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Mapping the irrecoverable carbon in Earth's ecosystems

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Avoiding catastrophic climate change requires rapid decarbonization and improved ecosystem stewardship at a planetary scale. The carbon released through the burning of fossil fuels would take millennia to regenerate on Earth. Though the timeframe of carbon recovery for ecosystems such as peatlands, mangroves and old-growth forests is shorter (centuries), this timeframe still exceeds the time we have remaining to avoid the worst impacts of global warming. There are some natural places that we cannot afford to lose due to their irreplaceable carbon reserves. Here we map 'irrecoverable carbon' globally to identify ecosystem carbon that remains within human purview to manage and, if lost, could not be recovered by mid-century, by when we need to reach net-zero emissions to avoid the worst climate impacts. Since 2010, agriculture, logging and wildfire have caused emissions of at least 4.0 Gt of irrecoverable carbon. The world's remaining 139.1 ± 443.6 Gt of irrecoverable carbon faces risks from land-use conversion and climate change. These risks can be reduced through proactive protection and adaptive management. Currently, 23.0% of irrecoverable carbon is within protected areas and 33.6% is managed by Indigenous peoples and local communities. Half of Earth's irrecoverable carbon is concentrated on just 3.3% of its land, highlighting opportunities for targeted efforts to increase global climate security.

The concept of irrecoverable carbon is intended to discriminate among the billions of tonnes of carbon stored in the biosphere[1] on the basis of three criteria relevant for conservation efforts. We assess ecosystem carbon stocks according to: (1) how they can be influenced by direct and local human action ('manageability'), (2) the magnitude of carbon lost upon disturbance ('vulnerability') and (3) the recoverability of carbon stocks following loss ('recoverability'). Applying the three criteria across all terrestrial, coastal and freshwater ecosystems reveals that some places contain irrecoverable carbon, or manageable carbon stocks that, if lost, represent a permanent debit from the remaining carbon budget[2], or the amount of carbon humans can emit while still keeping global warming within safe levels (1.5–2 °C above pre-industrial levels)[3]. Effective strategies to reduce the risk of catastrophic climate change will need to locate large irrecoverable carbon reserves that are at risk due to anthropogenic action and prioritize their protection and sustainable management, alongside efforts to phase out fossil fuel emissions and restore degraded ecosystems.

The concept of irrecoverable carbon in ecosystems was introduced in a 2020 study[2] which synthesized ecosystem-level data to estimate the magnitude of irrecoverable carbon across major ecosystems. Here, we map irrecoverable carbon globally and at high resolution (300 m), using remotely sensed or modelled products that were created or substantially improved on within the last year[4–6]. The resulting spatial product is relevant for both global and national planning and helps answer important questions which can only be addressed with spatially explicit data. Specifically, we identify areas with recent losses of irrecoverable carbon as well as those that face near- or medium-term risks from land-use conversion or climate change. We also map areas where irrecoverable carbon is within state-designated protected areas (PAs) or Indigenous peoples and local communities' (IPLC) lands and thus potentially more secure. This spatial perspective on irrecoverable carbon and its conservation status can inform upcoming efforts to manage the biosphere, such as the Convention on Biological Diversity's (CBD) Post-2020 Global Biodiversity Framework as well as upcoming revisions of nationally determined contributions (NDCs) to the Paris Agreement to keep global warming well below 2 °C. The findings are also important for civil society groups advocating for increased access to climate finance, for multilateral donors and foundations as a spatial input to targeting conservation investments and for companies sourcing forest-risk commodities or engaging in carbon markets.

Mapping three key dimensions of ecosystem carbon stocks

Our irrecoverable carbon map (Fig. 1) identified irrecoverable carbon reserves that are manageable, are vulnerable to disturbance and could not be recovered by 2050 if lost today. While irrecoverability can be considered over any timeframe, we selected 30 years as the most policy-relevant scenario to align with the Paris Agreement goal to reach net-zero emissions by mid-century[7]. All major global climate models that simulate Paris-aligned emissions reductions over the next several decades take for granted that nature's vast carbon stocks will remain stored rather than emitted and that these natural areas will continue to sequester carbon[8]. To assess criterion 1, manageability, we created a 'total manageable carbon' map from a comprehensive suite of carbon datasets across terrestrial, coastal and freshwater ecosystems globally, considering both biomass car-

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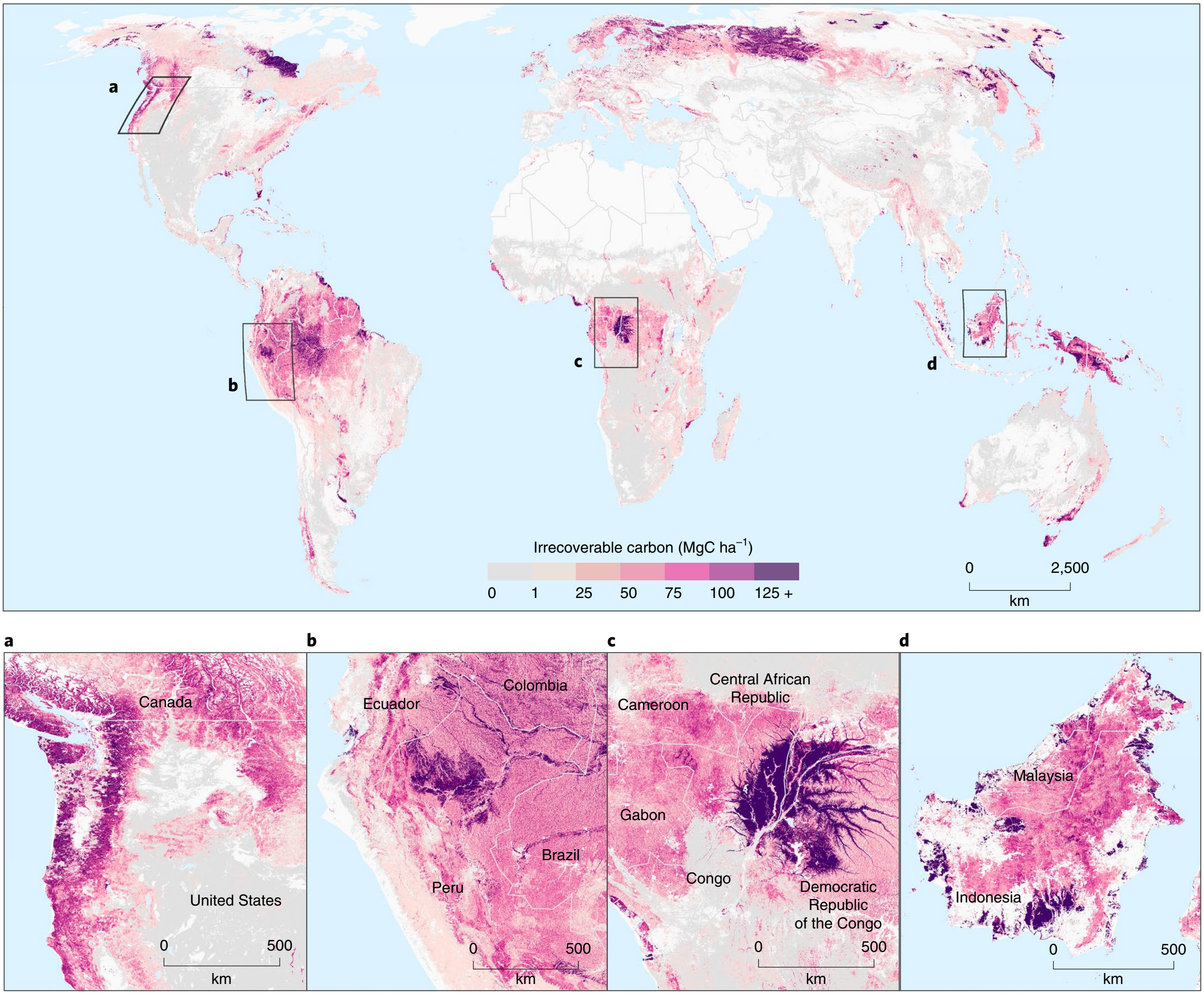

Fig. 1 | Irrecoverable carbon in Earth's ecosystems. a–d, Inlays show areas of high irrecoverable carbon density in the Pacific Northwest of North America (**a**), western South America (**b**), the Congo Basin (**c**) and the island of Borneo (**d**). Areas with zero irrecoverable carbon are displayed in grey to demonstrate the footprint of global manageable carbon.

bon[5] and soil organic carbon stocks to 30 cm depth globally or to 100 cm within inundated soils[6], the depths most relevant to common disturbances. To narrow our map to only manageable areas, we excluded cryosols, where permafrost soil carbon is imminently threatened due to warming itself and largely beyond the scope of direct management[9]. All other areas were considered manageable, either because carbon loss is driven by direct land-use conversion which could be halted or because climate change impacts affecting the area can potentially be directly mitigated through adaptive management. The resulting total manageable carbon map includes 731.7 ± 340.2 GtC.

