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Protecting irrecoverable carbon in Earth's ecosystems

Allie Goldstein[1]✉, Will R. Turner[1], Seth A. Spawn[2,3], Kristina J. Anderson-Teixeira[4], Susan Cook-Patton[5], Joseph Fargione[5], Holly K. Gibbs[2,3], Bronson Griscom[1], Jennifer H. Hewson[1], Jennifer F. Howard[1], Juan Carlos Ledezma[6], Susan Page[7], Lian Pin Koh[8], Johan Rockström[9], Jonathan Sanderman[10] and David G. Hole[1]

Avoiding catastrophic climate change requires rapid decarbonization and improved ecosystem stewardship. To achieve the latter, ecosystems should be prioritized by responsiveness to direct, localized action and the magnitude and recoverability of their carbon stores. Here, we show that a range of ecosystems contain 'irrecoverable carbon' that is vulnerable to release upon land use conversion and, once lost, is not recoverable on timescales relevant to avoiding dangerous climate impacts. Globally, ecosystems highly affected by human land-use decisions contain at least 260 Gt of irrecoverable carbon, with particularly high densities in peatlands, mangroves, old-growth forests and marshes. To achieve climate goals, we must safeguard these irrecoverable carbon pools through an expanded set of policy and finance strategies.

Scientific assessments provide increasingly strong evidence that global warming in excess of 1.5 °C above pre-industrial levels may trigger irreversible changes to the Earth system, with far-reaching social and economic costs for human societies around the world[1]. Limiting warming to 1.5 °C, according to the Intergovernmental Panel on Climate Change (IPCC), requires the world to slow global emissions immediately and reach net zero carbon dioxide (CO_2) emissions by around 2050. To do this, the IPCC estimates that our remaining carbon budget as of 2017, or the amount of CO_2 we can add to the atmosphere between now and mid-century, is about 420 Gt, equivalent to about 114 Gt of carbon, for a two-thirds chance of staying below 1.5 °C[1]. Given that emissions have not slowed since 2017, as of 2020, this carbon budget will be spent in approximately eight years at current emissions rates[2]. Staying within this carbon budget will require a rapid phase-out of fossil fuels in all sectors as well as maintenance and enhancement of carbon stocks in natural ecosystems, all pursued urgently and in parallel[3–6].

Natural climate solutions, which promote conservation, restoration and improved land management to increase carbon sequestration or reduce emissions from ecosystems and agricultural lands, could provide a quarter or more of the cost-effective mitigation (that is, ≤US$100 per tonne of CO_2e) needed by 2030 (refs. [7–9]). These natural climate solutions focus on either turning down the 'dial' of emissions—for example, by preventing the conversion of ecosystems to other land uses—or turning up the dial on ecosystems' ability to remove CO_2 from the atmosphere via restoration or enhanced productivity. Yet uncertainty remains regarding the responsiveness of various ecosystem carbon stocks to management actions as well as the relative reversibility of their loss. Are there ecosystem carbon stocks that, if lost, could not recover within a timescale meaningful to the remaining carbon budget? Any loss of such 'irrecoverable' carbon stocks would represent an effectively permanent debit from our remaining carbon budget. Ecosystems containing irrecoverable carbon may thus warrant distinct and unwavering conservation strategies akin to the concept of "unburnable reserves"[10] considered for limiting emissions from fossil fuels.

A more explicit characterization of the biological carbon stocks behind ecosystem emissions and removals would help answer critical questions about what actions are needed to proactively manage the biosphere. To what extent can people affect the loss or gain of ecosystem carbon through direct, localized actions? If lost, to what extent can ecosystem carbon be recovered, and is this possible given the short timeframe we have to stay within our carbon budget? What does this tell us about the strategies that should be developed or scaled up to prevent immediate as well as longer-term threats to Earth's manageable carbon stocks? The aim of this Perspective is to apply these questions to broad categories of ecosystems globally and to provide a framework for assessing irrecoverable carbon that could, in future research, be applied at finer scales.

Three key dimensions of ecosystem carbon stocks

Here, we present a framework describing three key dimensions of ecosystem carbon stocks that must be considered when prioritizing actions for climate change mitigation.

- **Manageability at the local scale:** whether an ecosystem's carbon stock is affected primarily by direct human actions that either maintain (for example, conservation), increase (for example, restoration) or decrease (for example, land conversion) its size. This was considered as a binary criterion to narrow our prioritization to those ecosystems that remain within the purview of local land-use decisions.

[1]Conservation International, Arlington, VA, USA. [2]Department of Geography, University of Wisconsin-Madison, Madison, WI, USA. [3]Nelson Institute for Environmental Studies, Center for Sustainability and the Global Environment, University of Wisconsin-Madison, Madison, WI, USA. [4]Smithsonian Conservation Biology Institute, Conservation Ecology Center, Front Royal, VA, USA. [5]The Nature Conservancy, Arlington, VA, USA. [6]Conservation International Bolivia, La Paz, Bolivia. [7]School of Geography, Geology and the Environment, University of Leicester, Leicester, UK. [8]Department of Biological Sciences, National University of Singapore, Singapore, Singapore. [9]Potsdam Institute for Climate Impact Research, Potsdam, Germany. [10]Woods Hole Research Center, Falmouth, MA, USA. ✉e-mail: agoldstein@conservation.org

- **Magnitude of vulnerable carbon:** the amount of carbon likely to be released if the ecosystem is converted—a function of its initial stock, the conversion driver and the vulnerability of its carbon pools.
- **Recoverability of ecosystem carbon, if lost:** the fraction of vulnerable carbon that could be recovered following a conversion event, assessed as a function of time and average sequestration rates. Recoverability can be considered over different timeframes depending on the decision context.

Assessing manageability, magnitude and recoverability

To quantify these three key dimensions of ecosystem carbon stocks we used a typology of ecosystems based on 15 major terrestrial biomes[11], adjusted to include all major marine, freshwater and coastal ecosystems (see Supplementary Fig. 1). We synthesized data on their ecosystem extent, absolute carbon stocks, relative carbon density in biomass and soil organic matter, and rates of carbon loss and gain after land-use conversion or other disturbance. Our analysis uses averages across ecosystems and does not consider non-greenhouse gas (GHG) aspects of climate forcing. Consequently, our results overestimate the climate benefits in boreal forests where carbon storage is at least partially counteracted by low albedo and underestimate the climate benefits of tropical forests that additionally create and regulate rainfall through evapotranspiration[12,13].

Manageability at the local scale. Effective management of the biosphere's climate-stabilizing function requires understanding which ecosystem carbon stocks can be influenced by local decision-making and which are beyond direct control. We assessed ecosystems as either manageable or unmanageable. Unmanageable ecosystems were those for which direct, local actions to increase carbon storage are impractical, unproven or have potential adverse effects, or where changes to carbon stores will be driven primarily by climate change impacts, such as permafrost thaw, rather than local actions. For example, although the open ocean contains 38,000 Gt C (ref. [14]) and absorbs about a quarter of anthropogenic CO_2 emissions[15], there is no practical way, without high risks of negative side effects[16], to change the rate of this carbon uptake. Similarly, the long-term fate of the estimated 1,300 Gt C contained in the permafrost underlying tundra and some boreal ecosystems is tied primarily to the extent of global warming rather than local land-use choices[17,18], though an estimated 65–85% of permafrost thaw can be prevented by achieving a low-emissions scenario (RCP 2.6 compared to RCP 8.5)[19,20]. Other ecosystems whose carbon stocks are not primarily affected by local human decisions were excluded as unmanageable, including rock and ice, deserts, kelp forests, coral reefs, lakes, rivers, and streams (see Supplementary Information, sub-section 'Ecosystem delineation and manageability of carbon stocks').

All other ecosystems met our manageability criterion, meaning that local choices can substantially influence these carbon stocks. Land-use decisions have been the primary driver of changes in carbon stocks in many categories of ecosystems, including most forests[21], grasslands[22], peatlands[23], mangroves, seagrasses and tidal wetlands[24]. Direct human activities may decrease carbon stocks through land conversion (for example, converting a forest to cropland) or increase them through restoration (for example, restoring abandoned fish ponds back to mangroves).

Magnitude of vulnerable carbon. For each ecosystem meeting the manageability criterion, we assessed the magnitude of vulnerable carbon stored both in terms of the global total and on a per-hectare basis (that is, its 'carbon density'; Table 1). We considered carbon in aboveground biomass (AGC; including plant stems, trunks and leaves), belowground biomass (BGC; including roots), and soil organic carbon (SOC) to a depth of 30 cm for upland mineral soils and 1 m for waterlogged peat and coastal systems. These reflected the typical depth vulnerable to most common anthropogenic disturbances[25,26]. Downed wood and leaf litter carbon pools are significant in some forest ecosystems, but we excluded them due to insufficient global data. We identified mean aboveground carbon densities based on a combination of field measurements for forest biomass[27], maps for grassland ecosystems and SOC (ref. [28]), and a literature review for peat and coastal ecosystems (see Supplementary Information, sub-section 'Magnitude of vulnerable carbon stocks'). This high-level assessment found substantial variation among ecosystems,

Table 1 | Estimated magnitude of global carbon stocks by ecosystem, based on geographic extent and average carbon content per hectare

Ecosystem	Global geographic extent (1,000 km^2)	Typical carbon density (t C ha^{-1})[a]	Estimated global carbon content (Gt C)[a]	Recent loss rate (percentage area per year)[c]
Mangroves	145	502	7.3	0.13%
Seagrasses	450	111	5.0	0.95%
Marshes	210	265	5.6	0.25%
Boreal forests	10,700	264	283	0.18%
Temperate broadleaf forests	4,960	268	133	0.35%
Temperate conifer forests	2,410	272	66	0.28%
Tropical dry forests	842	166	14	0.58%
Tropical moist forests	11,700	252	295	0.45%
Boreal peatlands	3,609[b]	500	181	0.00%
Temperate peatlands	185[b]	500	9.3	0.00%
Tropical peatlands	587[b]	504	30	0.60%
Temperate grasslands	5,080	77	39	0.14%
Tropical grasslands	7,000	43	30	0.14%
Montane grasslands	2,600	104	27	0.14%

[a]Typical carbon density is the sum of typical values for aboveground, belowground and soil organic carbon to depths of 30 cm (upland mineral soils) or 1 m (waterlogged peat and coastal systems). [b]The geographic extent of peatlands captured above overlaps with other ecosystems: 56% of the peatland area overlaps with forests and 21% overlaps with grasslands, and 16% underlies croplands or areas of mixed land-use[31]. [c]Forest and mangrove loss rates are based on a 2000–2012 timeframe; loss rates in other ecosystems are not tracked as closely and are based on different timeframes (see Supplementary Table 11).

