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Supplementary information

Mapping the irrecoverable carbon in Earth's ecosystems

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Supplementary Material for

Mapping the irrecoverable carbon in Earth's ecosystems

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Defining relevant ecosystem and their extents – extended discussion

To map irrecoverable carbon, we first create a map of relevant ecosystem extents. We start with the United Nations Food and Agricultural Organization's (FAO) map of ecozones[1], since ecozones are the broadest biogeographic division of the Earth's land surface, covering all terrestrial areas. We exclude Polar ecozones since there, carbon loss or gain (such as in the permafrost in frozen tundra) is primarily driven by global warming and not direct land-use decisions; this ecozone thus did not meet our manageability criterion[2].

We also exclude open water, as well as areas that are under cultivation for agriculture, urban, or otherwise developed. To do this, we overlay the FAO ecozones with a simplified Land Cover 2010 map from the European Space Agency's Climate Change Initiative Land Cover (ESA CCI LC) annual 300m dataset[3]. The source map provides a typology of 22 land cover classes based on the UN Land Cover Classification System. Since the focus of the analyses are natural areas relevant for carbon storage, we exclude classes 7-10 (Croplands, Settlements, Water, and Other lands) within the ecozones map, using Google Earth Engine[4]. The result of this combination is a terrestrial ecosystem extent map (**Fig. S1**).

By combining the FAO ecozones with the ESA land cover classes, we create a terrestrial ecosystem extent map that (1) includes only natural areas and (2) crosses the relevant land-cover (e.g., forest, grassland) with the relevant ecozone (e.g., temperate, tropical), both of which are important for determining carbon vulnerability and recoverability (**Table S1**). We prioritize the ESA land cover classes over the FAO ecozones since the former derives actual land-cover from remote sensing whereas the latter gives a more generalized picture of the dominant vegetation type across a large land area. For example:

- We identify Herbaceous wetlands, tree-covered wetlands, and grasslands and shrublands land covers using the FAO ecozones to distinguish between boreal, temperate, subtropical, and tropical, but otherwise override the ecozone classification (e.g., wetlands land cover within a 'forest' ecozone are classified as wetlands).
- Because of the unique vulnerability and recoverability of montane grasslands, we classify all grassland and shrublands in 'Mountain forest' areas as 'Montane grasslands and shrublands'.
- Forest land classes in desert ecozones are designated as forests (rather than excluded as desert).

Exclusion of planted forests

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 (SDPT, version 1.0)[5]. An estimated 173 million hectares, or 4% of total tree cover globally, lie in forests planted for harvesting or as tree crops. The SDPT derives almost all of its information from satellite-based observations and/or ground surveys rather than from the boundaries of areas administratively designated for planting trees (e.g., concession boundaries), meaning sections of the concessions not actively managed would still appear as "natural forests", and thus would be mapped within our definition of irrecoverable carbon. SDPT 1.0 is representative of planted tree cover in 2015 and covers 79 countries representing 82% of total global planted forest area.

Exclusion of tundra/ permafrost

In tundra ecosystems, carbon is typically stored in permafrost—the remnants of plants and animals accumulated in frozen soil. This carbon can be released to the atmosphere if these frozen soils thaw, increasing mineralization by microbes that convert it to carbon dioxide (CO_2) and methane (CH_4). A portion of this carbon is likely to be released under the current climate warming trajectory[6]. Though humans have indirect control over the level of thawing that occurs through global anthropogenic emissions, there are no proven direct, localized land-use management activities that can affect the carbon content of tundra ecosystems. We therefore exclude these areas, as they did not meet criterion 1 for irrecoverable carbon, manageability. To remove permafrost, we excluded soils defined by the cryosols class from SoilGrids[7]. (This is in addition to excluding the Polar ecozone.)