To assess criterion 2, vulnerability, we quantified average carbon losses from biomass and soils due to the most common anthropogenic disturbances: conversion to agriculture in grasslands, wetlands and tropical forests; forestry in boreal and temperate forests; and aquaculture or built infrastructure in coastal ecosystems[10–12]. We considered the feasible loss events that would alter the land cover (for example, forest to soy field) as opposed to activities that might reduce the carbon content but not constitute full conversion (for example, forest degradation due to charcoal collection or selective logging). Vulnerable carbon is therefore the portion that would be lost in a hypothetical but typical conversion event; it does not characterize the likelihood of that conversion event. Note that directly incorporating irrecoverable carbon into climate mitigation strategies would require further assessing the likelihood of disturbance or conversion due to direct anthropogenic pressures or climate shifts.

Finally, we assessed criterion 3, recoverability, by applying average sequestration rates representing the effects of restoring the original land cover to determine the amount of vulnerable carbon that could not be restored within 30 years.

$$\text{Irrecoverable carbon} = \text{Vulnerable carbon} - \text{Recoverable carbon}$$

where 'Vulnerable carbon' is defined as sequestration in 30 years. Biomass carbon sequestration rates were derived from best-available averages for non-forest ecosystems[13,14] and, for forest ecosystems, from logarithmic equations based on 2,741 georeferenced measurements, differentiated by forest type and region[4]. We used logarithmic equations because they most closely resemble the sequestration curves documented in studies of forest regrowth over many decades[15,16]. Soil carbon sequestration was modelled by applying carbon response functions or sequestration factors in forests and grasslands[17,18] and estimated using average annual sequestration rates in wetlands[19].

We found that Earth's ecosystems contain 139.1 ± 443.6 Gt of irrecoverable carbon. (Because irrecoverable carbon cannot be negative, we restrained the uncertainty to 0–582.7 Gt.) For comparison, humans have added 651 GtC to the atmosphere through burning fossil fuels and through land-use change, causing the average global surface temperate to rise 1.07 °C, even with more than half (56%) of this carbon being reabsorbed by lands and oceans[3]. The Intergovernmental Panel on Climate Change (IPCC) estimates the remaining carbon budget to be about 109 GtC for a two-thirds chance of staying below 1.5 °C (or 313 GtC for 2 °C)[3]. Loss of irrecoverable carbon cuts into this budget.

Irrecoverable carbon represents 20% of the total manageable ecosystem carbon. Globally, 79.0 Gt (57%) of irrecoverable carbon is found in biomass while 60.0 Gt (43%) is in soils. Additional carbon could be both vulnerable and irrecoverable under future scenarios in which drivers of land-use conversion change from the current scenario. For example, northward expansion of agriculture in temperate and boreal ecosystems[20] could make an additional 18.4 GtC both vulnerable and irrecoverable.

The largest and highest-density irrecoverable carbon reserves are in the tropical forests and peatlands of the Amazon (31.5 Gt), the Congo Basin (8.2 Gt) and Insular Southeast Asia (13.1 Gt); the temperate rainforest of northwestern North America (5.0 Gt); the boreal peatlands and associated forests of eastern Canada and western Siberia (12.4 Gt); and mangroves and tidal wetlands globally (4.8 Gt) (Fig. 1). Our analysis did not consider non-carbon dioxide (CO_2) driven climate forcing; hence irrecoverable carbon alone may overestimate the climate benefits of forests with low albedo (for example, boreal forests) and underestimate the benefits of tropical forests due to rainfall regulation through evapotranspiration[21,22].

Recent loss of irrecoverable carbon

Places with recent losses of irrecoverable carbon represent urgent priorities for intervention given the effectively permanent nature of this loss. Since 83% of irrecoverable carbon areas have tree cover, loss estimates based on global forest change[23] are a reasonable proxy for irrecoverable carbon loss over the last decade. An estimated 4.0 Gt of irrecoverable carbon was lost between 2011 and 2019, an average of 0.45 Gt irrecoverable carbon annually. Tree cover loss is caused primarily by commodity-driven deforestation for beef, soy, palm oil and wood fibre and shifting agriculture in the tropics and by forestry and wildfire in temperate and boreal zones[10]. This loss equates to 1.65 $GtCO_2$ equivalent, meaning up to a fifth of the 8.1 $GtCO_2e$ in annual emissions from deforestation and other disturbances[24] could be irreversible through ecosystem restoration for at least three decades. Irrecoverable carbon loss from ecosystems equates to 5% of fossil fuel emissions in 2019[25]. Ecosystems such as peatlands, mangroves and old-growth forests have century-long timescales for carbon recovery[2] that exceed the timeframe we have remaining to limit the accumulation of atmospheric CO_2 to safe levels.

Irrecoverable carbon loss in peatlands is difficult to track accurately since global remote sensing products only capture visible land cover or tree canopy changes. Peatlands drained for agriculture or forestry are estimated to cover >50 million hectares (ha) globally and release 0.5 GtC annually[11], all of which is irrecoverable due to the centuries-long timescales required for peat formation. Improved spatial maps of peatland extent and disturbance would increase our estimate of recent irrecoverable carbon losses. Grassland losses remain difficult to quantify over large areas due to the spectral similarity between grasses and the crops that often replace them; available estimates are all regional and no dedicated global estimate has yet been generated.

Future risks to irrecoverable carbon

Under business as usual, it is possible for at least 4.5 Gt of irrecoverable carbon to be lost each decade due to deforestation alone, meaning at least 10% of the irrecoverable carbon stock globally would be gone by 2050. However, the spatial distribution, types and pace of future risks cannot simply be extrapolated from historical trends. While areas of current irrecoverable carbon loss require immediate attention, a view towards future risks—both due to shifting human pressures and a changing climate—is needed to ensure these irrecoverable carbon reserves are maintained over the coming decades. Figure 2 provides an initial risk assessment and review of strategy options across terrestrial ecoregions. Ecoregions are 'relatively large units of land containing a distinct assemblage of natural communities and species'[26], making them ecologically relevant units for planning and prioritization. To approximate future risks to irrecoverable carbon due to direct anthropogenic pressures (Fig. 2a), we use the Human Footprint Index, which maps human pressures on natural land due to the built environment, population density, electric infrastructure, crop lands, pasture lands, roads, railways and navigable waterways[27]. We assumed that areas with a high Human Footprint Index are most likely to experience future anthropogenic disturbance. To estimate risks to irrecoverable carbon due to climate change at the ecoregion level, we use the Climate Stability Index[28], a zero-to-one metric representing how similar an ecoregion's future (in this case, 2050) climate is to its current climate, considering six climate variables. Climate change risks to irrecoverable carbon might include: warming temperatures that increase tree mortality[29]; changing precipitation patterns that increase the risk of peat combustion or forest fire[30]; sea-level rise and typhoons that can damage or subsume coastal ecosystems[31]; and tipping points beyond which an ecosystem may shift from a high-carbon to a low-carbon state[32].

There are many potential approaches to assessing future risks to irrecoverable carbon at different scales, from local to global. The Human Footprint Index maps preference historical pressure and may undervalue future risks to irrecoverable carbon in rapidly changing regions such as the Congo Basin and the island of New Guinea. The Climate Stability Index may undervalue climate change risks in regions such as the Amazon, which may face climate tipping points[33]. Alternative approaches to assess future land-use conversion risk could include the human modification gradient[34], development potential indices[35], spatially explicit predictions of future tree cover changes[36], maps of mining or agriculture concessions or analysis of regional land-use plans. See Supplementary Information and Supplementary Fig. 14 for one example of an alternative, pixel-based approach to future risk assessment.

Regardless of the methodology used to assess future risks, understanding the nature and severity of those risks spatially can inform the strategies necessary to secure irrecoverable carbon (Fig. 2b). Using our combination of the Human Footprint Index and the Climate Stability Index for illustrative purposes (Fig. 2a), we find that some ecoregions with high irrecoverable carbon, such as the Southern Hudson Bay taiga, the West Siberian taiga and the Congolian lowland forests, face high climate change risks but lower land-use conversion risks. In places with this profile, it may be possible to reduce some climate change risks through local strategies to increase ecosystem resilience, such as pest and fire management[37].

In other places, for example the tropical forests of Borneo, risks to irrecoverable carbon are primarily driven by anthropogenic pressures. In these high conversion-risk places, irrecoverable carbon can be secured by a variety of direct human actions at different scales. This might include the management of private lands for conservation; shifting national priorities towards protection of high-carbon