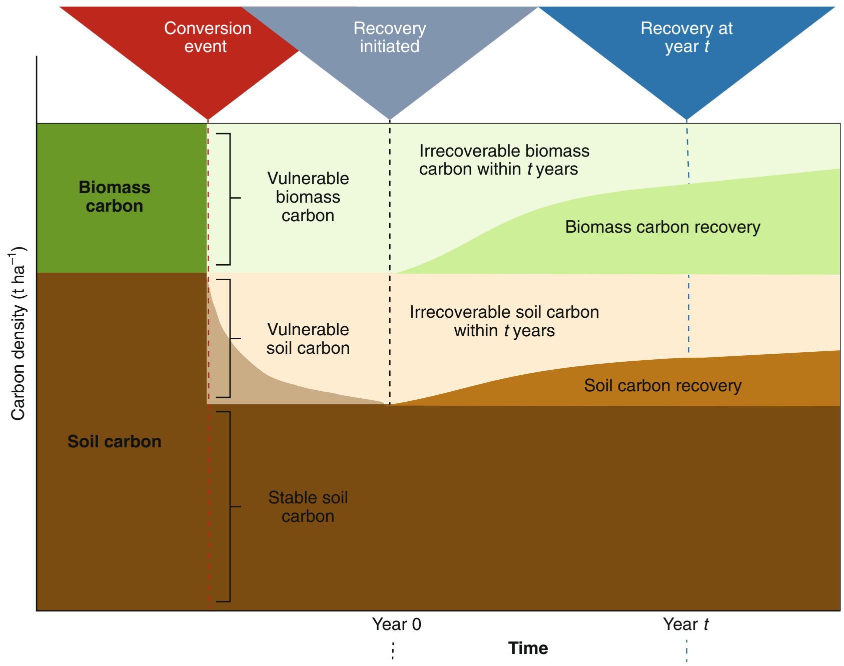

Fig. 1 | Illustration of vulnerable and irrecoverable carbon in a hypothetical terrestrial ecosystem. Recovery of carbon for a typical terrestrial ecosystem in which all of the biomass carbon is lost relatively quickly following a major conversion event (for example, shifting agriculture), whereas only a portion of the soil carbon is lost.

with mean carbon densities ranging from 43 t C ha^{-1} in tropical grasslands[28,29] to 504 t C ha^{-1} in tropical peatlands[30] (Supplementary Table 9). There is also wide variation within each of the ecosystems defined here. We estimated the manageable carbon in ecosystems to be more than 1,100 Gt C, about 350 Gt C of which is in biomass and 750 Gt C in soils at the depths described above.

We then assessed the amount of carbon lost in a typical anthropogenic disturbance event to determine the magnitude of vulnerable carbon. Though ecosystem degradation can drive significant carbon loss even without full conversion to a different land use[31,32], we considered the carbon stock likely to be lost due to the most common land-use changes. Specifically, we assumed that the conversion drivers were (1) agriculture for grasslands, peatlands and tropical forests; (2) forestry for boreal and temperate forests; and (3) aquaculture or development for coastal ecosystems[21,33,34]. These common drivers were used to estimate the maximum 'vulnerable carbon' per hectare by major ecosystem type (Supplementary Table 4).

When conversion occurs, ecosystems typically lose all of their biomass carbon (AGC and BGC) within a short timeframe—under a year in many cases[35]. Conversely, only a portion of an ecosystem's SOC is generally emitted in response to such disturbance, and the ensuing emissions occur over varied but often longer timescales. Across global forests and grasslands, previous studies suggest that, on average, 26% of the SOC contained within the top 30 cm is released to the atmosphere following conversion to agriculture[25], though this sensitivity varies. For mangroves and peatlands, which are typically converted to aquaculture or agriculture by draining and fundamentally changing the hydrology, SOC is more readily lost and is vulnerable at deeper depths. For example, mangrove conversion to shrimp ponds leads to loss of about 80% of the SOC within 1 m (ref. [36]). Peatland conversion, often to oil palm plantations in the tropics, can lead to rapid carbon loss immediately after the area is drained, followed by more gradual loss rates as the remaining SOC oxidizes over time[23]. Because soil carbon loss can occur across a longer, sometimes multi-decadal, timeframe, initiation of restoration within this timeframe can preemptively mitigate some emissions. Intervention before the full loss occurs could effectively reduce the amount of vulnerable carbon and improve prospects for recoverability. However, restoration quickly following conversion is rare, since most land-use changes (for example, to agriculture or aquaculture) persist for many years. Our analysis therefore considers vulnerable carbon to be the amount lost due to conversion assuming full release before recovery is initiated (see Supplementary Table 4).

Recoverability of ecosystem carbon, if lost. Ecosystems differ in the speed at which they recover the carbon lost in a typical disturbance event. To characterize recoverability, we used typical sequestration rates in biomass and soils for different ecosystems. We used recently observed sequestration rates, noting that these rates may change in the future under changing climate conditions for both biomass[37] and soil[38]. For example, forest biomass (AGC and BGC) accumulation is based on 2,790 observations of carbon accumulation in forests across 450 sites[39]. For soil carbon recovery, we applied carbon response functions in temperate forest and grassland soils[40], emissions factors from a meta-analysis in tropical forest and grassland soils[41], and average soil sequestration rates for coastal and peatland soils[42,43], the methodology of which is described in more detail in Supplementary Tables 5–8.

Irrecoverable carbon

These three dimensions allow us to identify ecosystems containing high amounts of 'irrecoverable carbon', which we define as carbon that (1) can be influenced by direct and local human action, (2) is vulnerable to loss during a land-use conversion and (3), if lost, could not be recovered within specified timeframe (t). Following a conversion event, both biomass and soil carbon could recover to some extent, but a portion would remain 'irrecoverable' by year t (Fig. 1). Following loss, recoverability depends on both the sequestration rate and the chosen timeframe (t), with longer timeframes allowing for greater recovery.

Irrecoverable carbon by mid-century. While the concept of recoverability can, in theory, apply to any timeframe, here we primarily consider carbon that could be recovered over 30 years to align with

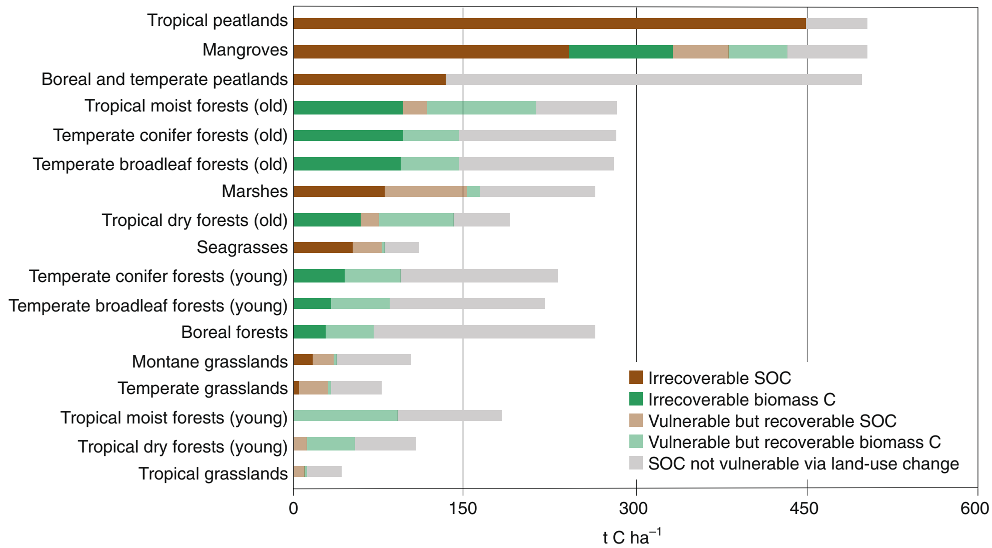

Fig. 2 | Estimated amount of carbon that is recoverable or irrecoverable in major ecosystems within 30 years. Colours distinguish carbon in soil (brown) and biomass (green) pools. Irrecoverable carbon (indicated by dark brown and green shading) is shown separately from carbon that is either not vulnerable (light grey shading) or is vulnerable but recoverable (light brown and light green shading).

the IPCC assessment that global CO_2 emissions must reach net zero by about 2050 to keep the risk of >1.5 °C warming below 66%[3]. Ecosystem carbon that, if lost, could not be recovered by mid-century represents a substantial and underappreciated risk to climate stability because it threatens our ability to reach carbon neutrality in time.

We therefore estimated irrecoverable carbon over a 30-year timeframe across major ecosystems (Fig. 2). Based on typical carbon stocks and recovery rates, tropical grasslands and young tropical forests have the potential to recover the full magnitude of their vulnerable carbon within 30 years. All other ecosystems harbour some proportion of carbon that, if lost, is irrecoverable within that timeframe. The amount and proportion of irrecoverable carbon differs across ecosystems, with boreal forests, for example, averaging 28 t C ha^{-1} and tropical peatlands 450 t C ha^{-1}. Compared to tropical peatlands, boreal and temperate peatlands contain lower amounts of carbon that would be irrecoverable 30 years after conversion (135 t C ha^{-1}) only because a smaller proportion of their carbon is vulnerable originally. However, recoverability in these systems is very slow, such that even partial recovery in any peatland could take millennia[34]. Aside from tropical peatlands, mangroves have the highest density of irrecoverable carbon (335 t C ha^{-1}), more than 70% of which is in soils. In forests, stand age is a major driver of differences in carbon storage in temperate and tropical forests, with older forests storing more carbon[27], hence the separation of older (≥100 years old) and younger (<100 years old) forests in our analysis. Relative to younger forests, older tropical moist forests, temperate conifer forests and temperate broadleaf forests all have high amounts of irrecoverable biomass carbon (97, 96 and 94 t C ha^{-1}, respectively). Irrecoverable carbon represents about half of the average biomass carbon in tropical forests, where sequestration rates are typically higher, versus two-thirds of the biomass carbon in temperate forests. When tropical forests are converted to agriculture, a portion of the soil carbon is released to the atmosphere, but our analysis suggests that all of this SOC could be recovered within 30 years. In contrast, when temperate and boreal forests are logged (the predominant driver of loss in these systems)[21], the SOC is not substantially disturbed[44,45]. However, conversion of temperate forests to cropland has recently been observed to a small extent in the US[46], and these land-use changes could lead to the additional loss of 25 t C ha^{-1} in temperate conifer forest soils and 49 t C ha^{-1} in temperate broadleaf forest soils that would be irrecoverable within 30 years (Supplementary Table 7).

Based on estimated, conservative geographic extents (Table 1) and average irrecoverable carbon densities across ecosystems (Fig. 2), ecosystems with carbon that is manageable through direct, localized human actions contain at least 264 Gt C that would not be re-sequestered within 30 years if lost in the near-term. Some ecosystem carbon, if lost, could not even be recovered by the end of this century or longer (Table 2). The effects of these potential losses would therefore be

Table 2 | Estimated time to full carbon recovery following conversion across major ecosystems

Ecosystem	Average time to recover vulnerable carbon, if lost (years)
Tropical grasslands	19
Temperate grasslands	35
Montane grasslands	205
Tropical moist forests	60
Tropical dry forests	77
Temperate broadleaf forests	78
Temperate conifer forests	78
Boreal forests	101
Marshes	64
Seagrasses	93
Mangroves	153
Boreal/temperate peatlands	>100
Tropical peatlands	>200

Time to recovery is based on average sequestration rates in biomass and carbon response functions in soils (see Supplementary Information, sub-section 'Recoverability of ecosystem carbon stocks'). Carbon accumulation curves of older forests are complex and without a fixed 'maximum' carbon storage level, so years to full recovery are approximate and should be considered conservative estimates.

