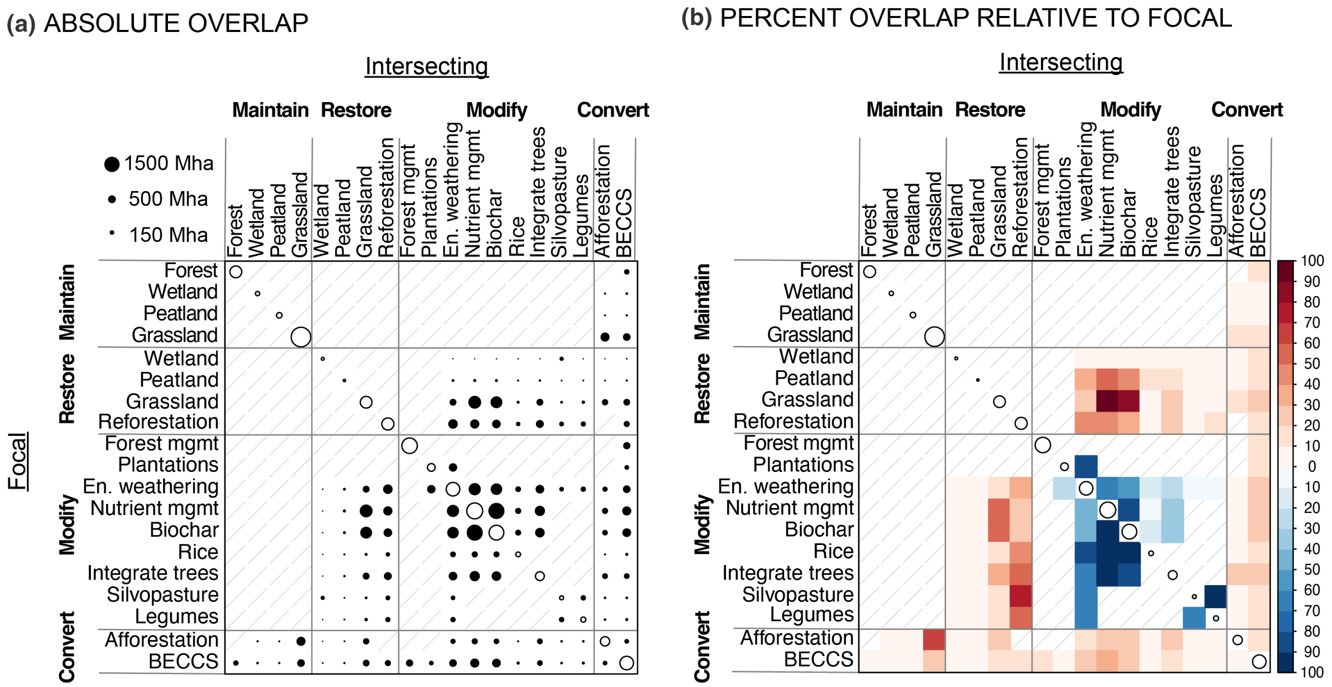

FIGURE 4 Pairwise overlap between land-based mitigation strategies. (a) The absolute area, scaled to Mha, where each pair of mitigation strategies is suitable across the globe. (b) Percent overlap, measured as the area of overlap from panel (a) divided by the total area suitable for the focal strategy listed in the rows (e.g., the suitable area for enhanced weathering, the intersecting strategy, overlaps with ~80% of the suitable area for improved plantations, the focal strategy). Because panel (b) presents intersections relative to the focal strategy, the plot is asymmetric across the diagonal. Blue intersections indicate compatible LBMS that can both be deployed in the same area, whereas red intersections indicate conflicting LBMS in which there is a choice between one or the other (Supporting Methods). In both plots, the circles along the diagonal are scaled to the total area suitable for the focal strategy (Figure 1) and grey lines indicate strategies that, by definition, do not overlap across space (e.g., reforestation cannot be applied to areas that are already forested). Strategies are grouped based on their approach to mitigation (Table 1)—maintaining ecosystems, restoring ecosystems, modifying agriculture and forestry management, and converting land to bioenergy or afforestation.

and 43% for forests. On the other hand, if reforestation is prioritized across its extent, it could significantly preclude opportunities for maintaining and modifying the management of agricultural lands, such as hybridizing agriculture via integrating tree cover into croplands (55%) or silvopasture (75%).

Converting land to bioenergy with carbon capture and storage (BECCS) or afforestation intersects with all other LBMS. But given the large extent of land that is suitable for ecosystem maintenance or for modifying agricultural lands, these intersections are only in the 10%–30% range. Even so, BECCS and afforestation are the only strategies that could conflict with maintaining extant ecosystems, meaning that their deployment could convert land currently storing carbon in the natural state of the ecosystem. Although for forests, wetlands, and peatlands, the absolute and proportional intersections with BECCS and afforestation are small, for unprotected grasslands, the intersections are much larger (Figure 4a). In fact, if suitable areas for afforestation were fully realized, it would convert up to 16% of unprotected grassland area. Similarly, BECCS intersects with 11% of grassland maintenance (Figure 4b), representing a large absolute area equal to 279 Mha of land (Figure 4a). Conversely, if maintaining extant grasslands was prioritized over the intersecting LBMS, the area available for afforestation and BECCS would be reduced by 69% and 22%, respectively (Figure 4b bottom rows).