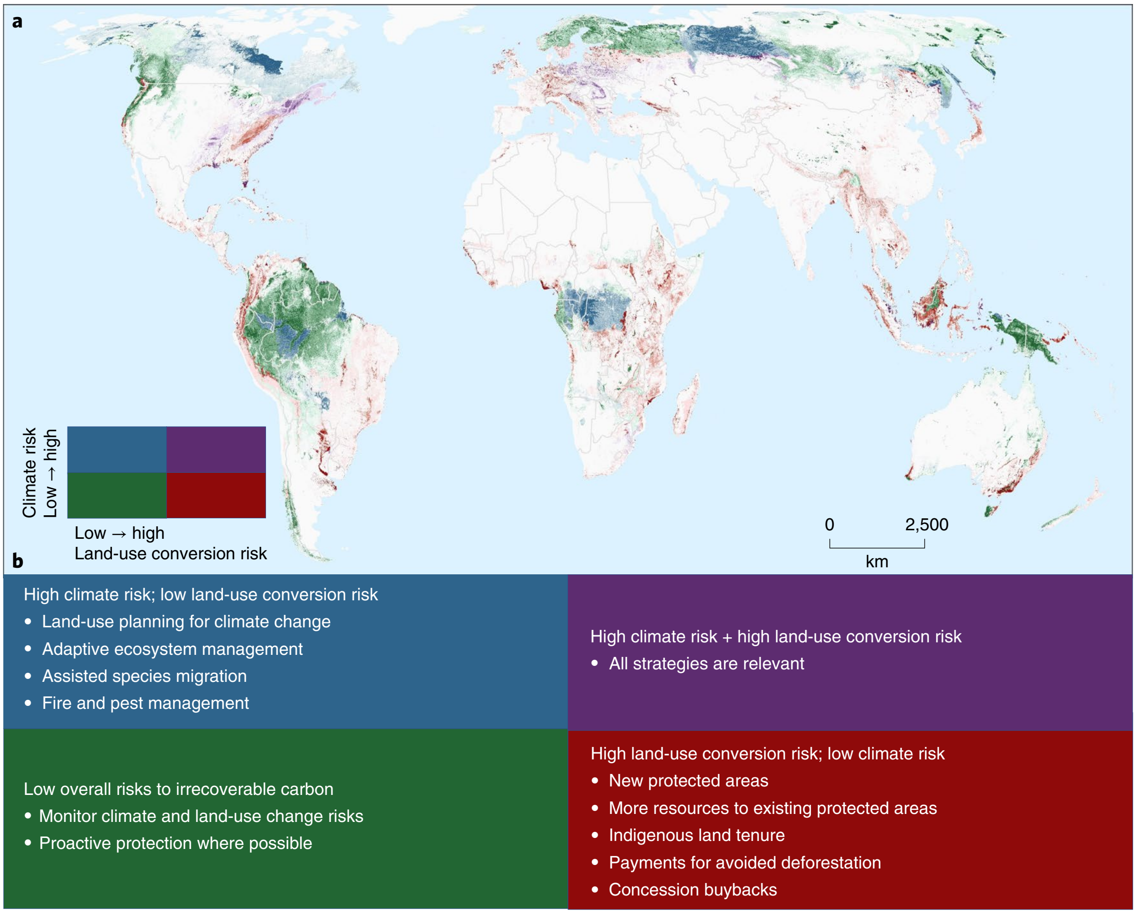

Fig. 2 | Climate and land-use conversion risks to irrecoverable carbon by ecoregion and strategies for risk mitigation. Irrecoverable carbon is shaded by density, with colours delineated by ecoregion according to their degree of human modification (with a Human Footprint Index of 6 or greater considered 'high') and climate change risk (with a Climate Stability Index of 0.5 or lower considered 'high'). Strategies for managing risks to irrecoverable carbon are depicted on the basis of the four major risk categories.

lands while concentrating development and agriculture on already converted or degraded areas; allocation of international finance to prioritize protection of lands with high irrecoverable carbon; enforcement of existing laws to maintain PAs; and recognition and support for IPLC rights.

For places facing both high climate risk and high land-use conversion risk, all strategies are relevant. Some irrecoverable carbon faces less immediate risk, including more than a third (47.3 GtC) found in intact forest landscapes[38], those remaining areas free of significant anthropogenic degradation. In places facing low levels of risk, irrecoverable carbon should still be identified, monitored for changes in threat and considered for proactive protection via PAs, community reserves or buffer zones to secure irrecoverable carbon before it becomes the next frontier of loss. To reduce climate change risks to irrecoverable carbon, global action to reduce emissions is the most important intervention, especially to avoid high-emissions scenarios to which some of these ecosystems would not be able to adapt.

Irrecoverable carbon in PAs and IPLC lands

Globally, half of the world's irrecoverable carbon is found on just 3.3% of its land area (4.9 million km^2), about equivalent to the land area of India and Mexico combined. This means that efforts to secure irrecoverable carbon from current and future risks could make rapid gains by first focusing on the areas with the highest concentrations of irrecoverable carbon per hectare. Ranking grid cells in descending order on the basis of irrecoverable carbon density, 50% of all irrecoverable carbon lies within a concentrated area comprising primarily of peatlands, mangroves, tropical wetlands and tropical forests (Fig. 3, top, and Supplementary Table 12 give more detail by ecosystem).

Assessing how much irrecoverable carbon already falls within state-designated PAs or IPLC lands provides an estimate of the magnitude of the irrecoverable carbon under some level of direct protection or management (Fig. 3, bottom). We find that 67.1 Gt of irrecoverable carbon (48.3% of the total) falls within either PAs or IPLC lands, while 51.7%—72.0 Gt—falls outside of these land designations. Specifically, 32.0 Gt (23.0%) of irrecoverable carbon is within PAs[39] and 46.7 Gt (33.6%) is within IPLC lands[40], with 11.6 Gt (8.3%) overlap.

While protected area designations do not guarantee conservation outcomes or long-term permanence[41], legally protected areas have been found to reduce tropical deforestation[42] and its associated emissions[43]. More than a third (11.3 Gt) of irrecoverable carbon within PAs is in Brazil, while Venezuela, Canada, Australia, Indonesia, the United States, Peru, the Republic of Congo and the Democratic Republic of Congo each protect between 1 and 2 Gt. Globally, 131 countries containing mapped IPLC lands cover nearly 30% of Earth's terrestrial surface[40] and 114 of these countries contain irrecoverable carbon. Similar to PAs, IPLC status does not guarantee conservation outcomes, however studies show that where legal land tenure exists in Amazonia (where 22.2% of IPLC-managed irrecoverable carbon is found), IPLCs

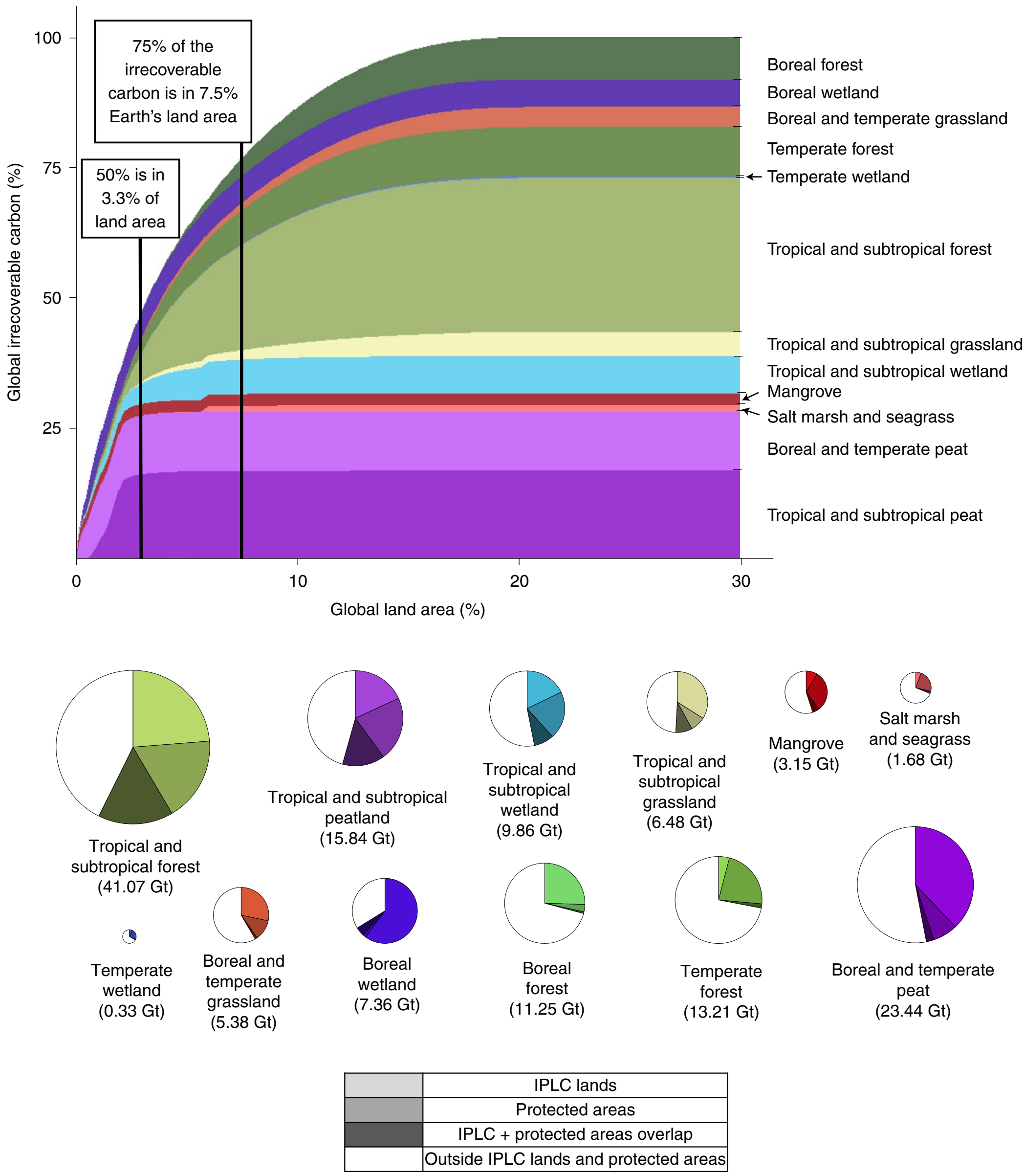

Fig. 3 | Irrecoverable carbon–area curve and proportion in Indigenous lands and protected areas by ecosystem. Globally, 33.6% of irrecoverable carbon is within IPLC lands and 23.0% is within PAs, with 8.3% of these areas common to both IPLC lands and PAs; the remaining 51.7% falls outside of these areas. Pie chart areas are proportional to each ecosystem's total irrecoverable carbon, which is listed below.

often manage the land in a way consistent with maintaining irrecoverable carbon[44].