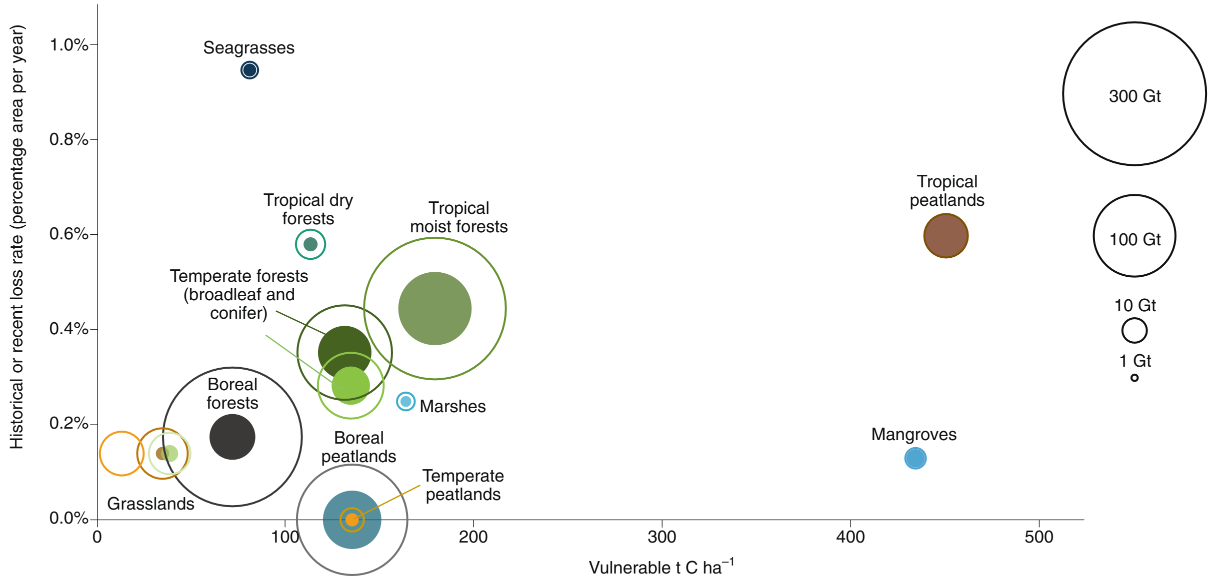

Fig. 3 | Estimated annual carbon loss and fraction irrecoverable for major ecosystem types. The size of outer bubbles indicates the ecosystem's estimated global carbon pool; the size of inner bubbles corresponds to the ecosystem's estimated global irrecoverable carbon pool. The *x* axis shows mean vulnerable carbon densities by ecosystem (also illustrated in Fig. 2). Loss rates plotted on the *y* axis are either recent or historical anthropogenic losses estimated on an ecosystem-wide scale (see Supplementary Table 11). Grassland bubbles from left to right indicate tropical grasslands, temperate grasslands and montane grasslands, respectively.

inherited by successive future generations. While it is unlikely that these irrecoverable carbon stores would be completely lost in the next several decades, few of them can be considered truly secure without proactive planning and concerted interventions. An understanding of irrecoverable carbon stocks globally and the risks they face is therefore essential to charting a path to address climate change.

The risks of irrecoverable carbon. The protection of the irrecoverable carbon we have identified is, to a large degree, within the direct, localized control of humans, and its loss would be irreversible within the time we have remaining to avoid the worst impacts of climate change. These carbon stocks face varying levels and types of risks, and thus warrant different types of interventions. How then should we prioritize their preservation?

To develop appropriate strategies, we must understand two types of risk to irrecoverable carbon: (1) the risk of release due to local drivers such as human land-use decisions and (2) the risk of release due to climate change itself. Today, many ecosystem carbon stocks remain substantially within the purview of local land-use decisions; the opportunity to protect this carbon is not yet precluded by climate change. From 2000–2012, the aggregate of thousands of local decisions drove the loss of 2.3 million km^2 of forest cover worldwide[47]. Human-driven loss was attributable primarily to agricultural expansion in tropical regions and to forestry in boreal and temperate regions[21]. Grasslands and savannas have also undergone extensive agriculture-driven land-use change, with, for example, corn and soybean expansion causing recent conversion of temperate grasslands in the US[46] and soybean expansion driving losses in the Brazilian Cerrado ecosystem[48]. Peatland conversion to agricultural land uses and plantations has been extensive in temperate and boreal regions, where 0.267 million km^2 have been drained since 1850, though conversion of northern peatlands slowed substantially between 1991 and 2015. The new frontier of peatland loss is the tropics where 0.242 million km^2 have been drained, mostly since the 1990s (ref. [49]).

The risk of carbon release due to human land-use decisions varies widely across ecosystems as a result of both the size of the irrecoverable carbon pool and its threat level (Fig. 3). Threat is approximated based on average recent loss rates, recognizing that variability within these major ecosystem categories is as important as the variability among them, and that threats to ecosystems can shift dramatically and sometimes unpredictably over time, putting previously intact[50] and even legally protected ecosystems at risk[51]. Figure 3 illustrates how ecosystems vary with respect to loss rates (for example, tropical peatlands are currently much more at risk of human-driven conversion than boreal or temperate ones) and the size of their irrecoverable carbon pool (for example, tropical moist forests have the largest irrecoverable carbon pool, estimated at more than 70 Gt C globally). Based on current loss rates, we estimate that approximately 0.8 Gt of irrecoverable carbon annually (equivalent to 3.0 Gt CO_2) is either released to the atmosphere or irreversibly committed to release due to land-use change.

Irrecoverable carbon stocks—particularly those that are irrecoverable over longer timeframes—face additional risks from both ongoing and future climate changes. The effects of these risks are highly dependent on the biophysical stresses imposed by future emissions trajectories. For example, across some boreal regions, particularly in North America, the annual area of peatlands burned in wildfires has more than doubled in the past several decades, partially due to relatively rapid regional warming[52]. This warming has also increased the occurrence of drought, fire and destructive pest outbreaks in forests such that areas of western Canada and Siberia may have already become net sources of carbon output to the atmosphere[53]. Some temperate and tropical forests are also 'on-the-brink' in that their ecological integrity and the stability of their irrecoverable carbon stocks is already being affected by climate change. For example, recent decades have seen large swaths of temperate forests in North America and Europe facing increased mortality due to hotter droughts, insect outbreaks and 'mega' fires exacerbated by climate change[54]. These disturbances can also affect trajectories of forest recovery and succession, meaning a disturbed forest could grow back at different rates with different species composition, or even fail to recover to forest[37,55]. In other words, climate change may affect

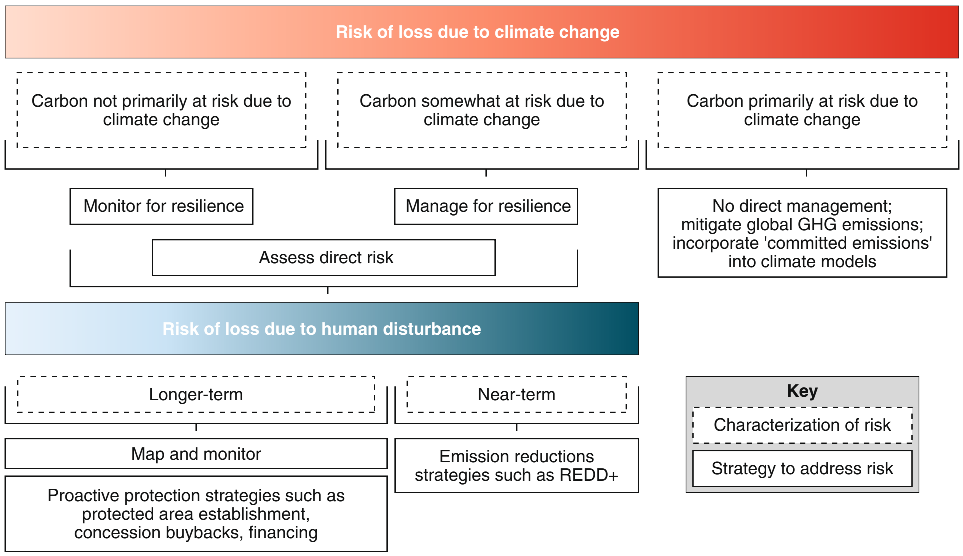

Fig. 4 | Different types and levels of risk suggest different strategies for protecting irrecoverable carbon in ecosystems. Irrecoverable carbon that is primarily at risk due to climate change may be beyond the point of direct management. In all other cases, the risk of irrecoverable carbon loss due to both climate change impacts and human disturbance (colored boxes) should be assessed, with the characterization of these two types of risk (text within dotted lines) informing the strategies to address them (text within solid lines).

all three dimensions of ecosystem carbon stocks considered here, and these impacts should be reassessed over time.

Although forest, grassland, coastal and peatland ecosystems all face some level of climate change risk, these ecosystems satisfied our manageability criterion in that their carbon storage function can still be managed through local land-use decisions and actions. While they are not yet beyond the point of no return, their future is not certain. To ensure that ecosystems with irrecoverable carbon remain manageable, strategies should strive to maintain ecosystem resilience. For example, climate change risks in forests can be managed through direct strategies to increase ecosystem resilience, such as pest and fire management[54], identifying areas of climate refugia[56], or even assisted migration[57]. Because biodiversity has been shown to increase carbon storage and resilience in ecosystems[58–60], strategies to help species adapt, such as the establishment of corridors for animal migration or other species-based conservation measures, may double as carbon protection strategies[61]. In addition, some fire-prone forest landscapes are at risk of shifting to non-forest states as the climate warms[55], but human management could help reduce the risk of transition[62]. In much of the tropics, reducing deforestation and forest degradation could reduce the risk of fire by limiting the spread of ignition sources that expand with human settlement as well as maintaining transpiration and moisture[63]. Maintaining ecosystem resilience to climate change risk is essential, in part because some ecosystems have multiple stable states[64] and may face irreversible tipping points beyond which they move from a high-carbon to a lower-carbon state[62,65]. For the many carbon stocks that are not yet beyond a climate tipping point, human decisions over the coming decades will determine whether this carbon remains stored or gets emitted into the atmosphere, which, in turn, will play a part in determining whether those tipping points are reached.

Figure 4 illustrates how a characterization of the two major types of risk to irrecoverable carbon could be used to design and prioritize interventions. For ecosystem carbon that is primarily at risk due to climate change itself (for example, permafrost), local action will be of limited use and the most important strategy is global GHG mitigation. For all other ecosystem carbon, local strategies should be designed according to the relative human disturbance and climate change risks. However, prioritizing solely based on recent loss rates is inadequate, since anthropogenic threats to ecosystems shift dramatically in both type and location over time, as countries go through often unpredictable political changes (for example, Sri Lanka and Colombia[66,67]) or as economic development creates new agricultural frontiers (for example, the rapid development of industrial palm oil in Borneo[68]). It is therefore essential to map and monitor all irrecoverable carbon in ecosystems and to proactively secure irrecoverable carbon, whether it faces imminent or longer-term (for example, decadal) threats.

Essential ecosystems for climate protection

Areas on Earth with high concentrations of carbon that (1) respond to human management and (2) are irrecoverable by mid-century, if lost, need to be identified and deserve special consideration in finance, policy and law. Our assessment of carbon recoverability shows that while some ecosystem carbon stocks can be regained relatively quickly following a disturbance, others would be irrecoverable within at least one or more human generations, thus jeopardizing our chances of staying within 1.5 °C of global warming and thereby threatening the future of people across the world.

We propose that the three dimensions of ecosystem carbon stocks could be applied spatially to map irrecoverable ecosystem carbon in detail. Future research should build on recent advances in global biomass and soil carbon mapping[28], remote sensing of ecosystem conversion[47] and spatialized data on ecosystem sequestration rates[39] to determine areas of concentrated irrecoverable carbon. These areas could be delineated and monitored by countries, triggering different interventions based on the pertinent human and climate change risks for that location (Fig. 4), and the social and economic context. Carbon that is irrecoverable by mid-century should be considered for prioritization in concert with other values such as biodiversity, watershed protection, cultural importance and other ecosystem services.

Our global synthesis reveals that some broad ecosystem classes may be considered irrecoverable and should be protected to avoid the most dangerous climate change impacts. Because their average irrecoverable carbon density is much higher than that of most other ecosystems, all peatlands should be considered priorities for protection. While many peatlands in Canada and Russia may already be compromised by climate change itself[23,52], extensive peatlands in the tropics, including in Indonesia, the Amazon Basin and the Congo Basin, contain vast quantities of irrecoverable carbon and are primarily within purview of local land-use decisions[34]; we should expand their protection and avoid their loss. All mangroves should also be considered high priorities for climate stability given their high irrecoverable carbon density, not to mention their additional coastal flood reduction benefits[69]. About 40% of mangroves are found in the Indo-Pacific region[70] where loss rates as high as 2–8% per year have been observed[71]. Among all anthropogenic and natural factors, conversion to fish and shrimp ponds is regarded as both the greatest single cause of historic mangrove degradation and decline as well as the conversion type with the highest impact on their carbon stocks[72].