Although conflicting pairs of strategies predominate, mutually compatible strategies were common among the various land management options (pairs within the "Modify" category). Specifically, 13 pairs of mutually compatible strategies occur across LBMS that involve modifying cropland, pasture, and forest management (Figure 4b). For example, enhanced chemical weathering can be added to a maximum of 83% of the area for improved plantations, 68% of areas where tree cover can be integrated into existing croplands, and up to 60% of areas suitable for sowing legumes in pastures. These proportional overlaps also represent large areas of the Earth in absolute terms (Figure 4a), meaning that mitigation can result from multiple strategies for adapting agricultural and forest management over much of the Earth's surface.

4 | DISCUSSION

Reducing global climate change to reach a net-zero emissions economy requires dramatic cuts to greenhouse gas emissions from the energy and agricultural sectors alongside increases in land-based climate mitigation (Griscom et al., 2017; IPCC, 2022; Seddon, 2022). To provide a synthesis of the land requirements and geographic constraints for the diversity of land-based approaches for reducing climate change, we (1) assembled spatially explicit estimates of the area of opportunity for 19 LBMS across the globe and (2) provided key messages from those estimates, including cases where scaling up one mitigation strategy might have consequences for the deployment of others.

Importantly, we estimated more than eight billion hectares of terrestrial Earth that is geographically suitable for one or more LBMS. Much of this area is only suitable for maintaining the current ecosystem type, and thus avoiding business-as-usual greenhouse emissions rather than removing atmospheric carbon. Even so, our area estimates likely exceed the global demand for land-based mitigation. U.N. member countries have pledged closer to 1 billion hectares for implementing LBMS (Dooley et al., 2023; IPCC, 2022), and for individual strategies, our area estimates fall toward the upper bound of land needed to mitigate climate change to <2°C by 2100 (IPCC, 2022; Smith et al., 2016). For example, to achieve a climate close to this goal following socioeconomic pathways S1–S5, the IPCC estimates between 150 Mha and 800 Mha needed for energy crops and 600–1500 Mha needed for increased forest cover (IPCC, 2022). We mapped a suitable area greater than these estimates, with ~1300 Mha for BECCS and ~1600 Mha for reforestation/afforestation (Figure 1). But as our analysis demonstrates, overlaps within this area of suitability make clear that society faces choices for scaling up land-based climate mitigation. To facilitate this decision-making, we show which strategies can be deployed across the globe and when overlapping strategies complement or conflict with one another.

Although we provide these data products at a relatively high resolution (1 km), our approach focuses on biophysical and geographic variables as the primary constraints on the mapped LBMS. In practice, the implementation of LBMS will be much further constrained by factors such as the current land use, its associated land tenure, and socioeconomic factors (Dooley et al., 2023; Smith et al., 2013). Importantly, we were not able to map rangelands, and thus, we were not able to quantify how much of the suitable area for LBMS could conflict with the livestock industry. Most climate mitigation scenarios expect some reduction in the extent of land used for agriculture (IPCC, 2022), but without major societal changes or incentive programs, land conflicts between LBMS and livestock management may stall mitigation efforts. Furthermore, we only consider mitigation strategies that rely on plant and soil processes to remove or offset emissions. Other demands on land for reducing climate change will come from technological solutions, such as the large area of land needed for the deployment of solar and wind energy. These technological solutions can be difficult to analyze at scale, are much more constrained by heterogeneous energy demand, and thus, their geographic placement is still uncertain (Seddon, 2022; Seddon et al., 2020). Future work is needed to understand the extent to which additional land-use conflicts affect LBMS implementation in the suitable areas we map.

We found that suitable areas for land-based climate mitigation—including individual strategies and their overlaps—are spatially biased given the Earth's non-random distribution of land-use types. For example, several mutually compatible LBMS are suitable in similar agricultural areas, including in particular, croplands and pastures in the eastern United States, throughout Europe, and in southeast Asia. It remains unknown how applying multiple LBMS in the same landscape affects greenhouse gas fluxes associated with any one strategy, but most of the pairs of compatible strategies we explore here would reduce emissions or increase storage in different pools of carbon or other greenhouse gases (e.g., soil carbon vs. carbon stored in aboveground biomass), and thus, we would expect these rates to complement one another (Kantola et al., 2017). By contrast, in natural forests, wetlands, and peatlands, maintaining the habitat is often the only suitable mitigation strategy. While, in principle, one could deploy other LBMS in these habitat types, the loss of naturally stored carbon from land-use change would rarely result in net carbon removals (Guo & Gifford, 2002; Harris et al., 2015). These habitat conversions are thus not considered LBMS in this paper. Indeed, at a global scale, we find that maintaining the current distribution of ecosystems accounts for the majority of the area where only one mitigation strategy is geographically suitable. Although ecosystem maintenance only minimizes emissions from land conversion that would otherwise occur, habitat loss from different types of land-use change (e.g., urbanization, agricultural expansion) remains an important source of emissions (Allan et al., 2022; Davis et al., 2020). Thus, protecting existing ecosystem carbon pools should be a top priority for mitigating climate change (Cook-Patton et al., 2021; Walker et al., 2022).