The proportion and patterns of irrecoverable carbon within PAs differs by country, with implications for national strategies to secure irrecoverable carbon, especially as risks to irrecoverable carbon shift over time. For example, Guyana has historically low deforestation rates but only five PAs covering <10% of its territory. The recent discovery of offshore oil in 2015 has ushered in a new era of development, especially along the country's northeastern border, where its mangroves and densest irrecoverable carbon reserves are located (Fig. 4a). Nearly a quarter of Gabon's irrecoverable carbon is within PAs (Fig. 4b) but IPLC-designated lands face pressures from concessions for logging, mining, oil and plantation agriculture. In Cambodia, the most concentrated area of irrecoverable carbon rings the forested lands around the seasonally flooded Tonle Sap Lake in the centre of the country (Fig. 4c) and, though much of this land is within PAs, it faces pressures from rice paddy development as well as extreme heat and drought that have exacerbated forest fires.

Managing Earth's irrecoverable carbon reserves

Today, as climate change intensifies, efforts to combat it must include protecting lands containing large reserves of irrecoverable carbon. Just as the concept of 'unburnable reserves' refers to the fossil fuels that must stay in the ground to limit global warming to 2 °C (ref. [45]), ecosystems with high densities or quantities of irrecoverable carbon should be considered 'unconvertible' or 'unexploitable'. In the field of biodiversity conservation, the concept of 'irreplaceability' is embedded in efforts to target threatened and endangered species as conservation priorities, protect the world's remaining primary tropical forests[46] and site and manage PAs to prevent extinctions[47]. Ecosystems with large concentrations of irrecoverable carbon should similarly be considered irreplaceable from a climate perspective.

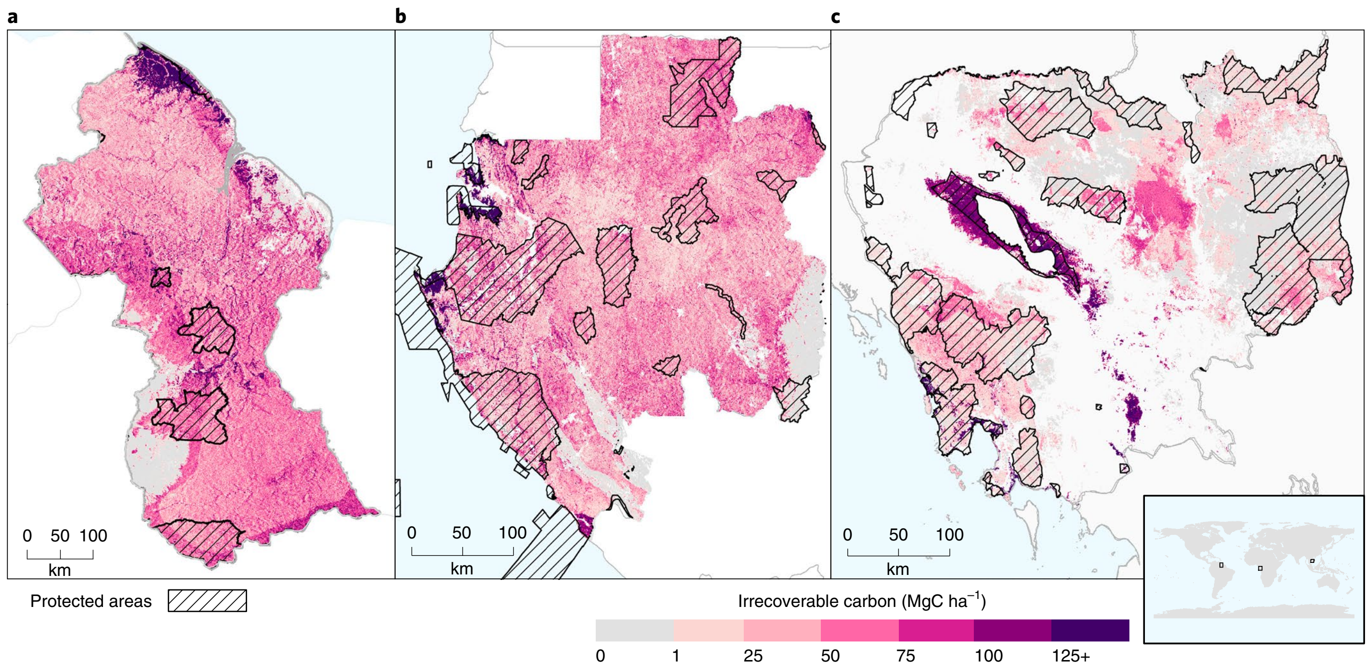

Fig. 4 | Irrecoverable carbon and protected areas in Guyana, Gabon and Cambodia. a–c, Illustrative examples of the spatial relationship between irrecoverable carbon and PAs in Guyana (**a**) for which 10.4% of irrecoverable carbon by mass lies in PAs, Gabon (**b**) (23.2%) and Cambodia (**c**) (42.3%).

The CBD now recognizes that its original biodiversity-related goals are intimately connected to the fate of the climate. Recent efforts by governments, including through the High Ambition Coalition for Nature and People, a group of (as of this writing) 70 countries cochaired by Costa Rica, France and the United Kingdom, support efforts to expand PAs and other effective area-based conservation measures to 30% of the planet's land and 30% of its ocean by 2030. A joint declaration by 34 Indigenous organizations calls for even more ambition within the CBD: protecting 50% of the planet through formally recognizing the rights and governance of Indigenous peoples and through expanding Indigenous and Community Conserved Areas (ICCAs)[48]. ICCAs give IPLCs the power to make decisions about how the territory is managed, with conservation of biodiversity as one of the intended outcomes of this management (not all IPLC lands are ICCAs)[40].

Irrecoverable carbon should be a key input to the spatial prioritization of new PAs, ICCAs and other conservation measures. Current PAs cover ~15% of the terrestrial planet and include just under a quarter (24.9 Gt) of the top three-quarters of the world's irrecoverable carbon (104.3 Gt), when ranked by highest-density hectares. The remaining 79.4 Gt of the top 75% of irrecoverable carbon could be secured by protecting or sustainably managing an additional 8 million km^2, about 5.4% of the planet's terrestrial surface. Given the concentration of vast sums of irrecoverable carbon within a relatively small land area, national governments as well as multilateral funders such as the Global Environment Facility, the Green Climate Fund and the World Bank can advance global climate security by prioritizing lands with high irrecoverable carbon for long-term protection efforts and investment. Beyond spatial prioritization, the concept of irrecoverable carbon could also inform new climate finance mechanisms.

Irrecoverable carbon maps complement and should improve existing spatial prioritization efforts. Several recent studies have aimed to map priority areas on the planet for both biodiversity and climate stability. In one approach, 'Climate Stabilization Areas' or places containing high carbon stocks, are mapped alongside critical areas for conserving biodiversity, together comprising a 'Global Safety Net' covering ~50% of the Earth's surface[49]. An alternate approach optimizes across biodiversity values, carbon stocks and water-provisioning areas to explore proportional overlap across these three dimensions, captured by 30 and 50% of the Earth's terrestrial surface[50]. These studies use total carbon stock (biomass and soil) as a simplified climate prioritization metric. Our irrecoverable carbon product goes beyond this by considering the key three criteria of manageability, vulnerability and recoverability, therefore pinpointing the subset of terrestrial carbon stocks that are within the purview of people to manage and are, to all intents and purposes, irreplaceable. The 300-m resolution maps can be used for both global and local planning.

Securing Earth's irrecoverable carbon requires both strategies to prevent imminent loss, such as payments for reducing deforestation and concessions buybacks, and proactive strategies to secure areas long-term, such as promoting Indigenous rights, expanding and adequately financing PAs and managing high-carbon ecosystems for climate resilience. In this epoch of the Anthropocene, humans have the unique ability to manage carbon storage and fluxes at the global scale. Decisions governing irrecoverable carbon in ecosystems today will affect the atmosphere of generations to come.

Methods

Irrecoverable carbon definition. Irrecoverable carbon in ecosystems is defined by three criteria[2]: (1) it can be influenced by direct and local human action ('manageability'), (2) it is potentially vulnerable to loss during land-use conversion ('vulnerability') and (3) if lost, it could not be recovered within a specified timeframe ('recoverability'). Here, we consider recoverability over 30 yr given the IPCC assessment that global emissions must reach net-zero by 2050 to limit global warming to <1.5 °C above pre-industrial levels[7].

To create the irrecoverable carbon map, we:

(1) Define relevant ecosystems that meet criteria 1, manageability.
(2) Create a 'total manageable carbon' map for terrestrial and coastal ecosystems. This includes aboveground biomass carbon (AGC), belowground biomass carbon (BGC) and soil organic carbon (SOC) stocks.
(3) Create a 'vulnerable carbon' map that considers the portion of biomass carbon (AGC + BGC) and SOC, respectively, that would be released in a typical land-use conversion. We used the most common drivers of recent destruction/loss in each major ecosystem.