While nearly all forest ecosystems contain some amount of carbon that is irrecoverable by mid-century, a few stand out as warranting particular attention and proactive protection. Older, intact forests are effectively long-term investments in carbon storage that have been sequestered over decades to centuries. Seventy percent of remaining tropical forests are largely intact[73], meaning they are mostly undisturbed and have had longer timeframes to accumulate carbon. Major expanses of tropical forests in the Amazon Basin, Guiana Shield, Congo Basin, southeast Asia, New Guinea, and elsewhere should therefore be considered irreplaceable from a climate perspective. Finally, though relatively few areas of old-growth temperate forests remain[74], those along the coasts of southern Chile, Tasmania, New Zealand, southeastern Australia and northwestern North America harbour some of the highest biomass carbon densities in the world[75], and much of it is likely irrecoverable.

Protecting the places we can't afford to lose

Increasing evidence shows that it will be impossible to hold the mean global temperature increase to below 1.5 °C without maintaining the capacity of the biosphere to reduce human-caused climate forcing[76]. Ecosystems with high amounts of irrecoverable carbon represent unambiguous targets for a range of urgent policy and investment decisions to prevent any future emissions from these ecosystems.

Within international and national policy fora there is an opportunity to design policies for the long-term and proactive protection of irrecoverable carbon, recognizing that doing so is interconnected with achieving annual mitigation targets. The Warsaw Framework for REDD+ (Reducing Emissions from Deforestation and Forest Degradation) and Articles 5 and 6 of the Paris Agreement create the conditions for tropical forest countries to receive performance-based payments for reducing deforestation. Our study reveals the need for policy pathways to ensure the long-term protection of irrecoverable carbon[50]. International trade agreements could consider benchmarks for ecological carbon protection, with irrecoverable carbon topping the list of priorities for which no loss is acceptable, and both exporting and importing countries sharing responsibility for compliance.

National governments also have opportunities to proactively protect irrecoverable carbon within their borders, potentially contributing to national development plans, nationally determined contributions to the Paris Agreement and national security. As a first step, countries could identify areas of concentrated irrecoverable carbon and determine their current level of legal protection, or lack thereof, and effectiveness of enforcement. Mechanisms for securing irrecoverable carbon at the national level might include new protected area designations, increased rights and resources to indigenous peoples, land-use planning that specifically incorporates irrecoverable carbon protection, ending or retiring concessions to agriculture, logging or aquaculture within areas of concentrated irrecoverable carbon, and designation of areas as critical biological carbon reserves deserving of a special protected status. Protection of areas with high irrecoverable carbon could also help many countries meet other goals, such as the biodiversity targets to be agreed in 2020 and the Sustainable Development Goals.

There are also opportunities for multilateral development banks, governments and the private sector to design financing mechanisms that promote the protection of irrecoverable carbon. The Green Climate Fund and other international climate finance bodies could consider proactive protection of irrecoverable carbon as part of project selection criteria and/or consider dedicated funding streams, including performance-based payments. Governments (both national and subnational) that have carbon pricing programs could dedicate a portion of the revenue from carbon taxes or cap-and-trade to the proactive management of irrecoverable carbon reserves in ecosystems. Companies should consider zero release of irrecoverable carbon as a key safeguard to be factored into land-use decisions, supply-chain management and environmental impact assessment. Proactive protection of irrecoverable carbon could be a component of corporate sustainability goals alongside efforts to rapidly draw down emissions. Investors could promote the protection of irrecoverable carbon by considering investments in companies that destroy it to be high-risk, as well as pushing for better practices, including through divestment.

It is essential to recognize that many ecosystems containing irrecoverable carbon are also home to indigenous peoples and local communities (IPLCs) whose fate is intertwined with that of their land. Advancing the rights of IPLCs can also advance climate protection. For example, indigenous peoples and local communities manage an estimated 293 Gt C of carbon overall in tropical forests, some 72 Gt C of which is stored on land where they lack formal tenure rights[77]. In Peru, land titling was shown to significantly reduce forest clearing and disturbance[78]. Securing irrecoverable carbon globally will depend significantly on recognizing and supporting IPLCs as stewards of ecosystem carbon reserves, including through titling unrecognized indigenous lands; ending the persecution of indigenous leaders; recognizing indigenous peoples' climate change contributions in the context of country climate plans; implementing the use of free, prior and informed consent; and supporting direct access to climate finance[79].

We have provided a framework for assessing ecosystems across three key carbon dimensions and thus identifying critical ecosystems with regards to climate stability. The application of this framework provides further support to the important notion that much of the carbon in ecosystems such as peatlands, mangroves and old-growth temperate and tropical moist forests must be considered, and thereby handled, similarly to fossil fuel reserves in that the loss of their carbon to the atmosphere is irrecoverable in the time we have remaining to prevent catastrophic climate impacts. However, unlike fossil fuel carbon, which will be converted to atmospheric GHGs only with human intervention, part of the Earth's biological carbon will be released to the atmosphere due to climate change itself. This reality only creates a greater imperative to mitigate climate change through both natural climate solutions and the decarbonization of the energy sector to prevent the biological carbon that is currently locked within ecosystems from sliding into committed emissions. We must understand and locate the carbon that we can still proactively protect under climate conditions in the near term, and this should be prioritized since much of it would be effectively irrecoverable if lost. Overall, Earth's ecosystems contain vast quantities of carbon that are, for the time being, directly within human ability to safeguard or destroy and, if lost, could overshoot our global carbon budget. Protecting these biological carbon stocks is one of the most important tasks of this decade.

Data availability

All data generated or analysed during this study are included in this published Perspective and its supplementary information files.

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Author contributions
W.T., D.H., J.R., J.F., J.F.H., L.P.K., J.S. and A.G. conceived the idea for the study. A.G., W.T. and S.S. interpreted the data and wrote the manuscript. All other authors edited the manuscript and advised on analysis. S.S. developed and performed the soil carbon analysis; K.A.T. developed the ForC-db on which much of the forest carbon analysis is based; S.C.P. developed the forest regeneration database on which forest sequestration rates are based; J.F.H. provided data and guidance on coastal ecosystems; and S.P. provided data and guidance on peatlands.

Competing interests
The authors declare no competing interests.

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Correspondence should be addressed to A.G.

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SUPPLEMENTARY INFORMATION

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Protecting irrecoverable carbon in Earth's ecosystems

Allie Goldstein[1]✉, Will R. Turner[1], Seth A. Spawn[2,3], Kristina J. Anderson-Teixeira[4], Susan Cook-Patton[5], Joseph Fargione[5], Holly K. Gibbs[2,3], Bronson Griscom[1], Jennifer H. Hewson[1], Jennifer F. Howard[1], Juan Carlos Ledezma[6], Susan Page[7], Lian Pin Koh[8], Johan Rockström[9], Jonathan Sanderman[10] and David G. Hole[1]

[1]Conservation International, Arlington, VA, USA. [2]Department of Geography, University of Wisconsin-Madison, Madison, WI, USA. [3]Nelson Institute for Environmental Studies, Center for Sustainability and the Global Environment, University of Wisconsin-Madison, Madison, WI, USA. [4]Smithsonian Conservation Biology Institute, Conservation Ecology Center, Front Royal, VA, USA. [5]The Nature Conservancy, Arlington, VA, USA. [6]Conservation International Bolivia, La Paz, Bolivia. [7]School of Geography, Geology and the Environment, University of Leicester, Leicester, UK. [8]Department of Biological Sciences, National University of Singapore, Singapore, Singapore. [9]Potsdam Institute for Climate Impact Research, Potsdam, Germany. [10]Woods Hole Research Center, Falmouth, MA, USA. ✉e-mail: agoldstein@conservation.org

SUPPLEMENTARY INFORMATION

Protecting irrecoverable carbon in Earth's ecosystems

Authors

Allie Goldstein*, Will R. Turner, Seth A. Spawn, Kristina J. Anderson-Teixeira, Susan Cook-Patton, Joseph Fargione, Holly K. Gibbs, Bronson Griscom, Jennifer H. Hewson, Jennifer F. Howard, Juan Carlos Ledezma, Susan Page, Lian Pin Koh, Johan Rockström, Jonathan Sanderman, Dave Hole

***Correspondence**

Correspondence to Allie Goldstein, agoldstein@conservation.org, +1 703-341-2508

List of Supplementary Materials

Ecosystem delineation and manageability of carbon stocks

While many ecosystems play an important role in cycling and storing carbon, our objective in this analysis was to identify those ecosystems containing carbon that is pertinent to human management decisions for climate mitigation. We started by delineating major categories of terrestrial, coastal and marine, and freshwater ecosystems and then narrowing the list to ecosystems containing carbon that is manageable through direct, localized human activities (i.e., the carbon content of the ecosystem could either increase or decrease depending on localized human decisions). We considered an ecosystem's carbon to be 'manageable' only if the localized action was widely applicable with current technology (i.e., not requiring geoengineering technology projected to be available at some future date) and if increasing the ecosystem's carbon content would not have other adverse impacts (e.g., ocean acidification).

Terrestrial ecosystems

To delineate terrestrial ecosystems, we started with Dinerstein et al's 15 terrestrial biomes[1]: boreal forests/taiga; temperate broadleaf and mixed forests; temperate conifer forests; tropical and subtropical coniferous forests; tropical and subtropical dry broadleaf forests; tropical and subtropical moist broadleaf forests; Mediterranean forests, woodlands and scrub; deserts and xeric shrublands; temperate grasslands, savannas, and shrublands; tropical and subtropical grasslands, savannas and shrublands; montane grasslands and shrublands; flooded grasslands and savannas; mangroves; tundra; and rock and ice. These biomes were chosen as the starting point because they represent a discrete list of ecosystem types, with climate and other biophysical factors driving differentiation in terms of carbon storage. Tropical and subtropical coniferous forests; flooded grasslands and savannas; and Mediterranean forests, woodlands, and scrub were excluded due to low data availability and limited geographic coverage: 0.5%. 0.9% and 2.4% of terrestrial land, respectively[1].

Other terrestrial ecosystems were eliminated from further consideration due to their irrelevance to local carbon management:

- **Rock and ice** was excluded because its carbon content is not of recent biotic origin and is not responsive to direct human management.
- **Deserts and xeric shrublands** were excluded because, although the saline aquifers below deserts may store a significant amount of carbon – perhaps around 1,000 Gigatonnes (Gt) – that has been leached from soils by past irrigation and accumulated in groundwater[2]. Dissolved CO_2 can only be re-released from storage if this groundwater is discharged into surface water systems or if it is pumped to the surface for subsequent irrigation where, in both cases, turbulence will release dissolved CO_2 to the atmosphere. However, discharge from these aquifirs is low and the cited total storage already accounts for the aquifir's relative CO_2 gains and losses. Irrigation represents the only potential conduit within the purview of human management and is unlikely given that the saline groundwater is often toxic to crops[2].
- **Tundra** ecosystems cover an estimated 1,878 million hectares of the Earth's surface and the permafrost – the remnants of plants and animals accumulated in frozen soil – within them stores an estimated 1,300 Gt of carbon[3,4], twice as much carbon as is currently in the atmosphere. This carbon can be released to the atmosphere if these frozen soils thaw, increasing mineralization by microbes that convert it to carbon dioxide (CO_2) and methane (CH_4). A portion of this carbon is likely to be released under the current climate warming trajectory[4]. However, though humans have indirect control over the level of thawing that occurs through global anthropogenic emissions, there are no proven direct, localized land-use management activities that can affect the carbon content of tundra ecosystems.