Addition of coastal ecosystems

We supplement spatial data for coastal ecosystems which have unique characteristics in terms of carbon vulnerability and recoverability and are not included in the FAO ecozone or ESA land cover maps. We define ecosystem extents from the following sources:

- Mangroves: Global Mangrove Watch v2.0 2010[8,9]
- Seagrasses: UNEP-WCMC 2018[10]
- Salt marshes : McOwen et al. 2017[11]

Where these coastal ecosystem extents overlap with terrestrial ecosystem extents as defined by ESA, we prioritize mangroves (which are carefully mapped), followed by salt marshes, then seagrasses (for which global extents are modeled rather than mapped).

Addition of peatlands

Finally, peatlands, a type of freshwater wetland, are not identified as a separate land-use class in ESA because they are characterized specifically by their high density of soil organic carbon (SOC). To create the peat dataset, we prioritize datasets: 1) where PEATMAP[12] identifies areas of presence/absence of peat (available for most countries) or 2) where the histosols classification from SoilGrids Most Probable Class World Reference Base[13] overlap with a probabilistic occurrence of peat (for Canada, Mongolia, North Korea and Hokkaido, Japan, where binary presence/absence of peat is not available). The peat classification defines the areas to which we later apply peat-specific assumptions on vulnerability and recoverability. In these areas, we apply peat-specific assumptions only to the soils and still classify the aboveground vegetation using the ecosystem approach described above.

Study spatial and temporal resolution and extent – extended discussion

The final irrecoverable carbon dataset is updated to remove non-natural areas from: 1) plantation forests in 2015[5] and 2) previously natural areas converted to crops or developed as urban areas as of 2018. For the latter, we use specified land cover classes using the ESA CCI LC product to create a non-natural land cover mask for 2010 to match the aboveground and belowground data, which are from the year 2010. This serves as the baseline year for all carbon datasets. To reflect the latest changes in land cover, we update the final product to the year 2018, removing any areas that have been converted to non-natural ESA classes since 2010. The final dataset extent covers all-natural terrestrial areas as well as coastal ecosystems (salt marshes, seagrasses, and mangroves).

We resample the final product to match the coarsest native resolution, resulting in a 300-m global dataset of irrecoverable carbon with three bands 1) irrecoverable carbon in biomass, 2) irrecoverable carbon in soils, and 3) total irrecoverable carbon (the sum of biomass and soils). We process all datasets in Google Earth Engine, saving each carbon layer as an asset, which is then resampled to 300m and exported to Google Cloud. We prepare all mosaicked datasets and summarize area and carbon statistics as described in subsequent sections using ArcMap v. 10.8.1. We analyze each carbon dataset at the ecosystem-level using the above-described dataset for ecosystems. We also summarize carbon outputs at the national level using a dataset that combines land area and exclusive economic zones (EEZ)[14] defined by territory. This ensures continuity in our analysis outside terrestrial areas, so that we capture all carbon in coastal ecosystems that fall within that countries' EEZ. See **Table S2** for details on the spatial and temporal resolutions for datasets used in this analysis.

Total manageable carbon in coastal ecosystems

Mangroves

To calculate the biomass carbon of mangroves, we use a dataset based on remotely sensed and in situ field measurements for aboveground biomass (AGB) [15]. To calculate below-ground biomass (BGB) in mangroves, we then apply the following conversion[16]:

$$BGB = (0.073) \times AGB^{1.32}$$

These coastal datasets are summed and converted to aboveground carbon (AGC) by multiplying 0.47 for conversion of biomass to carbon[17]. To update this 2000 data product to the year 2010, we clip the AGC to the extent of mangroves to reflect any loss in mangroves between 2000-2010. We used a kernel approach to fill in the gaps where pixels are missing within the Global Mangrove Watch extent but where we expect mangroves to be present. This approach takes the closest pixel with data and extrapolates the values. The standard error around mangrove biomass carbon is 37.1 MgC ha^{-1} for AGC and 8.6 MgC ha^{-1} for BGC. Mangrove soils were added using Sanderman et al. 2018's 30-m resolution dataset for mangroves, at 0-100 cm depth.[18] From the original source, we assessed standard error around mangrove SOC values to be 136 MgC ha^{-1}.