(4) Determine the amount of lost carbon that could be recovered within 30 yr following a conversion, assuming land abandonment and natural regeneration. Recoverability is based on biomass and SOC sequestration rates by ecosystem.
(5) Subtract 'recoverable carbon' from the 'vulnerable carbon' map. The balance is the 'irrecoverable carbon' map.

Defining ecosystem extents. We used the United Nations Food and Agricultural Organization's map of ecozones[51], to identify and map 'manageable ecosystems'. We excluded polar regions and permafrost[9] and added coastal ecosystems[52–55] and peatland soils[56] which have unique characteristics in terms of carbon vulnerability and recoverability. We then excluded areas that are under cultivation for agriculture, urban or otherwise developed by overlaying the relevant ecozones with the European Space Agency (ESA) Climate Change Initiative Land Cover annual 300-m dataset[57]. The result of this combination (Supplementary Table 1) is a terrestrial ecosystem extent map (Supplementary Fig. 1).

Since ESA land cover classes do not distinguish between natural and planted forests, we exclude plantation forests and tree crops (including rubber, oil palm, coffee, cocoa and orchards) from our map using the World Resources Institute's Spatial Database of Planted Trees[58]. See Supplementary Discussion and Supplementary Table 2 for more detail on defining ecosystem extents and the study's spatial and temporal resolution.

Total manageable carbon. We mapped total manageable carbon using comprehensive global maps of biomass carbon and SOC. We used the harmonized global biomass carbon map of Spawn et al. for all explicitly terrestrial ecosystems (forests, grasslands and inland wetlands)[5]. These maps integrate remotely sensed aboveground biomass for a wide range of land-cover types using a method that uniquely accounts for biomass in both the primary and secondary vegetation types of each grid cell. Equivalent maps of belowground biomass use the same integration method and vegetation-specific root biomass data derived from allometric relationships. As such, the biomass carbon maps represent a more comprehensive inventory of total biomass carbon stocks than any previously published map, are temporally consistent and have been validated at multiple scales.

Coastal ecosystems are not explicitly included in the maps of Spawn et al.[5], so for these ecosystems we use default carbon stock values (Supplementary Table 3).

SOC stocks were mapped using the SoilGrids 250 m v.2.0, released 5 June 2020[6] (hereafter 'SoilGrids') in soils across explicitly terrestrial ecosystems. SoilGrids maps are produced at a 250-m spatial resolution for the globe using a machine learning algorithm trained by relating >250,000 soil profiles and 400 remotely sensed covariate grids[59]. SoilGrids provides accurate depth-specific SOC estimates for most ecosystems. Our total manageable soil carbon map considers SOC from 0 to 30 cm depth for forests and grasslands, the depth in which the disturbance effects of a typical land-use conversion are concentrated[60].

For coastal ecosystems and wetlands, we consider SOC to a depth of 100 cm since the effects of the most common anthropogenic disturbances (for example, drainage and excavation), transcend surface soils[12,61]. Since SoilGrids products do not extend to coastal ecosystems, we use alternate methodologies to calculate SOC. For mangroves, we used the 30-m resolution SOC data from 0 to 100 cm depth from Sanderman et al.[62]. In the absence of global SOC maps for seagrasses and salt marshes, we apply default values of 108 ± 55.9 MgC ha^{-1} and 255 ± 154.8 MgC ha^{-1}, respectively, to estimate SOC down to 100 cm (refs. [63–65]).

For peat we also considered effects of disturbance to 100 cm depth, which is consistent with the IPCC Wetlands Supplement[63] and with studies of peatlands emissions converted to palm oil in Southeast Asia[61]. Peatlands were treated as a soil type; we maintained the ecosystem classification of the aboveground biomass. Because the current release of SoilGrids v.2.0 does not currently extend below 30 cm, we linearly extrapolated the surficial estimate to 30–100 cm, assuming that peatland carbon is homogenous throughout the depth profile, on the basis of the way that peat accumulates[66]. For non-peat wetlands, we used a linear extrapolation factor of 2.574 to convert the available 0–30 cm values from SoilGrids to the 100 cm depth of interest. This extrapolation factor is calculated from Nahlik and Fennessy's study[67] of 967 wetlands sites in the United States, which documents SOC stocks at depth increments of 30 cm each, down to 120 cm.

To create the final total manageable carbon dataset, we combine the biomass and soil carbon maps (Supplementary Figs. 2 and 3). Where there was spatial overlap among ecosystem maps, we prioritized datasets in the following order: mangroves, peat, other terrestrial ecosystems, salt marshes and seagrasses. Supplementary Table 4 summarizes the total manageable carbon values by ecosystem.

Vulnerable carbon. Across ecosystems, we assess the probable amount of carbon that would be lost in a typical conversion event. The 'typical' conversion event is considered as the most common driver of land cover change/ecosystem loss (for example, forest to soy field or clear-cut), as opposed to activities that reduce carbon content but do not constitute full conversion (for example, forest degradation due to charcoal collection or selective logging). We aimed to capture the 'maximum feasible loss' of carbon in the event of conversion. We assume the following conversion drivers: forestry for boreal and temperate forests[10]; crop cultivation for tropical forests[10], grasslands[68] and peatlands[11]; drainage for aquaculture or agriculture for non-peat wetlands[69]; and aquaculture/ development for all coastal ecosystems[12]. 'Vulnerable carbon' (Supplementary Fig. 4) therefore represents the portion that would probably be lost in a hypothetical but typical conversion event; it does not characterize the likelihood of that conversion event. For the latter, see the subsequent sections on risk.

For biomass carbon, we assume that 100% of the biomass is potentially vulnerable in a conversion event. This follows IPCC Tier 1 methodology for forest land[70] and is consistent with the assumption made in other estimations of carbon flux to the atmosphere associated with biomass loss in forests[71–73]. We apply the same 100% biomass loss assumption in grasslands, seagrasses and salt marshes, which have smaller initial biomass carbon stocks.

In contrast to biomass, ecosystem conversion does not typically result in complete loss of SOC. The relative magnitude of SOC loss is related to the type of ecosystem converted, subsequent management and biophysical conditions, among other factors, as documented in meta-analyses[17,18] commonly used to model expected changes to the size of the initial SOC stock resulting from specific land cover changes[74,75]. We use this approach to estimate expected losses from initial SOC stocks. See the section on 'Vulnerable SOC—extended discussion' and Supplementary Table 5 in the Supplementary Information. Vulnerable carbon by ecosystem type is quantified in Supplementary Table 6.

Irrecoverable carbon. To determine carbon recoverability for each ecosystem, we evaluate carbon sequestration rates in both biomass and soils. Recoverability can be assessed over any timeframe and can include natural regeneration (reducing threats and allowing the ecosystem to recover on its own) as well as active restoration/planting. We look at recoverability over 30 yr as the key illustrative example, as explained in the main text.

Biomass sequestration. We use sequestration rates by ecosystem type and region/ continent, calculated from a spatially explicit database, the Global Reforestation Opportunity Assessment (GROA). GROA compiles carbon accumulation rates in naturally regrowing forests derived from 256 studies and 13,033 measurements[4]. We use the 2,741 measurements of aboveground forest biomass that are publicly available. Using latitude and longitude, we intersect these point data with the ESA land cover map and the region/continent. We then calculate sequestration as a function of the natural log of time for each ecosystem and region/continent (Supplementary Table 7). Logarithmic models are used to approximate the observed saturation in biomass sequestration through time[15,16].

A sensitivity analysis shows that total irrecoverable carbon could be lower (113.2 Gt) or higher (179.2 Gt) with more optimistic or more conservative assumptions about forest regrowth. Specifically, Cook-Patton et al.'s[4] modelled spatial product of carbon accumulation from natural forest regrowth results in lower overall irrecoverable carbon. The model assumes linear carbon accumulation and is based on 13,122 georeferenced measurements (including national inventory data that are not publicly available), applying 66 environmental covariates. Alternatively, the IPCC's accumulation rates, including the Suarez et al.[76] 2019 updates for tropical forests, limits its inputs to chronosequence data to which they fit saturating curves, resulting in more conservative carbon accumulation estimates, particularly for the tropics[76,77]. Our chosen approach is a compromise between these two, using the larger dataset from Cook-Patton et al.[4] but assuming saturating growth. See also the section 'Sequestration rates in forests—extended discussion' in Supplementary Information.

For non-forest ecosystems, we compile biomass carbon sequestration rates through literature review (Supplementary Table 8). Grassland ecosystems fully recover their biomass carbon stock within 30 yr[13,78]. Mangrove biomass sequestration rates are from the Global CO_2 Removals Database based on 63 mangrove sites from Bernal et al.[14]. For seagrasses and salt marshes, an estimate of annual sequestration was not available; however, given the low initial biomass values, we assume full biomass recovery within 30 yr.

Soil sequestration. We determine whether SOC lost during the initial conversion could be fully recovered through subsequent restoration by applying restoration sequestration factors (SFs), carbon response functions (CRFs) or average annual recovery rates from literature review, depending on the ecosystem type and data availability.