Global opportunities for restoration are also key to mitigating climate change, and here we provide spatial estimates for where restoration could be implemented to restore forests, grasslands, peatlands, and coastal wetlands (Figure S18–S21). We also show where scaling up alternative mitigation strategies could displace opportunities for restoration, such as incentivizing novel cropland management strategies (e.g., enhanced weathering, biochar), and BECCS to a lesser degree (Figure 4b). The economics of food production in these regions will likely be the deciding factor. In particular, the area we map as suitable for restoration likely further conflicts with rangeland management, although we were not able to quantify this overlap in the present study. Even so, many nations have pledged to restore large extents of ecosystems (Dooley et al., 2023), and here, we show where that could be implemented, including reforestation throughout China and Brazil, peatland restoration in northern Europe, and coastal wetland restoration in Central America.

Together, our results highlight important choices that governments and local communities must make in order to scale up land-based climate mitigation. We identify some opportunities where LBMS could work in concert, especially on agricultural land, but we find that LBMS are often in conflict with one another. A key take-home from our analysis is that incentives for increasing the land area for a particular LBMS, such as policy initiatives that encourage bioenergy with carbon capture and storage (Boysen et al., 2017; IPCC, 2022; Robertson et al., 2017), should carefully consider the opportunity cost of reducing the land available to alternative approaches (e.g., better land stewardship). These opportunity costs may be unavoidable in many locations and will certainly have broad implications for not only climate change but also for global biodiversity and human livelihoods.

The collection of maps assembled here, synthesized from high-quality data and models on the geography of land-based climate mitigation, serves as an important resource for future studies on how and where we allocate land to meet varying demands on LBMS. Nonetheless, several limitations are worth noting and provide room for further exploration. For example, greater uncertainties are associated with emerging LBMS, such as enhanced chemical weathering and BECCS, and the underlying datasets used to map these are often at a coarser spatial resolution (Bertagni & Porporato, 2022; Li et al., 2020). The area available to restoration and to several of the cropland management strategies is likely to be overestimated given a lack of data on current land-use practices (Bai & Cotrufo, 2022; Leifeld & Menichetti, 2018; Schlesinger, 2022). More generally, remote sensing products tend to underestimate the extent of certain land cover types used to map LBMS, such as wetlands, pastures, and other types of grazing lands (Erb et al., 2016; Jung et al., 2020). This would lead the current study to underestimate the potential of strategies applied to these lands. At fine spatial scales, the maps may be sensitive to the limitations of underlying datasets and the rules we used to define suitability (Supporting Methods). However, the sources we used are based on well-validated remotely sensed products, empirical data, and theoretical models (Baruch-Mordo et al., 2019; Dinerstein et al., 2017; Jung et al., 2020). We discuss sources of uncertainty in greater detail in the Supporting Methods, and we expect the spatial patterns and broader take-homes to be robust to minor changes in the input layers.

Finally, we focused on mapping the area where LBMS could *possibly* be implemented, and conflicts/complementarities could *possibly* arise. The probability of different outcomes likely depends on political and socioeconomic factors as much as the biophysical environment (IPCC, 2022; Novick et al., 2022), and for many LBMS, major uncertainties remain in their scalability, durability, and feasibility (Anderson & Peters, 2016; Buma et al., 2024). These uncertainties should be explored in future work. Nonetheless, our analysis provides a key step to estimating how much land is actually suitable for LBMS, with the hope that these data products can guide future studies on optimizing pathways for reducing climate change.

AUTHOR CONTRIBUTIONS

Evelyn M. Beaury: Conceptualization; data curation; formal analysis; methodology; validation; visualization; writing – original draft; writing – review and editing. **Jeffrey Smith:** Conceptualization; methodology; visualization; writing – review and editing. **Jonathan M. Levine:** Conceptualization; funding acquisition; methodology; supervision; visualization; writing – review and editing.

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CONFLICT OF INTEREST STATEMENT

We declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data and code supporting the findings of this study are openly available on Figshare at https://doi.org/10.6084/m9.figshare.26980447 and on GitHub at https://github.com/ebeaury/Land-based-climate-mitigation. Output maps of each mitigation strategy are openly available on Figshare at https://doi.org/10.6084/m9.figshare.24933312. The data sources used to derive maps are listed in Supporting Methods, Table S1.

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SUPPORTING INFORMATION

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