Coastal and marine ecosystems

To delineate coastal and marine ecosystems, we used the systems delineated in Howard et al 2017[5]. They were: mangroves, tidal marshes, seagrasses, coral reefs, kelp forests, and the open ocean. Again, a few coastal and marine ecosystems were eliminated from further consideration due to their irrelevance to local management:

- **Kelp forests** are so quickly consumed by marine fauna that relatively little carbon (at most 0.13 Gt globally) can be considered part of a long-term sink. Though we may be able to expand the extent of kelp forests, doing so would have little effect on global carbon stores[5].
- **Coral reefs** do not store significant carbon. Reef growth through calcification occurs when calcium carbonate ($CaCO_3$) precipitates out of the water column onto the reef structure, releasing a small amount of CO_2 to the atmosphere; the opposite happens with reef dissolution. With future conditions of ocean acidification, many reefs are expected to enter a net dissolution phase, capturing CO_2 but ultimately destroying the reefs[5].
- **The open ocean** contains 38,000 Gt carbon[6] and serves as a major carbon sink as CO_2 in the atmosphere reacts with seawater and gets pumped into the ocean's deep waters (the "solubility pump", a chemical process) and as marine organisms sequester CO_2 through photosynthesis, beginning with phytoplankton (the "biological pump"). Additional organic matter is also transported to the open ocean through rivers[7], but this effect is smaller than either the solubility pump or the biological pump. All told, oceans have absorbed 40% of the CO_2 humans have added to the atmosphere since the dawn of the industrial era[8]. However, the rate of CO_2 uptake by the ocean is dependent mainly on the concentration of CO_2 in the atmosphere, and the open ocean is not responsive to direct carbon management except through unproven and highly risky strategies such as fertilizing the ocean with iron[9]. Additionally, unlike in coastal and terrestrial ecosystems, uptake of carbon in the oceans has

a negative biological consequence: ocean acidification, which is harmful to marine creatures[10].

Freshwater ecosystems

For freshwater ecosystems, we considered lakes, rivers/streams, and peatlands. Peatlands were further delineated as tropical, temperate, and boreal. Peat is the accumulation of organic material that occurs when water prevents the remains of dead plants and mosses from decomposing due to the absence of oxygen. Peat may occur within a forest, grassland, savanna, or wetland and therefore overlaps spatially with the Dinerstein biome delineations. We decided to assess peatlands separately despite the spatial overlap because of their huge carbon reserves, unique carbon dynamics, and low recoverability, since some peatlands take millennia to form[11].

Lakes, rivers and streams were excluded because it is unclear whether they represent an additional carbon sink. While these freshwater ecosystems play an important role in the global carbon cycle, receiving an estimated 2.7-5.1Gt of carbon annually from terrestrial ecosystems; of this, between 0.7-3.9 Gt is respired back to the atmosphere, 0.9 Gt is transported to the ocean, and 0.2-0.6 Gt is retained and buried in sediments[7,12-14]. The carbon that does make it into sediments can remain there for 10,000 years or more, and over time the world's lakes have accumulated an estimated 820 GtC[15], mostly in shallow sediments[12]. Carbon burial in freshwater sediments is an order of magnitude greater than carbon burial in the ocean[16]. However, it is unclear whether freshwater ecosystems represent an additional carbon sink, or whether they are simply the resting point for carbon that would have otherwise been stored in terrestrial ecosystems or the ocean floor[17].

Ecosystems considered in subsequent analysis

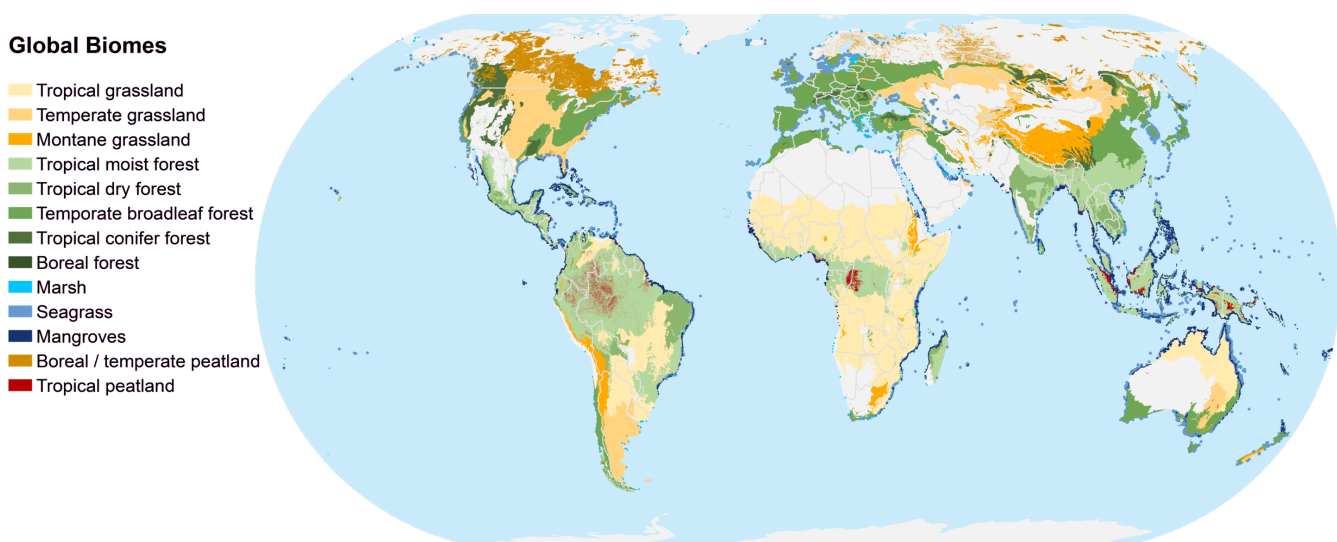
The remaining ecosystems we considered against the subsequent criteria were:

- Boreal forests/taiga (abbreviated as "Boreal forest")
- Temperate broadleaf and mixed forests ("Temperate broadleaf forest")
- Temperate conifer forests

- Tropical and subtropical dry broadleaf forests (“Tropical dry forest”)
- Tropical and subtropical moist broadleaf forests (“Tropical moist forest”)
- Temperate grasslands, savannas, and shrublands (“Temperate grassland”)
- Tropical and subtropical grasslands, savannas and shrublands (“Tropical grassland”)
- Montane grasslands and shrublands (“Montane grassland”)
- Mangroves
- Seagrasses
- Tidal marshes (“Marshes”)
- Boreal peatlands (“Boreal peatlands”)
- Temperate peatlands (“Temperate peatlands”)
- Tropical peatlands (“Tropical peatlands”)

Supplementary Figure 1 shows the geographic distribution of the ecosystems considered in this analysis. The subsequent analysis is spatial only to the extent that we sometimes used this ecosystem delineation to calculate average values by ecosystem based on point data.

Supplementary Figure 1: Ecosystem delineation map



Notes: This map was created by overlaying the manageable Dinerstein biomes[1] with coastal ecosystem layers (Bunting et al 2018 for mangroves[18], UNEP-WCMC 2018 for seagrasses[19], and Mcowen et al 2017 for marshes[20]) and peatlands (using PeatMAP[21]).

Magnitude of vulnerable carbon stocks

Initial biomass (aboveground and belowground carbon)

Forests

We derived average aboveground biomass carbon (AGC) values for forests from the Forest C database (ForC-db), an open access global carbon database that contains previously published data on ground-based measurements of ecosystem-level C stocks and annual fluxes in forests globally[22]. ForC-db contains >23,000 records from >3,300 sites. We used values for biome average aboveground biomass carbon per hectare. Coordinates were given for all sites in ForC-db and we used these coordinates to tag each site to a Dinerstein biomes, as discussed above. We averaged values by geographic area to reduce the impact of heavily sampled areas on the mean values.

Because the carbon storage of forests differs significantly by age[23,24] and because there are large areas of secondary forest across the planet due to deforestation and subsequent regrowth, we delineated the major forest ecosystem types as either 'young' (<100 years since natural regeneration or replanting initiated) or 'old' (≥100 years) to capture differences in carbon storage per hectare and based on the cutoff for secondary forest versus old-growth stands used in Suarez et al 2019[25]. We used the 'stand age' at the time of measurement (ForC-db compiles this based on the age as reported in the original publication or calculated based on the date of initiation of forest regrowth).

We derived average belowground biomass carbon (BGC) values for forests using a root-to-shoot conversion based on Mokany et al 2006[26]. Forest root-to-shoot ratios were adjusted to align with the Dinerstein ecoregions and differentiated based on the aboveground carbon content, using low, medium, or high delineations based on the ranges shown in Table S1. We calculated BGC for each of the ForC-db sites that reported an AGC value and then averaged the BGC per ecosystem.

Supplementary Table 1: Root-to-shoot conversion rates for estimating belowground carbon

Ecosystem	Aboveground C Range ($MgC\ ha^{-1}$)	Root-to-shoot ratio
Boreal forest	<35.3	0.392[a]
Boreal forest	≥35.3	0.239[a]
Temperate broadleaf forest	<35.3	0.456[a]
Temperate broadleaf forest	35.3-70.5	0.226[a]
Temperate broadleaf forest	>70.5	0.241[a]
Temperate conifer forest	<23.5	0.403[a]
Temperate conifer forest	23.5-70.5	0.292[a]
Temperate conifer forest	>70.5	0.201[a]
Tropical moist forest	<58.8	0.205[a]
Tropical moist forest	≥58.8	0.235[a]
Tropical dry forest	<9.4	0.563[a]
Tropical dry forest	≥9.4	0.275[a]
Tropical grassland	All	1.887[a]
Temperate grassland	All	4.224[a]
Montane grassland	All	4.504[b]
Mangroves	All	0.580[c]
Seagrasses	All	2.650[d]
Marshes	All	1.098[c]
Sources: [a] Mokany et al. 2006[26] [b] Used Mokany value for 'cool temperate grasslands' [c] Average R:S ratio across all mangrove subtypes in the IPCC Wetlands Supplement[27] [d] Midpoint value from Purvaja et al. 2018[28]		

Grasslands

For grasslands, AGC density was tabulated separately within each off the three grassland biomes from a global map of grassland herbaceous biomass carbon density[29]. Grassland BGC density was then calculated using the corresponding root-to-shoot ratios reported in Table S1. These estimates only account for the herbaceous (i.e. grass) biomass within these ecosystems and thereby exclude the biomass of trees and shrubs that may also be located within grassland areas.

Coastal ecosystems

For coastal ecosystems our average AGC and BGC density values were derived from a literature review. The results of all biomass analyses and the coastal ecosystem literature review are summarized in Table S2 below.

Peatlands

Peatlands are excluded from this table because they underly other land-use classes and their AGC and BGC is therefore captured under other ecosystem types.

Supplementary Table 2: Mean aboveground and belowground carbon densities across ecosystems

Ecosystem	Mean AGC (MgC ha^{-1})	Min. AGC (MgC ha^{-1})	Max. AGC (MgC ha^{-1})	Mean BGC (MgC ha^{-1})	Min. BGC (MgC ha^{-1})	Max. BGC (MgC ha^{-1})	Count
Boreal forest	56.9	0.7	141.9	14.3	0.3	33.9	83
Temperate broadleaf forest (young)	67.6	2.1	242.0	16.7	1.0	58.3	106
Temperate broadleaf forest (old)	116.1	17.4	720.5	28.3	7.9	173.6	65
Temperate conifer forest (young)	76.2	4.1	246.0	17.0	1.7	49.5	34
Temperate conifer forest (old)	119.4	22.7	360.9	25.2	7.7	72.5	70
Tropical moist forest (young)	72.9	5.0	287.2	16.7	1.0	67.5	64
Tropical moist forest (old)	154.7	22.7	361.5	36.3	4.8	84.9	153
Tropical dry forest (young)	31.8	0.7	56.4	8.9	0.1	15.5	5
Tropical dry forest (old)	96.9	14.0	162.6	26.7	3.8	44.7	12
Temperate grassland	0.8	0.1	1.6	3.6	0.2	6.8	NA
Tropical grassland	1.0	0.1	1.6	1.8	0.4	3.2	NA
Montane grassland	0.6	0.01	1.6	2.6	0.05	7.2	NA
Mangroves	89.5	2.6	236.0	51.9	1.5	136.9	30
Seagrasses	0.8	<0.1	5.6	2.1	<0.1	17.8	251
Marshes	5.0	0.1	31.2	5.5	.1	34.3	409

Notes: ‘Count’ represents the number of geographic areas on which the mean value was based, if available. BGC values were calculated based on the root-to-shoot ratios specified in Table S1 unless otherwise specified. Peatlands excluded from this table because peatlands underly other aboveground land-uses. We captured peatlands SOC only. “Young” refers to forests <100 years old and “old” is ≥100 years old. This was a meaningful distinction in all forest types except boreal.