For tropical forests and grasslands, we use SFs taken from the meta-analysis of Don et al.[17] which represent the average total SOC gain (%) resulting from restoration of crop lands in the tropics to either (1) secondary forest or (2) grasslands (Supplementary Table 9). These SFs suggest that tropical soils previously disturbed by agriculture could fully recover their lost carbon within 30 yr.

For temperate and montane grasslands, we use a CRF derived in a meta-analysis of 95 published studies conducted throughout the temperate zone[18] which estimates SOC gains resulting from restoration of crop lands to grasslands. CRFs are simple statistical models that predict SOC emissions associated with specific land-use transitions on the basis of the empirical effects of environmental covariates over a user-specified duration. This CRF predicts the proportional change relative to an initial SOC stock on the basis of soil clay content (%), mean annual temperature (MAT; °C), soil depth (metres) and the time (t) since conversion (yr)[75]. CRF models and coefficients were taken from Poeplau et al.[18] and implemented spatially following the general approach of Spawn et al.[75].

For temperate and boreal forests, we assume that no SOC is vulnerable in the first place in the typical conversion scenario (forestry)[79–81]. However, we perform a sensitivity analysis to understand a future scenario in which agriculture rather than forestry becomes the primary driver of forest loss in the temperate and boreal zones (see the section 'Scenarios: different land-use change assumptions' in Supplementary Information). For wetlands and coastal ecosystems, annual SOC recovery rates were determined from literature review and applied to a 30-yr period (Supplementary Tables 10 and 11).

Irrecoverable carbon values by ecosystem are summarized in Supplementary Table 12 and mapped in biomass and soils in Supplementary Figs. 5 and 6, respectively. Supplementary Fig. 7 visualizes irrecoverable, vulnerable but recoverable and not vulnerable carbon in biomass and soils, by ecosystem type.

Differences from concept study. Our estimate of total irrecoverable carbon is 54% lower than previously reported in Goldstein et al.[2] because the previous study was based on biome-level averages. The use of spatially explicit data allows us to quantify irrecoverable carbon globally more accurately. Some of the changes driving the lower number include the explicit exclusion of permafrost and planted forests and the more accurate quantification of irrecoverable carbon in soils. In particular, the 2020 SoilGrids update reduced estimates of initial soil carbon stocks by a factor of >2 relative to earlier SoilGrids estimates[59,82], bringing its estimated global totals in line with a comprehensive independent assessment[83].

Uncertainty assessment. We created a raster of initial carbon stock uncertainty by mosaicking the pixel-level uncertainty layers that accompanied each of our global input datasets (AGC, BGC and SOC). Uncertainty, here, represents the standard error of each pixel's estimated mean value (s.e.m.). When a land-cover-specific s.e.m. estimate was not provided (for example, mangrove biomass, salt marsh and seagrass biomass and SOC), we estimated the associated s.e.m. using the original data.

To bound our mean estimates of vulnerable, recoverable and irrecoverable carbon, we propagated the s.e.m. of the initial stock and those associated with each of our emission/sequestration factors sequentially through all calculations using summation in quadrature. Most emission/sequestration factors were constants (for example, percentage change) such that error of the factor was a single value representing s.e.m.. In cases where multivariate models were used (for example, CRFs), the s.e.m. estimates of the model's coefficients were used to estimate the error associated with the model's prediction. When error was reported as a metric other than s.e.m., we used the given metric to estimate the standard error by assuming error was distributed normally around the mean. Error was propagated sequentially through irrecoverable calculations such that the uncertainty of initial stocks and emissions factors were used to estimate the uncertainty of the vulnerable carbon stock and sequestration factors were used to estimate that of recoverable carbon. Finally, the uncertainty of vulnerable and recoverable carbon was ultimately used to calculate that of the irrecoverable carbon stock. See Supplementary Figs. 8–12 for the uncertainty maps. Because, in the absence of sufficient information to do otherwise, we assume the error is normally distributed around the mean, we may overestimate error of our derived values if the true error distributions of one, some or all our data inputs are in fact skewed. For our estimate of total irrecoverable carbon, we bound the lower estimate to zero because, conceptually, the stock of irrecoverable carbon cannot be negative.

Land-use conversion and climate change risks. Figure 2 in the main text estimates land-use change and climate risks to irrecoverable carbon across key ecoregions[84]. Pressures due to land-use change were approximated by the total accumulated human impact in an ecoregion on the basis of the Human Footprint Index dataset[27]. These maps offer a 0–1 scale of human pressure on the environment globally, at 1-km resolution, compiling data across eight drivers of pressure: built environments, population density, electric infrastructure, crop lands, pasture lands, roads, railways and navigable waters. Human footprint statistics for each ecoregion were calculated using the zonal statistics tool in the R 'raster' package.

To assess the projected climate change risk in each ecoregion, we use a Climate Stability Index (CSI) that has been used previously for global ecoregion-based analysis[28,85]. CSI is a measure of how much of the climate space that currently exists within each ecoregion in baseline (1960–1990) climate is projected to be retained under scenarios of climate change. CSI ranges from 0 to 1, with 1 being the highest climate stability. Climate space for each ecoregion is defined from sampled grid points of the loadings on the first two principle components derived from global 30-yr normals of six bioclimatic variables. To derive CSI, we used 2.5-arcmin resolution climate data from WorldClim v.2 (ref. [86]) for both baseline climate and Coupled Model Intercomparison Project Phase 6 (CMIP6) future projections for 2040–2060. Principle components surfaces were derived from a random sample ($n = 100{,}000$) of global climate grids of the bioclimatic variables. Principle components derived for baseline climate are then mapped onto the future climate projections for the same bioclimatic variables. CSI is calculated for each ecoregion following the methods of Iwamura et al.[85] using the kernel density estimation function of the MASS package in R v.3.5.3.

For the future projection, we use the shared socioeconomic pathway 2 (SSP2), representative concentration pathway 4.5 (RCP 4.5) scenario and calculate the median across nine CMIP6 global climate models. The SSP2 scenario represents a 'middle of the road' development pathway with some progress toward sustainable development goals and some reduction in resource use intensity by 2050. Likewise, the RCP 4.5 is also recognized as an intermediate scenario, with emissions peaking in 2040. Alternate scenarios are shown for comparison in Supplementary Fig. 13.

Protected areas and irrecoverable carbon. To calculate the amount of irrecoverable carbon within PAs globally, we use the World Database of Protected Areas[39] from the World Conservation Monitoring Centre (WCMC), including all PAs reported as 'designated', 'inscribed', 'adopted' or 'established'. We exclude the points-only dataset as it required too many assumptions to estimate PA coverage. Due to these exclusions, we underestimate the total PA coverage by 7.5% in terms of land area.

Indigenous lands and irrecoverable carbon. We use a technical report from WCMC that combines spatial datasets from Garnett et al.[87], LandMark and Conservation International covering 132 countries (and three disputed territories), allowing us to approximate the amount of irrecoverable carbon in IPLC lands globally[40]. Supplementary Table 13 provides a breakdown of the proportion of irrecoverable carbon in different ecosystems within IPLC lands and PAs. See the section on 'Importance of Indigenous lands' in the Supplementary Information.

Recent loss of irrecoverable carbon. To estimate recent loss of irrecoverable carbon due to deforestation, we create a mask using the annual tree cover loss dataset (2011–2019) produced by Hansen et al.[23], which we intersect with the irrecoverable carbon map. The Hansen et al. dataset has the highest temporal and spatial resolution available globally and monitors tree cover loss across a wide swath of the planet, both in forests but also in other ecosystem types with tree cover (for example, some grasslands and shrublands). Overall, the Hansen dataset covers 83% of the irrecoverable carbon stock. See the section 'Limitations to loss estimates' and Supplementary Table 14 in the Supplementary Information for a summary of irrecoverable carbon loss by ecosystem.

Reporting Summary. Further information on research design is available in the Nature Research Reporting Summary linked to this article.

Data availability

All data used in this analysis came from publicly available datasets with the exceptions of the IPLC lands map and the planted tree dataset for China and Papua New Guinea, each of which required permission from the data provider. The modified IPLC dataset is available on request from UNEP-WCMC. Permission was received from the data provider for use of datasets in PNG and China within the planted trees dataset and can be accessed through request from the World Resources Institute. The remainder of the datasets are publicly available. All code and data outputs are publicly available on Zenodo at https://doi.org/10.5281/zenodo.4091029. Processing steps are described in the Supplementary Information.

Code availability

To ensure full reproducibility and transparency of our research, we provide all the scripts used in our analysis. The code used for this study is permanently and publicly available on Zenodo at https://doi.org/10.5281/zenodo.4091029

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References

1. Folke, C., Polaksy, S., Rockstrom, J., Galaz, V. & Westley, F. Our future in the Anthropocene biosphere. *Ambio* **50**, 834–869 (2021).
2. Goldstein, A. et al. Protecting irrecoverable carbon in Earth's ecosystems. *Nat. Clim. Change* **10**, 287–295 (2020).
3. IPCC *Climate Change 2021: The Physical Science Basis* (eds Masson-Delmotte, V. et al.) (Cambridge Univ. Press, 2021).
4. Cook-Patton, S., Leavitt, S., Gibbs, D. & Harris, N. Mapping carbon accumulation potential from global natural forest regrowth. *Nature* **585**, 545–550 (2020).
5. Spawn, S. A., Sullivan, C. C., Lark, T. J. & Gibbs, H. K. Harmonized global maps of above and belowground biomass carbon density in the year 2010. *Sci. Data* https://doi.org/10.1038/s41597-020-0444-4 (2020).
6. *SoilGrids250m 2.0—Soil Organic Stock* (0–30cm, t/ha) (ISRIC, accessed 5 June 2020); https://doi.org/10.17027/isric-soilgrids.713396f4-1687-11ea-a7c0-a0481ca9e724
7. IPCC *Special Report on Global Warming of 1.5 °C* (eds Masson-Delmotte, V. et al.) (WMO, 2018).
8. Rockström, J. et al. We need biosphere stewardship that protects carbon sinks, builds resilience. *Proc. Natl Acad. Sci. USA* **18**, e2115218118 (2021).