Seagrasses and Salt Marshes

Because there is no spatial dataset explicitly capturing the biomass carbon in seagrasses and salt marshes (and most of the carbon in these ecosystems lies within the soil), we create a dataset using the extent and default mean carbon values for these ecosystems (**Table S3**).

Vulnerable SOC – extended discussion

The following sections provide more details on the calculations and assumptions summarized in **Table S5**.

Tropical forests and grasslands

To estimate the SOC lost in a typical conversion event (to agriculture)[19] in tropical forests and grasslands, we derive emissions factors (EFs) from a meta-analysis of 385 studies conducted throughout the tropics[20]. These EFs describe changes resulting from the conversion of (i) primary forests, (ii) secondary forests, and (iii) natural grasslands to cropland. Since each EF was based on observations from different average maximum depths (36 to 44 cm) and since our analysis only considers changes in these systems to a depth of 30 cm, we calibrate each EF to reflect expected changes in the upper 30 cm of the soil profile by fitting an exponential function derived from global SOC change data (Figure S8 in Sanderman et al. 2017)[21], such that the average change to the literature-reported sample depth was equal to the literature-reported EF. As a result, EFs used for the entire 30-cm profile were slightly less than those reported in the meta-analysis.

The equations in **Table S5** reflect the mean SOC loss due to land-use change across tropical forests and grasslands; this mean was applied across the Total Manageable Carbon map.

Temperate grasslands and shrublands

A different analysis maps the vulnerable and irrecoverable SOC of temperate grasslands. Inputs include SOC and clay data layers from the SoilGrids version 2.0 database[13] and the mean annual temperature (1970-2000) layer from WorldClim v2[22]. Carbon response function (CRF) models and coefficients were taken from Poeplau et al. (2011)[23] and are implemented spatially following the general approach of Spawn et al. (2019)[24].

The most common driver of loss of temperate grasslands is conversion to agriculture, which often causes substantial SOC losses. We model these losses using a CRF—a simple statistical model that predicts SOC emissions associated with specific land-use transitions based on the empirical effects of environmental covariates over a user-specified duration. This CRF is derived in a meta-analysis of 95 published studies conducted throughout the temperate zone[23]. CRFs are utilized by others to estimate SOC emissions from land use change[24,25]. This CRF predicts the proportional change relative to an initial SOC stock based on soil clay content (%), mean annual temperature (MAT; °C), soil depth (meters), and the time (t) since conversion (years)[24]. We quantify total changes expected as a result of land use change by using the CRF setting t equal to

30 years since, according to these models, stocks stabilize after 17 years on average, and we aim to capture the full effect of conversion events.

Freshwater wetlands

Globally, estimates range between 54-57% of wetlands lost since the beginning of the twentieth century due to disturbances such as rice paddies and aquaculture (mainly in floodplain wetlands), dams and inundation (for river floodplains), and draining for agriculture requiring tilling and drainage ditches (for inland wetlands). These drivers may have varying impacts on SOC[26]. For example, conversion to rice paddies, a crop that requires continuous inundation, may retain carbon storage[27]. However, lacking spatial data on what drives wetlands loss in different places, we assume that drainage for agriculture is the primary driver and that this type of conversion influences the SOC to a depth of at least one meter. This depth is consistent with the IPCC Wetlands Supplement[28], and a review of peatlands emissions converted to palm oil in Southeast Asia that found drainage depths to be between 80 and 110 cm[29].