Sources: ForC database for all forest values[22]; Xia et al. 2014[29] for grasslands (min and max values here refer to the 0.01 and 99.9 percentiles); Kaufmann et al. 2017[30] for mangrove AGC values; Fourqurean et al. 2012[31] for seagrass AGC and BGC; Byrd et al. 2018[32] for tidal marshes AGC.

Soil organic carbon (SOC)

Forests and grasslands

Summarizing average soil organic carbon (SOC) density values per biome required a different approach. To maximize methodological consistency across ecosystems and holistically represent the spatial variation within each, we tabulated SOC carbon stocks from the SoilGrids250v2 gridded soils database[33] (hereafter "SoilGrids"). SoilGrids maps are produced at a 250m spatial resolution for the globe using a machine learning algorithm that is trained by relating more than 150,000 soil profiles to nearly 160 remotely sensed covariate grids. SoilGrids provides accurate depth-specific SOC estimates for most ecosystems, with a few exceptions (see boreal, below). The global root mean square error of SoilGrids SOC predictions is 32.8 MgC ha^{-1}, indicating tight agreement with corresponding field measurements. While a small number of alternative global soil maps exist and were considered, none report a quantitative accuracy assessment to which we could compare. Independent comparisons, though, suggest that SoilGrids' predictions are likely closest to reality [34]. We considered the effects of land use changes on SOC stocks to a depth of 30 cm for forests and grasslands.

Within each ecosystem, we summarized a representative sample of the initial (i.e. pre-conversion), depth-specific SOC stocks that underlie the primary natural land cover from the SoilGrids maps. A series of masks were applied to each SOC grid in Google Earth Engine (GEE)[35] to exclude non-representative areas from each tabulation. We began by masking each SOC grid to the biome's extent. Since our analysis only considers the effects of the changes to the primary vegetation type within each biome, we then masked each grid to the extent of that land cover (e.g. tree covered areas of forested biomes and herbaceous and shrubland classes of grasslands biomes) using the ESA CCI land cover map for the year 2010[36], which was used to represent land cover within the SoilGrids algorithm[33]. Lacking a map of forest age, we were not able to further differentiate SOC in "old" vs. "young" forests in our stock tabulations and thus assumed no significant difference. Finally, since peat soils (Histosols) were examined separately, we removed grid cells that SoilGrids identified as probable Histosols (prob. ≥ 95%) to avoid double counting.

Summaries of SOC stocks were then generated from the remaining SOC grid cells within each biome's extent using GEE. We determined the median stock density of each relevant SoilGrids depth increment (0-5cm, 5-15cm, 15-30cm). In addition, we also generated percentile estimates (p = 0.1%, 1.0%, 2.0%, 2.5%, 5.0%, 10.0%, 25.0%, 75.0%, 90.0%, 95.0%, 97.5%, 99.0%, 99.9%) of each depth increment to which we could fit probability distributions and quantify/propagate uncertainty associated with the stock's spatial variation. Probability distributions were fit using the *rriskDistributions* package[37] in the R statistical computing environment[38]. In the rare case of a bimodal distribution, the distribution was approximated using a monotone cubic Hermite spline. Depth specific median and percentile estimates were integrated by depth to report estimates of these metrics for the upper 30 cm of soil.

Corresponding information on clay content and mean annual temperature was required to model land use induced SOC stock changes in some ecosystems and were similarly tabulated from additional maps using the masking procedure described above. We used depth-specific maps of soil clay content from SoilGrids and a map of mean annual temperature (1970-2000) from the WorldClim2 dataset to represent these variables[39].

In the organic rich soils of the boreal region, SoilGrids is known to overestimate SOC stocks[34] due to a lack of representative bulk density data[40]. For this reason, we instead used a modified, though less resolved version of SoilGrids in which this issue has been resolved to tabulate boreal SOC stocks to depth of 30 cm[31]. These grids were only used for stock tabulations in the boreal forest ecosystem since the primary anthropogenic land use change here was assumed to not significantly influence SOC stocks (see below) and thus more resolved, depth-specific estimates and matching soil property information were not necessary. These modified grids were, however, subject to the same masking procedure described above such that our estimates only consider stocks in forested areas and exclude peatland areas to avoid double counting.

Coastal ecosystems and peatlands

SoilGrids does not explicitly cover coastal ecosystems or peatlands. The SOC values for mangroves were thus derived from Sanderman et al. 2018[41]; values for seagrasses and tidal marshes were derived from the IPCC Wetlands Supplement 2013, Table 4.11[27]. The values for peatlands were derived from Page et al. 2011 for tropical peatlands and Christensen et al. 2004 for temperate and boreal peatlands[42,43]. For coastal ecosystems and peatlands, we considered SOC down to 1 m as the relevant depth vulnerable to the most common anthropogenic disturbances[44,45].

Supplementary Table 3: Average initial soil organic carbon stocks by ecosystem

Ecosystem	**Average SOC (MgC ha^{-1})**	**Min. SOC (MgC ha^{-1})**	**Max. SOC (MgC ha^{-1})**	**Depth considered**
Boreal forest	193	130	302	30 cm
Temperate broadleaf forest	137	80	214	30 cm
Temperate conifer forest	138	89	207	30 cm
Tropical moist forest	92	56	151	30 cm
Tropical dry forest	67	44	123	30 cm
Temperate grassland	73	31	151	30 cm
Tropical grassland	40	18	152	30 cm
Montane grassland	101	42	202	30 cm
Mangroves	361	86	729	100 cm
Seagrasses	108	9	829	100 cm
Marshes	255	16	623	100 cm
Boreal & temperate peatlands	500	392	1,531	100 cm
Tropical peatlands	504	424	1,357	100 cm

Sources/ Notes: Forest and grasslands values are the median; all other values are the mean. Boreal forests estimates come from Sanderman et al. 2017[46]. Mangrove estimates come from Sanderman et al. 2018[41]. Seagrasses estimates come from Fourqurean et al. 2012[31]. Marshes estimates come from the 2013 IPCC Wetlands Supplement[27]. Tropical peatlands estimates come from Page et al. 2011[39]. Temperate and boreal peat estimates come from Christensen et al. 2004[43]. All other estimates come from SoilGrids and exclude Histosols (peat). The min and max represent the 1st and 99th percentile of mapped values, respectively, which we think is a good proxy for the true range.

Vulnerability of initial carbon stocks

Across ecosystems, we assessed the likely amount of the initial carbon that would be lost per hectare in a typical conversion event, expressed as a percentage of the initial stock. The 'typical' conversion event was considered to be the most common driver of ecosystem loss, considering events that would alter the land cover (e.g., forest to soy field or clear-cut) as a maximum feasible loss event, as opposed to activities that might reduce the carbon content but not constitute full conversion (e.g., forest degradation due to charcoal collection or selective logging). Our assumptions about the typical conversion events that would result in carbon loss are defined in Table S4. In tropical forests, agriculture drives the vast majority of deforestation, while in temperate and boreal regions, the main anthropogenic driver is forestry[47]. Grassland conversion is also largely driven by agriculture[48] while coastal ecosystem loss is driven by aquaculture, agriculture, and coastal development[45]. Peatland conversion is largely driven by agriculture[11]. These common drivers were used to estimate the maximum 'vulnerable carbon' per hectare by major ecosystem type. We assumed complete conversion to a different land-use rather than degradation, however, we recognize that degradation through activities such as selective logging is a major driver of carbon loss in tropical forests, accounting for additional biomass losses on the order of 47-75% of deforestation[49].

Supplementary Table 4: Assumed % vulnerable carbon per hectare by ecosystem type due to typical conversion

Ecosystem	% of initial biomass typically lost in conversion	% of initial SOC typically lost in conversion	Typical / assumed conversion event
Boreal forest	100%	0%	Forestry
Temperate broadleaf forest	100%	0%	Forestry
Temperate conifer forest	100%	0%	Forestry
Tropical moist forest (young)	100%	18%	Agriculture
Tropical moist forest (old)	100%	23%	Agriculture
Tropical dry forest (young)	100%	18%	Agriculture
Tropical dry forest (old)	100%	23%	Agriculture
Temperate grassland	100%	39%	Agriculture
Tropical grassland	100%	23%	Agriculture
Montane grassland	100%	34%	Agriculture
Mangroves	100%	81%	Aquaculture / development
Seagrasses	100%	72%	Aquaculture / development
Marshes	100%	60%	Aquaculture / development
Boreal Peat / Temperate Peatlands	NA	27%	Agriculture
Tropical Peatlands	NA	89%	Agriculture

We separated our analysis by biomass and SOC, assuming that 100% of the biomass was potentially vulnerable in a conversion event. This follows IPCC Tier 1 methodology for forest land[50] and is also consistent with the assumption made in other estimations of carbon flux to the atmosphere associated with biomass loss in forests[51-53]. We applied the same 100% assumption to grasslands and coastal ecosystems as the maximum but reasonable amount of 'vulnerable carbon' by ecosystem.

In contrast to biomass, ecosystem conversion to a human appropriated land-use does not typically result in complete loss of the SOC stock. Instead, a fraction of the initial SOC stock is often lost following conversion due to changes in the ecosystem carbon balance that result from both biomass removal and physical disruption of otherwise-stable, carbon-containing soil aggregates. The relative magnitude of these losses has been related to both the type of ecosystem converted and its subsequent land use, among other factors, by numerous meta-analyses[54,55], and their findings are commonly used to model expected changes to the size of the initial SOC stock resulting from specific land use changes[56,57]. Likewise, we used this approach to model expected losses from the initial SOC stocks tabulated in each biome as described above. In the event of forestry/logging being the main driver of loss, we assumed that no (0%) of the SOC was vulnerable based on studies that show no significant change in SOC for harvested temperate forests (more details in subsequent section)[58,59]. This is a conservative assumption given uncertainties about SOC disturbance due to logging/ harvesting.

Boreal Forests SOC

We assumed that timber harvest of boreal forests – when followed by forest regeneration – induced no signification change in the magnitude of their underlying SOC stocks. While data is limited, we found multiple studies suggesting that such a transition had no meaningful effect on mineral SOC stocks and a minimal transient effect of forest floor carbon[60,61] – the organic layer containing litter and woody debris at the soil surface. For these reasons, we assumed no net change due to land use change and/or subsequent recovery in our analyses.

Temperate Forests SOC

Similar to boreal forests, introduced forestry was assumed to have no significant long-term effect on temperate forest SOC. In a meta-analysis of 75 studies reporting 432 SOC response ratios for harvested temperate forests, Nave et al. (2010) report no significant SOC change in forest mineral soils[58]. A recent analysis of SOC responses in harvested temperate forests found that forest floor carbon losses due to conventional harvest were offset by SOC accumulation in deeper mineral soils[59]. When SOC changes were integrated to a depth of 20 cm or more, this study found no statistically significant effect of conventional harvest. We therefore assumed for this analysis that temperate forest SOC is not lost to any significant degree upon harvest, by far the most common cause of conversion in temperate forests[47]. This is the assumption driving the 'irrecoverable carbon' calculation.