9. Schuur, E. A. G. et al. Climate change and the permafrost carbon feedback. *Nature* **520**, 171–179 (2015).
10. Curtis, P. G., Slay, C. M., Harris, N. L., Tyukavina, A. & Hansen, M. C. Classifying drivers of global forest loss. *Science* **361**, 1108–1111 (2018).
11. Leifeld, J. & Menichetti, L. The underappreciated potential of peatlands in global climate change mitigation strategies. *Nat. Commun.* https://doi.org/10.1038/s41467-018-03406-6 (2018).
12. Pendleton, L. et al. Estimating global "blue carbon" emissions from conversion and degradation of vegetated coastal ecosystems. *PLoS ONE* https://doi.org/10.1371/journal.pone.0043542 (2012).
13. Xia, J. Z. et al. Spatio-temporal patterns and climate variables controlling of biomass carbon stock of global grassland ecosystems from 1982 to 2006. *Remote Sens.* **6**, 1783–1802 (2014).
14. Bernal, B., Murray, L. T. & Pearson, T. R. H. Global carbon dioxide removal rates from forest landscape restoration activities. *Carbon Balance Manag.* https://doi.org/10.1186/s13021-018-0110-8 (2018).
15. Poorter, L. et al. Biomass resilience of Neotropical secondary forests. *Nature* https://doi.org/10.1038/nature16512 (2016).
16. Martin, P. A., Newton, A. C. & Bullock, J. M. Carbon pools recover more quickly than plant biodiversity in tropical secondary forests. *Proc. R. Soc. B* https://doi.org/10.1098/rspb.2013.2236 (2013).
17. Don, A., Schumacher, J. & Freibauer, A. Impact of tropical land-use change on soil organic carbon stocks—a meta-analysis. *Glob. Change Biol.* **17**, 1658–1670 (2011).
18. Poeplau, C. et al. Temporal dynamics of soil organic carbon after land-use change in the temperate zone—carbon response functions as a model approach. *Glob. Change Biol.* **17**, 2415–2427 (2011).
19. Villa, J. A. & Bernal, B. Carbon sequestration in wetlands, from science to practice: an overview of the biogeochemical process, measurement methods, and policy framework. *Ecol. Eng.* **114**, 115–128 (2018).
20. Hannah, L. et al. The environmental consequences of climate-driven agricultural frontiers. *PLoS ONE* https://doi.org/10.1371/journal.pone.0228305 (2020).
21. Li, Y. et al. Local cooling and warming effects of forests based on satellite observations. *Nat. Commun.* https://doi.org/10.1038/ncomms7603 (2015).
22. Bonan, G. B. Forests and climate change: forcings, feedbacks, and the climate benefits of forests. *Science* **320**, 1444–1449 (2008).
23. Hansen, M. C. et al. High-resolution global maps of 21st-century forest cover change. *Science* **342**, 850–853 (2013).
24. Harris, N. L. et al. Global maps of twenty-first century forest carbon fluxes. *Nat. Clim. Change* **11**, 234–240 (2021).
25. Friedlingstein, P. et al. Global carbon budget 2019. *Earth Syst. Sci. Data* **11**, 1783–1838 (2019).
26. Olson, D. M. et al. Terrestrial ecoregions of the worlds: a new map of life on Earth. *Bioscience* **51**, 933–938 (2001).
27. Venter, O. et al. Global terrestrial Human Footprint maps for 1993 and 2009. *Sci. Data* https://doi.org/10.1038/sdata.2016.67 (2016).
28. Watson, J. E. M., Iwamura, T. & Butt, N. Mapping vulnerability and conservation adaptation strategies under climate change. *Nat. Clim. Change* **3**, 989–994 (2013).
29. Sullivan, M. J. P. et al. Long-term thermal sensitivity of Earth's tropical forests. *Science* **368**, 869–874 (2020).
30. Cochrane, M. A. & Barber, C. P. Climate change, human land use and future fires in the Amazon. *Glob. Change Biol.* **15**, 601–612 (2009).
31. Alongi, D. M. Mangrove forests: resilience, protection from tsunamis, and responses to global climate change. *Estuar. Coast. Shelf Sci.* **76**, 1–13 (2008).
32. Reyer, C. P. O. et al. Forest resilience and tipping points at different spatio-temporal scales: approaches and challenges. *J. Ecol.* **103**, 5–15 (2015).
33. Malhi, Y. et al. Exploring the likelihood and mechanism of a climate-change-induced dieback of the Amazon rainforest. *Proc. Natl Acad. Sci. USA* **106**, 20610–20615 (2009).
34. Kennedy, C. M., Oakleaf, J. R., Theobald, D. M., Baruch-Mordo, S. & Kiesecker, J. Managing the middle: a shift in conservation priorities based on the global human modification gradient. *Glob. Change Biol.* **25**, 811–826 (2019).
35. Oakleaf, J. R. et al. Mapping global development potential for renewable energy, fossil fuels, mining and agriculture sectors. *Sci. Data* https://doi.org/10.1038/s41597-019-0084-8 (2019).
36. Bastin, J. F. et al. The global tree restoration potential. *Science* **365**, 76–79 (2019); erratum **368**, https://doi.org/10.1126/science.abc8905 (2020).
37. Millar, C. I. & Stephenson, N. L. Temperate forest health in an era of emerging megadisturbance. *Science* **349**, 823–826 (2015).
38. Watson, J. E. M. et al. The exceptional value of intact forest ecosystems. *Nat. Ecol. Evol.* **2**, 599–610 (2018).
39. *Protected Planet: The World Database on Protected Areas (WDPA) and World Database on Other Effective Area-based Conservation Measures (WD-OECM)* (UNEP-WCMC and IUCN, accessed 8 May 2020); www.protectedplanet.net
40. *The State of Indigenous Peoples' and Local Communities' Lands and Territories: A Technical Review of the State of Indigenous Peoples' and Local Communities' Lands, their Contributions to Global Biodiversity Conservation and Ecosystem Services, the Pressures they Face, and Recommendations for Actions* (WWF, UNEP-WCMC, SGP/ICCA-GSI, LM, TNC, CI, WCS, EP, ILC-S, CM, IUCN, 2021).
41. Kroner, R. E. G. et al. The uncertain future of protected lands and waters. *Science* **364**, 881–886 (2019).
42. Andam, K. S., Ferraro, P. J., Pfaff, A., Sanchez-Azofeifa, G. A. & Robalino, J. A. Measuring the effectiveness of protected area networks in reducing deforestation. *Proc. Natl Acad. Sci. USA* **105**, 16089–16094 (2008).
43. Bebber, D. P. & Butt, N. Tropical protected areas reduced deforestation carbon emissions by one third from 2000–2012. *Sci. Rep.* https://doi.org/10.1038/s41598-017-14467-w (2017).
44. Walker, W. S. et al. The role of forest conversion, degradation, and disturbance in the carbon dynamics of Amazon indigenous territories and protected areas. *Proc. Natl Acad. Sci. USA* **117**, 3015–3025 (2020).
45. McGlade, C. & Ekins, P. The geographical distribution of fossil fuels unused when limiting global warming to 2 °C. *Nature* **517**, 187–190 (2015).
46. Gibson, L. et al. Primary forests are irreplaceable for sustaining tropical biodiversity. *Nature* **478**, 378–381 (2011).
47. Le Saout, S. et al. Protected areas and effective biodiversity conservation. *Science* **342**, 803–805 (2013).
48. *Joint Declaration of the Indigenous Peoples of the World to the CBD* (New York Times, 2019); https://int.nyt.com/data/documenttools/joint-declaration-of-the-indigenous-peoples-of-the-world-to-the-cbd-34/20b4fa27750039d7/full.pdf
49. Dinerstein, E., Joshi, A. R., Vynne, C. & Lee, A. T. L. A "Global Safety Net" to reverse biodiversity loss and stabilize Earth's climate. *Sci. Adv.* **6**, eabb2824 (2020).
50. Jung, M. et al. Areas of global importance for conserving terrestrial biodiversity, carbon, and water. *Nat. Ecol. Evol.* https://doi.org/10.1038/s41559-021-01528-7 (2021).
51. *Global Ecological Zones for FAO Forest Reporting: 2010 Update* FRA Working Paper 179 (FAO, 2012).
52. Bunting, P. et al. The global mangrove watch—a new 2010 global baseline of mangrove extent. *Remote Sens.* **10**, 1669 (2018).
53. Thomas, N. et al. Distribution and drivers of global mangrove forest change, 1996–2010. *PLoS ONE* **12**, e0179302 (2017).
54. *Global Distribution of Seagrasses (version 6)* (UN Environment World Conservation Monitoring Centre, accessed 27 September 2018); http://data.unep-wcmc.org/datasets/7
55. McOwen, C. et al. A global map of saltmarshes. *Biodivers. Data J.* **5**, e11764 (2017).
56. Xu, J. R., Morris, P. J., Liu, J. G. & Holden, J. PEATMAP: refining estimates of global peatland distribution based on a meta-analysis. *Catena* **160**, 134–140 (2018).
57. *Annual Land Cover maps (1992–2018) 300m* (ESA, accessed 20 February 2020); https://maps.elie.ucl.ac.be/CCI/viewer/
58. Harris, N. L., Goldman, E. D. & Gibbes, S. *Spatial Database of Planted Trees (SDPT Version 1.0)* (World Resources Institute, accessed 16 May 2020).
59. Poggio, L. et al. SoilGrids 2.0: producing soil information for the globe with quantifies spatial uncertainty. *Soil* **7**, 217–240 (2021).
60. Sanderman, J., Hengl, T. & Fiske, G. J. Soil carbon debt of 12,000 years of human land use. *Proc. Natl Acad. Sci. USA* **114**, 9575–9580 (2017).
61. Hooijer, A. et al. Current and future CO_2 emissions from drained peatlands in Southeast Asia. *Biogeosciences* **7**, 1505–1514 (2010).
62. Sanderman, J. et al. A global map of mangrove forest soil carbon at 30 m spatial resolution. *Environ. Res. Lett.* https://doi.org/10.1088/1748-9326/aabe1c (2018).
63. Hiraishi, T. et al. *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands* (IPCC, 2014).
64. Fourqurean, J. W. et al. Seagrass ecosystems as a globally significant carbon stock. *Nat. Geosci.* **5**, 505–509 (2012).
65. Byrd, K. B. et al. A remote sensing-based model of tidal marsh aboveground carbon stocks for the conterminous United States. *ISPRS J. Photogramm. Remote Sens.* **139**, 255–271 (2018).
66. Agus, F., Hairiah, K. & Mulyani, A. *Measuring Carbon Stock in Peat Soils: Practical Guidelines* (World Agroforestry Centre & Indonesian Centre for Agricultural Land Resources Research and Development, 2011).
67. Nahlik, A. M. & Fennessy, M. S. Carbon storage in US wetlands. *Nat. Commun.* https://doi.org/10.1038/ncomms13835 (2016).
68. Lark, T. J., Spawn, S. A., Bougie, M. & Gibbs, H. K. Cropland expansion in the United States produces marginal yields at high costs to wildlife. *Nat. Commun.* **11**, 4295 (2020).
69. Reis, V. et al. A global assessment of inland wetland conservation status. *Bioscience* **67**, 523–533 (2017).
70. Aalde, H. et al. in *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (eds Eggelston, S. et al.) Ch. 4 (IGES, 2006).
71. Harris, N. L. et al. Baseline map of carbon emissions from deforestation in tropical regions. *Science* **336**, 1573–1576 (2012).
72. Houghton, R. A. The annual net flux of carbon to the atmosphere from changes in land use 1850–1990. *Tellus Ser. B* **51**, 298–313 (1999).

