Protecting irrecoverable carbon in Earth's ecosystems

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Preface

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 gigatonnes 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.

Main Text

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 gigatonnes (Gt), equal to about 114 Gt of carbon, for a two-thirds chance of staying below 1.5 ˚C[1]. Given 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 maintaining and enhancing 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 (i.e. ≤USD100 / t CO_2e) needed by 2030[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 and regarding the relative reversibility of their loss. Are there ecosystem carbon stocks that, if lost, could not recover within a time scale 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.

1. ***Manageability*** *at the local scale* **-** Whether an ecosystem's carbon stock is affected primarily by direct human actions that either maintain (e.g., conservation), increase (e.g., restoration), or decrease (e.g., 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.
2. ***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.
3. ***Recoverability*** *of ecosystem carbon, if lost* - The fraction of vulnerable carbon that, if lost, could be recovered following a conversion event, assessed as a function of average sequestration rates and time. 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 Material). 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. 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, which 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, 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[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 in a low-emissions scenario (RCP2.6 compared to RCP8.5)[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, and lakes, rivers, and streams (see Supplementary Material for more detailed explanations).

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 (e.g., converting a forest to cropland) or increase them through restoration (e.g., 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 (i.e., its 'carbon density'; Table 1). We considered carbon in aboveground biomass (plant stems, trunks, leaves; AGC), belowground biomass (roots; BGC), and soil organic matter (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[28], and literature review for peat and coastal ecosystems (see Supplementary Material). This high-level assessment found substantial variation among ecosystems, 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] (see Table S9). 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 as follows: agriculture for grasslands, peatlands, and tropical forests; forestry for boreal and temperate forests; and aquaculture/development for coastal ecosystems[21,33,34]. These common drivers were used to estimate the maximum 'vulnerable carbon' per hectare by major ecosystem type (Table S4).

When conversion occurs, ecosystems typically lose all of their biomass carbon (AGC + 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[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 (e.g., 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 methods for modeling SOC loss in the Supplementary Material).

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-analyais in tropical forest and grassland soils[41], and average soil sequestration rates for coastal and peatland soils[42,43]. Our methodology is described in more detail in the Supplement, Tables S5-8.

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 a specified timeframe. Figure 1 illustrates recovery of carbon for a typical terrestrial ecosystem in which all of the biomass carbon is lost relatively quickly following a major conversion event (e.g., shifting agriculture) whereas only a portion of the soil carbon is lost. 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 roughly 30 years to align with 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 (Figure 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 harbor 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 U.S.[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 (Table S7).

Based on estimated, conservative geographic extents (Table 1) and average irrecoverable carbon densities across ecosystems (Figure 2), ecosystems with carbon that is manageable through direct, localized human actions contain at least 264 Gt of carbon 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 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 United States[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[49].

The risk of carbon release due to human land-use decisions varies widely across ecosystems due to 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 (e.g., 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 (e.g., 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 outbreak in forests such that areas of western Canada and Siberia may have already become net sources of carbon 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 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 passed 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 and also by 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 charactertization 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 (e.g., 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 (e.g., Sri Lanka, Colombia[66,67]) or as economic development creates new agricultural frontiers (e.g., 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 (e.g., 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, 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 (see Figure 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 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 per-hectare 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 and 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 midcentury, a few stand out as warranting particular attention and proactive protection. Older, intact forests are effectively long-term investments in carbon storage that has been sequestered over decades to centuries. Seventy percent of the remaining 19.5 M km^2 of tropical forests are largely intact[73], meaning they are largely 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 harbor 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 ºC 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+ 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 (NDCs) 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, and should push 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 GtC 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, 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, similar 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 greenhouse gases only with human intervention, part of 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 that 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.

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 it 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. S.P. provided data and guidance on peatlands.

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Data availability

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

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Table 1: Estimated magnitude of global carbon stocks based on geographic extent and average carbon content per hectare
Typical carbon density is the sum of typical values for aboveground, belowground, and soil organic carbon. Note that the geographic extent of peatlands captured above overlaps with other ecosystems: 56% of the peatland area overlaps with forests and 21% overlaps with grasslands, while the remaining 16% underlies croplands or areas of mixed land-use[31]. 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 as described in the Supplement. See Supplementary Material for sourcing information.