Conversion of temperate forests to cropland is relatively rare (e.g., Lark et al. 2015)[48] but represents a more drastic change to the local carbon cycle that leads to significant SOC losses., To get as sense of the potential implications of this sort of land use change, we also modeled SOC responses expected when temperate forests are converted to cropland. We used a carbon response function (CRF; see implementation details in "Temperate Grassland SOC") for forest conversion to cropland from Poeplau et al. 2011[42] to model the SOC response of this transition as described above. This analysis is captured in Table S6.

Temperate Grasslands SOC

The most common driver of loss of temperate grasslands is conversion to agriculture, which often causes SOC losses. We modeled these losses using a carbon response function (CRF) – a simple statistical model that predicts SOC emissions associated with specific land use transitions based on the empirical effects of environmental covariates over a user-specified duration. This CRF was derived in a meta-analysis of 95 published studies conducted throughout the temperate zone[55]. CRFs have been used by others to estimate SOC emissions from land use change[56,57]. The CRF used in this analysis predicts the proportional change relative to an initial SOC stock based on soil clay content (%), mean annual temperature (MAT; °C), soil depth (meters), and the time (*t*) since conversion (years).

The CRF was applied to depth-specific SOC estimates following the general approach of Spawn et al. 2019[57]. We quantified total changes expected as a result of land use change by setting *t* equal to 30 years since, according to these models, stocks stabilize after 17 years on average[42], and we aimed to capture the full effect of conversion events. To quantify uncertainty associated with the modeled SOC stock change, we used a bootstrapping procedure that resampled (n = 10,000) the probability distributions of SOC, clay and MAT (described previously), as well as those representing the error associated with CRF coefficients. Probability distributions for CRF coefficients were created from mean and standard error estimates (obtained from Poeplau et al. 2011 and reported in Table S10 of Spawn et al. 2019) and were assumed to be normally distributed. All distributions were sampled without replacement to generate novel distributions of (i) expected SOC change (ii) the post conversion SOC stock, from which we report the median and spread.

Tropical Forest and Grasslands SOC

CRFs were not available for tropical ecosystems so we instead used emissions factors (EFs) representing the average total SOC loss resulting from specific land use changes. These EFs (Table S6) were derived in a meta-analysis of 385 studies conducted throughout the tropics[54]. We used EFs describing changes resulting from the conversion of (i) primary forests, (ii) secondary forests, and (iii) natural grasslands to cropland. Since each EF was based on observations from different average maximum depths (36 to 44cm) and since our analysis only considers changes in these systems to a depth of 30cm, we calibrated each EF to reflect expected changes in the upper 30cm of the soil profile by fitting an exponential function derived from global SOC change data (Figure S8 in Sanderman et al. 2017[46]), such that the average change to the literature reported sample depth was equal to the literature reported EF. As a result, EFs used for the entire 30cm profile were slightly less than those reported in the meta-analysis[54].

As with the temperate grassland SOC loss calculation, we used a bootstrapping procedure (n = 10,000) to quantify uncertainty associated with modeled tropical SOC changes. In addition to probability distributions of depth-specific SOC densities, distributions were also fit to the mean, standard error and range estimates of the literature reported EFs by assuming a truncated normal distribution bounded by the given EF's reported minimum and maximum estimate[54]. Distributions describing the time since LUC and sample depth were also created and assumed to be normally distributed. All distributions were sampled without replacement to generate novel distributions of (i) expected SOC change and (ii) the post-conversion SOC stock from which we report the median and spread.

Coastal Ecosystems SOC

SOC loss rates from coastal ecosystems were estimated through literature review. The mangrove SOC loss value of 81% was derived from a study that compared ecosystem carbon stocks from 30 relatively undisturbed mangrove forests and 21 adjacent shrimp ponds or cattle pastures[30]. Another study across 25 mangrove sites in the Indo-Pacific found 25-100% SOC loss in mangroves following disturbance, with the lower end applying to moderate soil disturbance and the upper end applying to heavier activities such as shrimp aquaculture[62]; the 81% derived from Kauffman et al. falls towards the upper end of this range[30]. SOC loss in seagrasses remains uncertain, as it is unclear whether the entire top meter of soil is remineralized in the event of seagrass loss, however, one study in Jervis Bay, Australia which examined a seagrass area disturbed 50 years prior found that 72% of the SOC was lost[63]. (This study looked at just the top 30 cm of soil). Finally, the tidal marsh SOC loss assumption was derived from a study of salt marsh conversion in the Scheldt estuary in the Netherlands[64].

Peatlands

We considered the top meter of peatland SOC to determine the maximum vulnerable carbon in a conversion event. The 1 m drainage depth is consistent with the IPCC Wetlands Supplement[27] and with studies of peatlands emissions converted to palm oil in Southeast Asia that found likely drainage depths to be between 0.8 and 1.1 meters[44]. Our goal was to capture the full effects of a conversion event to estimate ‘vulnerable carbon’. While *all* carbon in peatlands might be lost eventually, good data on this does not exist, so we looked at subsidence over 30 years, assuming that peatlands converted to palm oil, for example, would not be restored within several decades. This gives us a realistic but conservative estimate of the proportion of SOC in peatlands that would be vulnerable in a typical conversion event. In tropical peatlands, we estimate that 89% of the original SOC is vulnerable. This percentage is based on average annual loss of 15 MgC ha^{-1}

following a conversion event, reaching 450 MgC ha^{-1} within 30 years (and compared to the the original 504 MgC ha^{-1} as captured in Table S4). The 15 MgC ha^{-1} is an expert estimate of carbon loss based on IPCC emissions factors of 11-20 MgC ha^{-1} per year for plantations on tropical peatlands as well as documented subsidence rates of tropical peat of 4-5 cm / yr following conversion events[44]. For temperate and boreal peatlands, rate of carbon loss is somewhat lower, and we estimate that 27% of the original soil carbon is vulnerable following a conversion. This is again based on IPCC ranges, from which we assumed a conservative annual loss of 4.5 MgC ha^{-1}, reaching 135 MgC ha^{-1} over 30 years (compared to the original 500 MgC ha^{-1} as captured in Table S3). If drainage is stopped and/or restoration is initiated soon after conversion, some of the carbon loss can be prevented, however, this avoided emissions scenario is rare in peatlands, and beyond the scope of this analysis.

Recoverability of ecosystem carbon stocks

To determine carbon recoverability for each ecosystem, we used average sequestration rates for biomass and soils. Though these could be assessed for any timeframe, for the purposes of Figures 2 and 5 in the main text, we looked at recoverability over 30 years as a key illustrative example given the need to reach net-zero emissions by mid-century. Recovery can include natural regeneration (reducing threats and allowing the ecosystem to recover on its own) as well as active restoration / planting. The deficit between the 'vulnerable carbon' and the carbon that can subsequently be recovered within 30 years is considered the 'irrecoverable carbon'.

Biomass recovery

Forest biomass (AGC and BGC) rates are based on 2,790 observations of carbon accumulation in forests across 450 sites[65]. To assess recoverable carbon within 30 years, we applied a best fit linear equation of forest carbon with respect to either stand age or log of stand age, whichever provided a better fit, and looked at the carbon density at year 30 (Table S5).

Supplementary Table 5: Average biomass recovery in 30-year-old forests

Ecosystem	**Biomass recovery in 30 years (MgC ha^{-1})**
Boreal forest	43.2
Temperate broadleaf forest	50.3
Temperate conifer forest	48.5
Tropical moist forest	94.4
Tropical dry forest	65.5

For grassland ecosystems, where peak biomass is achieved prior to 30 years of recovery, we assumed that the sequestration rate was equal to the total stock observed in these ecosystems divided by the biomass turnover time. Total stocks were taken to be those tabulated above from the Xia et al. 2014 grassland aboveground biomass carbon density map[25] and corresponding root-to-shoot ratios. Turnover times were taken from an ecosystem specific meta-analysis[66] whereby we assumed that root biomass turnover is representative of total grassland biomass stocks since roots comprise the majority of the total stock, and that montane grasslands were representative of those reported as “boreal grasslands”. Mangrove biomass sequestration rates are not well-constrained, so to estimate mangrove biomass recovery, we multiplied our best expert estimate (by co-author Jen Howard) of annual sequestration by 30 years. The other coastal ecsoystems, seagrasses and marshes store the vast majority of their carbon in their soils, and even an estimate of annual sequestration was not available; however given the low initial biomass values, we assumed full biomass recovery within 30 years for these coastal ecosystems.

Supplementary Table 6: Average biomass recovery rates in grasslands and mangroves

Ecosystem	Biomass sequestration rate (MgC ha^{-1})	Source(s) for sequestration rate	Biomass recovery over 30 years (MgC ha^{-1})
Temperate grassland	1.95	Xia et al 2014 & Gill & Jackson 2000[29,66]	Full recovery
Tropical grassland	2.36	Xia et al 2014 & Gill & Jackson 2000	Full recovery
Montane grassland	0.50	Xia et al 2014 & Gill & Jackson 2000	Full recovery
Mangroves	2.69	Expert estimate	80.7
Note: Peatlands were excluded from this table because peatlands underly other aboveground land-uses. Annual sequestration rates for seagrasses and marshes are not well documented but we assumed full recovery.			

Soil organic carbon recovery

We determined whether SOC lost during the initial conversion could be fully recovered through subsequent restoration by applying restoration CRFs and EFs to the post-conversion SOC stock determined previously.. Due to a lack of globally consistent emissions factors, we divided our analysis into temperate and tropical zones to conform with data availability.

Boreal Forests

As mentioned previously, we assume no net change to initial boreal forest SOC stocks following wood harvest, so they were not considered in these calculations.

Temperate Forests

As mentioned previously, we assume no net change to temperate forest SOC stocks following wood harvest in the main assessment of 'irrecoverable carbon', but we did model forest recovery from row-crop cultivation using a representative CRF from Poeplau et al. 2011 as described above to determine the additional 'irrecoverable carbon' in temperate forests should agriculture the driver of forest loss.

Temperate Grasslands

Similar to the method used to determine SOC losses due to temperate grassland conversion, we used CRFs describing SOC gains resulting from restoration of croplands to grassland[42] to determine how much of the vulnerable carbon could be recovered within 30 years if the ecosystem reverted to the previous land use. Like the previous conversion CRF, this restoration CRF considers MAT and clay content in its predictions of SOC gain which were again represented using WorldClim2 and SoilGrids, respectively. The CRF was applied to the previously determined post-conversion SOC as before using a bootstrapping procedure to propagate and quantify uncertainty associated with the spatial variation of SOC and its covariates and the uncertainty of the model coefficients. This procedure resulted in a novel distributions of (i) SOC gain and (ii) post-restoration SOC stocks, from which we report the median and spread.

Tropical Forests and Grasslands

Emissions factors (EFs) were, likewise, used to determine expected gains to the post conversion SOC stocks of tropical ecosystems due to restoration. Once again, these EFs were taken from the meta-analysis of Don et al. 2011[43] and represent the average total SOC gain (%) resulting from restoration of croplands to either (i) secondary forest or (ii) grasslands. While EFs don't allow for the explicit consideration of change over a specified time period, those used represent the mean of observed changes of grassland and forest restoration, 22 (SE = 5) and 32 (SE = 7) years, respectively, after restoration was initiated and thus largely conform with our definition of irrecoverable carbon.

We applied these EFs to the previously determined post-conversion SOC stocks for the corresponding tropical ecosystems. Once again, EFs were adjusted such that they represent change to a depth of 30 cm as and were applied to the SOC estimates using the same bootstrapping procedure to propagate and quantify uncertainty associated with the spatial variation of SOC and the uncertainty of the depth correction and the EF estimate. This procedure resulted in a novel distributions of (i) SOC gain and (ii) post-restoration SOC stocks, from which we report the median and spread (Table S6).