73. Baccini, A. et al. Estimated carbon dioxide emissions from tropical deforestation improved by carbon-density maps. *Nat. Clim. Change* **2**, 182–185 (2012).
74. Nyawira, S. S., Nabel, J., Don, A., Brovkin, V. & Pongratz, J. Soil carbon response to land-use change: evaluation of a global vegetation model using observational meta-analyses. *Biogeosciences* **13**, 5661–5675 (2016).
75. Spawn, S. A., Lark, T. J. & Gibbs, H. K. Carbon emissions from cropland expansion in the United States. *Environ. Res. Lett.* https://doi.org/10.1088/1748-9326/ab0399 (2019).
76. Suarez, D. R. et al. Estimating aboveground net biomass change for tropical and subtropical forests: refinement of IPCC default rates using forest plot data. *Glob. Change Biol.* **25**, 3609–3624 (2019).
77. *Refinement to the IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC, 2019); https://www.ipcc-nggip.iges.or.jp/public/2019rf/index.html
78. Gill, R. A. & Jackson, R. B. Global patterns of root turnover for terrestrial ecosystems. *New Phytol.* **147**, 13–31 (2000).
79. Nave, L. E., Vance, E. D., Swanston, C. W. & Curtis, P. S. Harvest impacts on soil carbon storage in temperate forests. *For. Ecol. Manag.* **259**, 857–866 (2010).
80. Seedre, M., Shrestha, B. M., Chen, H. Y. H., Colombo, S. & Jogiste, K. Carbon dynamics of North American boreal forest after stand replacing wildfire and clearcut logging. *J. For. Res.* **16**, 168–183 (2011).
81. Seedre, M., Taylor, A. R., Brassard, B. W., Chen, H. Y. H. & Jogiste, K. Recovery of ecosystem carbon stocks in young boreal forests: a comparison of harvesting and wildfire disturbance. *Ecosystems* **17**, 851–863 (2014).
82. Tifafi, M., Guenet, B. & Hatte, C. Large differences in global and regional total soil carbon stock estimates based on soilGrids, HWSD, and NCSCD: intercomparison and evaluation based on field data from USA, England, Wales, and France. *Glob. Biogeochem. Cycles* **32**, 42–56 (2018).
83. Jackson, R. B. et al. The ecology of soil carbon: pools, vulnerabilities, and biotic and abiotic controls. *Annu. Rev. Ecol. Evol. Syst.* **48**, 419–445 (2017).
84. Dinerstein, E. et al. An ecoregion-based approach to protecting half the terrestrial realm. *Bioscience* **67**, 534–545 (2017).
85. Iwamura, T., Guisan, A., Wilson, K. A. & Possingham, H. P. How robust are global conservation priorities to climate change? *Glob. Environ. Change Hum. Policy Dimens.* **23**, 1277–1284 (2013).
86. Fick, S. E. & Hijmans, R. J. WorldClim 2: new 1-km spatial resolution climate surfaces for global land areas. *Int. J. Climatol.* **37**, 4302–4315 (2017).
87. Garnett, S. T. et al. A spatial overview of the global importance of Indigenous lands for conservation. *Nat. Sustain.* **1**, 369–374 (2018).

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Author contributions

M.L.N., A.G., J.C.L., W.R.T., D.G.H., S.C.C.-P. and J.R. conceived the idea for the study. M.L.N., A.G., J.C.L., P.R., T.M.W., S.A.S.-L., M.G.-R. and W.R.T. developed the methodology. M.L.N., J.C.L., P.R.R., A.G. and S.A.S.-L. analysed the data. A.G., J.C.L. and M.L.N. wrote the manuscript. M.L.N., A.G., J.C.L. and P.R.R. wrote the Supplementary Information; M.G.-R. edited the Supplementary Information. All other authors edited the manuscript and advised on analysis. S.A.S.-L. developed and performed the soil carbon analysis for grasslands and temperate/boreal forests. S.C.C.-P. developed the forest regeneration database on which forest sequestration rates are based. M.L.N., P.R.R., J.C.L. and A.G. prepared the figures for the manuscript and the Supplementary Information.

Competing interests

The authors declare no competing interests.

Additional information

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Our web collection on statistics for biologists contains articles on many of the points above.

Software and code

Policy information about availability of computer code

Data collection	Based on analysis of existing data
Data analysis	All data were analyzed using Google Earth Engine and exported for statistical analysis in ArcGIS for Desktop (v10.8.1).

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Ecological, evolutionary & environmental sciences study design

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Study description
This study is based on a global analysis of the best available carbon datasets and an analysis derived from the Cook-Patton et al (2020) study to derive sequestration rates for ecosystems. The resulting output defines global datasets of vulnerable and irrecoverable carbon in biomass and soil carbon.

Research sample
The sample size used to determine sequestration rates was derived from the Cook-Patton et al (2020) study gathering samples from over 13,000 measurements and 256 studies. The final layer is based on global remote sensing data and has global coverage except for the areas described below in data exclusions.

Sampling strategy
We filtered the sequestration database to determine the measurements with stand age and above ground carbon to derive sequestration rates for each of our defined ecosystems. The sample sizes and statistics are reported in Table S7 of the supplement.

Data collection
The study is based on an analysis of existing data from Spawn 2020 (GlobBiomass: biomass carbon), ISRIC 2020 (SoilGrids: soil carbon), and sequestration database (Cook-Patton et al 2020).

Timing and spatial scale
The study produces several global datasets at 300m resolution for 2010. The sequestration rates were estimated using a range of field measurements taken from 1-100 years stand age.

Data exclusions
The irrecoverable carbon map was created using global remote sensing products. We initially included all biomass and soil carbon. In keeping with our definition of irrecoverable carbon as carbon within natural, manageable areas, we excluded urban areas, crops, tree plantations, and cryosols (permafrost). These exclusions are detailed in the Methodology.

Reproducibility
This study is replicable using the openly available datasets and public code used for this analysis.

Randomization
Not relevant for this study

Blinding
Not relevant for this study

Did the study involve field work? ☐ Yes ☒ No

Reporting for specific materials, systems and methods

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Methods

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☒	☐	ChIP-seq
☒	☐	Flow cytometry
☒	☐	MRI-based neuroimaging