Ecosystem	Global geographic extent (1000 km^2)	Typical carbon density ($t\ C\ ha^{-1}$)	Estimated global carbon content (Gt C)	Recent loss rate (%/year)
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	500	181	0.00%
Temperate peatlands	185	500	9.3	0.00%
Tropical peatlands	587	504	30	0.60%
Temperate grasslands	5,080	77	39	0.14%
Tropical grasslands	7,000	93	30	0.14%
Montane grasslands	2,600	263	27	0.14%

Figure 1: Illustration of vulnerable and irrecoverable carbon in a hypothetical terrestrial ecosystem

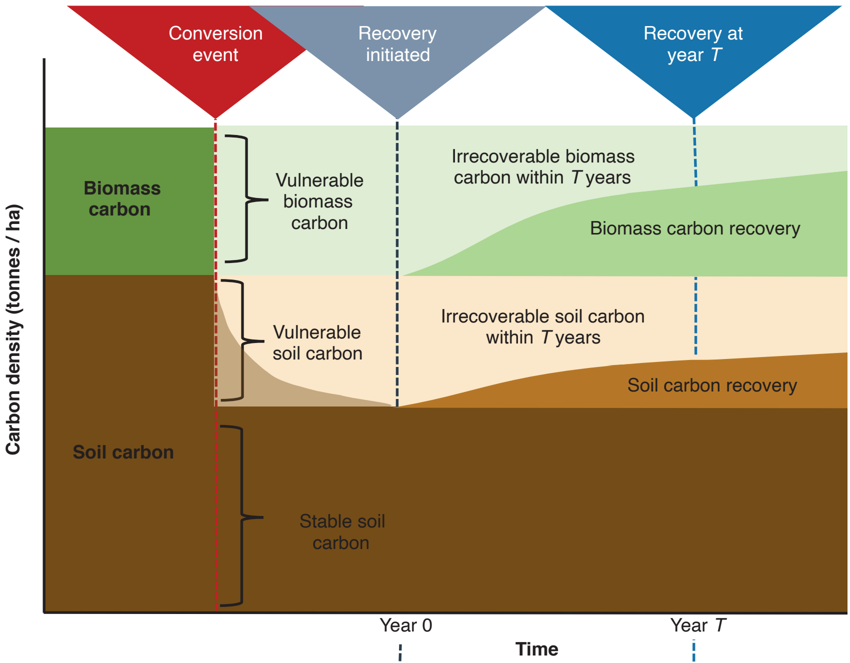

Figure 2: Estimated amount of carbon that is recoverable or irrecoverable in major ecosystems within 30 years. Colors distinguish carbon in soil (brown colors) and biomass (green colors) pools. Dark shades separate irrecoverable carbon from carbon that is either not vulnerable (light gray) or is vulnerable but recoverable (other light shades).