Supplementary Table 7: Summary of modelled SOC loss due to conversion for agriculture and potential restoration by ecosystem

Ecosystem	Original median SOC (mean absolute deviation) (MgC ha^{-1})	Median % SOC lost in disturbance (mean absolute deviation)	Median SOC after disturbance (mean absolute deviation) (MgC ha^{-1})	Median % SOC that could be recovered with restoration (mean absolute deviation)	Median SOC after recovery (mean absolute deviation) (MgC ha^{-1})	Median % irrecoverable SOC (mean absolute deviation)
Temperate broadleaf forest (young)	137 (±20)	-34 (±19)	88 (±29)	22 (±14)	106 (±31)	19 (±19)
Temperate broadleaf forest (old)	137 (±20)	-34 (±19)	88 (±29)	22 (±14)	106 (±31)	19 (±19)
Temperate conifer forest (young)	138 (±18)	-16 (±16)	113 (±27)	11 (±11)	124 (±26)	9 (±15)
Temperate conifer forest (old)	138 (±18)	-16 (±16)	113 (±27)	11 (±11)	124 (±26)	9 (±15)
Tropical moist forest (young)	92 (±13)	-18 (±12)	74 (±15)	45 (±7)	92 (±22)	0 (±19)
Tropical moist forest (old)	92 (±13)	-23 (±15)	70 (±17)	45 (±7)	92 (±24)	0 (±22)
Tropical dry forest (young)	67 (±8)	-18 (±12)	54 (±11)	45 (±7)	67 (±16)	0 (±19)
Tropical forest (old)	67 (±8)	-23 (±15)	51 (±12)	45 (±7)	67 (±18)	0 (±22)
Temperate grassland	73 (±16)	-39 (±6)	43 (±11)	59 (±26)	68 (±18)	6 (±13)
Tropical grassland	40 (±9)	-23 (±15)	30 (±9)	45 (±7)	40 (±13)	0 (±22)
Montane grassland	101 (±22)	-34 (±5)	66 (±16)	25 (±16)	85 (±21)	16 (±10)

Notes: Any modeled values less than 0% were changed to 0% to reflect full recovery of the C content in 30 years. The median % C recovery over 30 years is relative to the pre-conversion SOC stock. A model for boreal SOC loss was not available, but not material to our analysis because boreal forests are primarily threatened by forestry / logging and unlikely to be converted to agriculture.

Coastal Ecosystems and Peatlands

SOC recovery rates for coastal ecosystems and peatlands were estimated based on literature review.

Supplementary Table 8: Average soil carbon recovery rates by major ecosystem type

Ecosystem	**Typical SOC sequestration rate (MgC ha^{-1} yr^{-1})**	**% carbon recovery over 30 years**	**Source / explanation**
Mangroves	1.68	33%	Taillardat et al 2018[67]
Seagrasses	0.83	51%	
Marshes	2.42	68%	
Boreal / Temperate Peatlands	0	0%	Peatland restoration following disturbance may reduce emissions but will not lead to net sequestration[27]
Tropical Peatlands	0	0%	
Notes: For coastal ecosystems, % recovery is estimated based on the SOC sequestration rate x 30 years / the average original carbon density.			

Global estimates of irrecoverable carbon

We estimated the typical amount of 'irrecoverable carbon' per hectare by subtracting the 'recoverable carbon' from the 'vulnerable carbon'. The summary numbers in Table S8 below inform Figure 2 in the Main Text.

Supplementary Table 9: Average irrecoverable carbon density 30 years following loss, by ecosystem

Ecosystem	Irrecover-able biomass carbon	Irrecover-able SOC	Vulnerable but recoverable biomass carbon	Vulnerable but recoverable SOC	Biomass carbon not vulnerable to disturbance	SOC not vulnerable to disturbance	Total average carbon
Boreal forest	28.0	0.0	43.2	0.0	0.0	193.0	**264.2**
Temperate broadleaf forest (young)	33.3	0.0	50.3	0.0	0.0	137.0	**220.6**
Temperate broadleaf forest (old)	94.1	0.0	50.3	0.0	0.0	137.0	**281.4**
Temperate conifer forest (young)	44.7	0.0	48.5	0.0	0.0	138.0	**231.2**
Temperate conifer (old)	96.1	0.0	48.5	0.0	0.0	138.0	**282.6**
Tropical moist forest (young)	0.0	0.0	91.4	0.0	0.0	92.0	**183.4**
Tropical moist forest (old)	96.6	0.0	94.4	22.0	0.0	70.0	**283.0**
Tropical dry forest (young)	0.0	0.0	40.7	13.0	0.0	54.0	**107.7**
Tropical dry forest (old)	58.3	0.0	65.5	16.0	0.0	51.0	**190.8**
Temperate grassland	0.0	5.0	4.4	25.0	0.0	43.0	**77.4**
Tropical grassland	0.0	0.0	2.8	10.0	0.0	30.0	**42.8**
Montane grassland	0.0	16.0	3.2	19.0	0.0	66.0	**104.2**
Mangroves	90.4	242.0	51.0	50.4	0.0	68.6	**502.4**
Seagrasses	0.0	52.9	2.9	24.9	0.0	30.2	**110.9**
Marshes	0.0	80.4	10.5	72.6	0.0	102.0	**265.5**
Boreal /temperate peatlands	NA	135.0	NA	0.0	NA	365.0	**500.0**
Tropical peatlands	NA	450.0	NA	0.0	NA	54.0	**504.0**

Note: All values are in MgC ha^{-1}.

We then estimated the amounts of irrecoverable carbon and vulnerable-but-recoverable carbon in manageable ecosystems globally. These estimates are based on the global geographic extent of each ecosystem (generated using the Dinerstein biomes crossed with ESA land classes as described above, or literature review in the case of coastal and peatland ecosystems) and the average values of irrecoverable carbon and vulnerable but recoverable carbon by hectare and should be considered indicative values. Because our geographic extent numbers only consider the primary landcover in each biome (e.g., forested land classes within the boreal forest biome), our estimates of global irrecoverable carbon are conservative.

Supplementary Table 10: Global irrecoverable carbon and vulnerable but recoverable carbon 30 years following loss, by ecosystem

Ecosystem	**Global geographic extent (1000 km^2)**	**Irrecoverable carbon density (MgC ha^{-1})**	**Global irrecoverable carbon (Gigatonnes, estimated)**	**Vulnerable but recoverable carbon density (MgC ha^{-1})**	**Global vulnerable but recoverable carbon (Gigatonnes, estimated)**
Boreal forest	10,700	27	30	44	47
Temperate broadleaf forest	4,960	82	41	49	24
Temperate conifer forest	2,410	87	21	47	11
Tropical moist forest	11,700	66	77	113	132
Tropical dry forest	842	33	2.8	79	6.7
Temperate grassland	7,000	5	2.5	29	15
Tropical grassland	5,080	0	0	13	9.0
Montane grassland	2,600	16	4.2	22	5.8
Mangroves	145	335	4.9	99	1.5
Seagrasses	450	36	1.6	44	1.3
Marshes	210	88	1.8	76	1.7
Boreal peatlands	3,609	135	49	0	0
Temperate peatlands	587	135	2.5	0	0
Tropical peatlands	185	450	26	0	0
Total			**264**		**256**

Note: Because global geographic extent of forest ecosystems could not be delineated by 'young' and 'old', we used typical values across all age classes by ecosystem. The geographic extent of coastal ecosystems was derived from Howard et al, 2017[5] and peatlands from Leifeld et al, 2018[11].

Recent loss rates

We used recent loss rates in each ecosystem based as documented in the literature to estimate the amount of irrecoverable carbon and vulnerable but recoverable carbon that could be at risk of release to the atmosphere over the next decade if recent loss rates continued. Timeframes differed slightly based on available data. For all forests and mangroves, we looked at annual average loss rates between 2000-2012. Other ecosystems are not tracked as consistently, so we used historical loss rates as available in the literature. These are documented in Table S11. Loss rates are indicative only and not necessarily predictive of future risk.

Supplementary Table 11: Historical/recent loss rates by ecosystem and carbon at risk

Ecosystem	% loss / year	Source
Boreal forest	0.18%	Based on Hansen et al. 2013;[68] 2000-2012 loss rates at 25% tree cover, refined using Curtis et al. 2018 to exclude tree cover loss due to wildfire[47] (not considered an anthropogenic driver)
Temperate broadleaf forest	0.35%	
Temperate conifer forest	0.28%	
Tropical moist forest	0.45%	
Tropical dry forest	0.58%	
Temperate grassland	0.14%	Based on Ramankutty et al. 1999[69] reported loss rate of 0.7 M ha per year (1980-1990), as cited in Griscom et al. 2017[70]
Tropical grassland	0.14%	Based on Ramankutty et al. 1999 reported loss rate of 1 M ha per year (1980-1990), as cited in Griscom et al. 2017
Montane grassland	0.14%	Assumed same loss rate as temperate and tropical grasslands
Mangroves	0.13%	Based on Global Mangrove Watch loss rates from 2000-2012[70]
Seagrasses	0.95%	Based on Waycott et al. 2009;[71] loss rates from 1980-2000.
Marshes	0.25%	Estimated based on Bridgham 2006;[72] 25% marsh loss since the 1800s (we assumed most loss occurred in the last century).
Boreal peatlands	0.0%	Based on recent loss rates reported Leifeld et al, 2019[73] (1990 to now)
Temperate peatlands	0.0%	
Tropical peatlands	0.6%	

Time to recovery

While 30 years was the key timeframe considered in our analysis, the recoverability criterion may be applied over any timeframe. To estimate the average number of years to recovery of vulnerable carbon by ecosystem (as shown in Table 2 in the Main Text), we used average biomass and soil sequestration rates and/or models (the same ones described above) to find the length of time necessary for all previously lossed carbon to be fully recovered after restoration is initiated. We used average vulnerable carbon densities by ecosystem, or the typical amount of carbon lost per hectare in the most common conversion event. In forest ecosystems, where more biomass carbon that SOC is originally vulnerable to loss during a conversion, the time to recovery is driven primarily by the biomass. Conversely, in grasslands and coastal ecosystems, the vulnerable biomass carbon would typically recover fully before the vulnerable SOC, so time to full recovery is driven by SOC. For peatland ecosystems, sequestration rates are extremely slow and not well-constrained, so our time to recovery is conservative and based on an expert estimate (by co-author Susan Page). To recover completely, tropical peatlands not only need to reestablish hydrological functioning but also vegetation cover that is capable of sequestering carbon and transferring it to an accumulating peat layer, and there is no field data to guide how long this might take.

Supplementary Table 12: Years to recovery of vulnerable carbon

Ecosystem	Average vulnerable biomass carbon (MgC ha^{-1})	Average time to recover biomass carbon (years)	Average vulnerable SOC (MgC ha^{-1})	Average time to recover SOC (years)
Boreal forest	71.5	**101**	0	NA
Temperate broadleaf forest	131.0	**78**	0	NA
Temperate conifer forest	134.3	**78**	0	NA
Tropical moist forest	160.1	**60**	19	29
Tropical dry forest	99.2	**77**	14	29
Temperate grassland	0.8	~1	30	**35**
Tropical grassland	1	~1	10	**19**
Montane grassland	0.6	~1	35	**205**
Mangroves	141.4	15	256	**153**
Seagrasses	2.6	5	78	**93**
Marshes	18.2	2	153	**64**
Boreal peatlands	NA	NA	135	**>100**
Temperate peatlands	NA	NA	135	**>100**
Tropical peatlands	NA	NA	450	**>200**

Note: Values in bold are the longer time to recovery and thus the number of years used in Table 2.

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