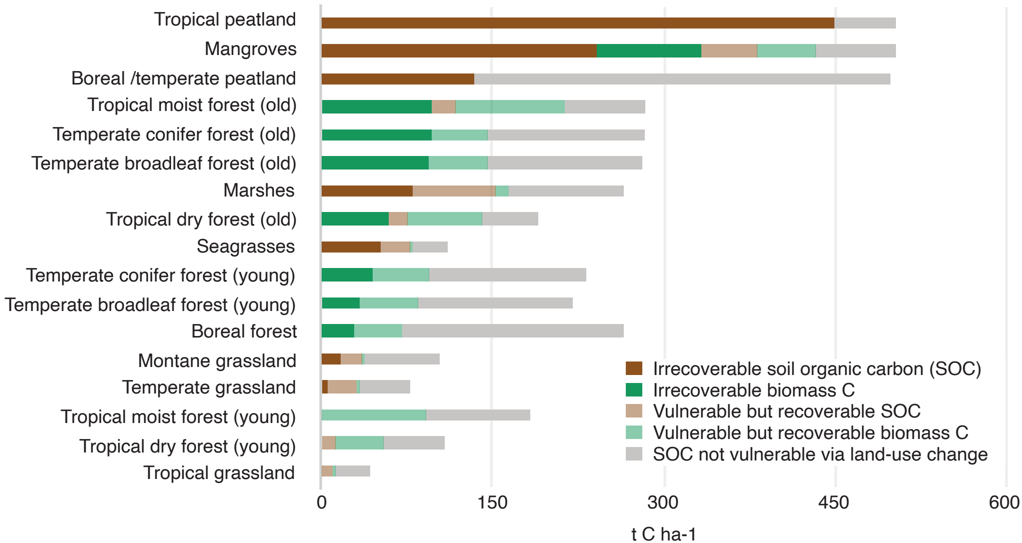

Table 2: Estimated time to full carbon recovery following conversion across major ecosystems
Time to recovery is based on average sequestration rates in biomass and carbon response functions in soils (see Supplement for details). Carbon accumulation curves of older forests are complex, without a fixed "maximum" carbon storage level, so years to full recovery are approximate and should be considered conservative estimates.

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

Figure 3 : Estimated annual carbon loss and fraction irrecoverable for major ecosystem types
Size of outer bubble indicates the ecosystem's estimated global carbon pool; size of inner bubble corresponds to the ecosystem's estimated global irrecoverable carbon pool. The x axis shows mean vulnerable carbon densities by ecosystem (also illustrated in Figure 2). Loss rates plotted on the y axis are recent or other historical anthropogenic loss estimated ecosystem-wide (see Table S11). Grassland bubbles from left to right are: tropical grasslands, temperate grasslands, and montane grasslands.

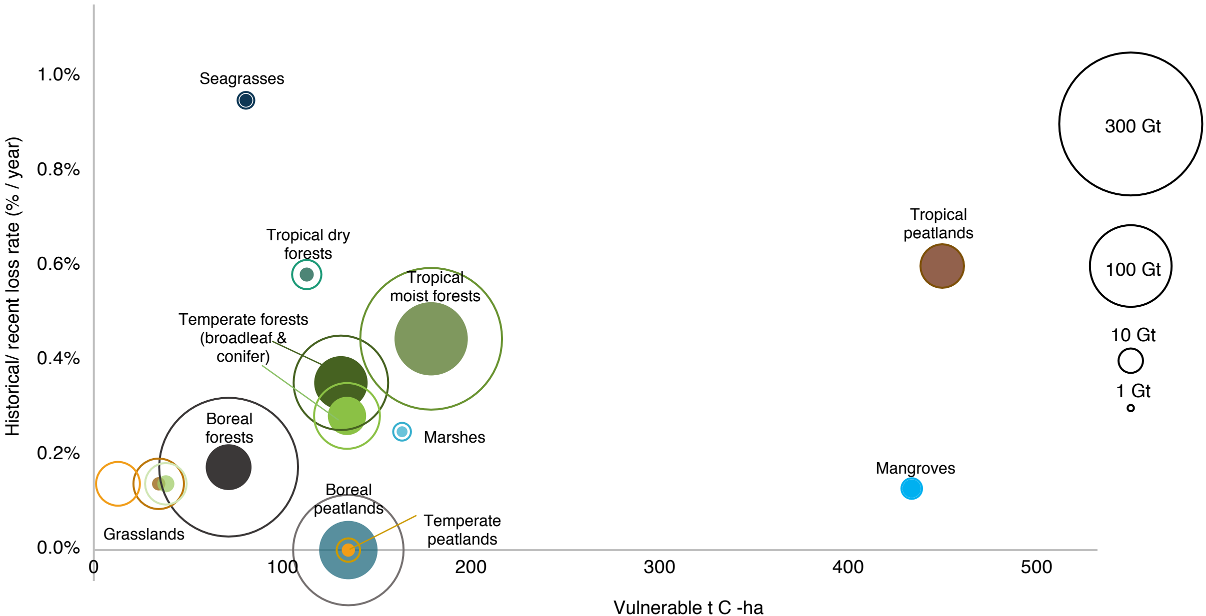

Figure 4: Different types and levels of risk suggest different strategies for protecting irrecoverable carbon in ecosystems.