We estimate SOC loss rates in wetlands through literature review. A 2016 study of 967 wetlands sites in the United States finds an average 42% difference (of 171 t C ha^{-1}) between the least and most disturbed sites; therefore, we apply this rate across all non-peat temperate and boreal wetlands as the maximum potential SOC loss due to disturbance[30]. As noted in **Table S5**, a metanalysis of greenhouse gas fluxes from tropical wetlands across the tropics[31] finds no significant difference in CO_2 fluxes between tropical wetlands on organic (peat) and mineral soils; we therefore apply our assumptions about the vulnerability of SOC in tropical peatlands to non-peat tropical wetlands. Specifically, we use 15 Mg C ha^{-1}, the midpoint of IPCC emissions factors for plantations on tropical peatlands (based on documented subsidence rates of 4-5 cm per year following conversion events) and multiply this rate by 30 years to capture the full effect of a typical conversion[2]. Vulnerable carbon for temperate and boreal peatlands are calculated using IPCC emissions factors, in this case 4.5 Mg C ha^{-1} over 30 years. If drainage is stopped and/or restoration is initiated soon after conversion, some of the carbon loss can be prevented (meaning lower vulnerable carbon values), however this avoided emissions scenario is rare and beyond the scope of this analysis.

It is also important to note that disturbed wetlands also typically emit methane and may continue to do so as they are being restored[32,33]. Methane emissions vary widely and tend to be low in brackish or saltwater wetlands[34]. Methane (and other greenhouse gases other than carbon dioxide) were beyond the scope of this analysis, but methane emissions from restored wetlands only compound the importance of protecting existing wetlands and their carbon content, since restoration following disturbance could lead to emissions.

Coastal ecosystems

We estimate SOC loss rates from coastal ecosystems through literature review. We derive the mangrove SOC loss value of 81% from a study that compares ecosystem carbon stocks from 30 relatively undisturbed mangrove forests and 21 adjacent shrimp ponds or cattle pastures[35]. Another study across 25 mangrove sites in the Indo-Pacific found 25-100% SOC loss in mangroves following disturbance, with the lower end applying to moderate soil disturbance and the upper end applying to heavier activities such as shrimp aquaculture[36]; we derive the 81%

from Kauffman et al. 2017 falling towards the upper end of this range[35]. SOC loss in seagrasses remains uncertain, as it is unclear whether the entire top meter of soil is remineralized in the event of seagrass loss, however, one study in Jervis Bay, Australia which examines a seagrass area disturbed 50 years prior finds SOC loss up to 72%[37]. (Though this study looked at just the top 30 cm of soil, it is the best available data.) Finally, we derived the salt marsh SOC loss assumption from a study of salt marsh conversion in the Scheldt estuary in the Netherlands[38].

Sequestration rates in forests – extended discussion

Table S7 shows the equations log equations for sequestration in forests. We calculate the log equations using all datapoints/ stand ages rather than the log equation for stands only up to 30 years old because the overall fit of the equation was better (an average R^2 value of 0.3898 when including all years versus 0.3314 when limiting the data to stands 30 years or younger). We combine ecosystem types and regions in a few instances (e.g., we use one equation for Subtropical humid forests since there are too few (<10) measurements in Asia and Africa to do a separate breakdown). We check the sequestration at 30 years derived from the log equations against the actual measurements of AGC in forests stands aged 25-35 from the original database (Cook-Patton's GROA)[39] and found the equations to be a reasonable approximation of real-world sequestration, especially in the ecosystems with the most measurements (e.g., Tropical moist forests in America). The mean value for 25- to 35-year-old forest stands of each ecosystem and region are included in **Table S7** for comparison. We also calculate the mean root of squared error for each forest ecosystem and use this to calculate low-end and high-end sequestration for each. These values are used in our uncertainty product (described later).

Sensitivity analysis for forests

A sensitivity analysis shows that total irrecoverable carbon could be lower (113.2 Gt) or higher (179.2 Gt) depending on estimates of forest regrowth rates. Specifically, Cook-Patton et al.'s 2020 modeled spatial product of carbon accumulation (both aboveground and belowground carbon) estimates higher natural forest regrowth rates than the IPCC, resulting in lower overall irrecoverable carbon. The model has high spatial resolution, with 13,122 georeferenced measurements combined with 66 environmental covariates, but it assumes linear carbon accumulation. This method is a significant departure from the IPCC rates, resulting in biomass carbon accumulation rates that are 32% higher on average, and 53% higher in tropical forests[39].

Alternatively, the IPCC accumulation rates, including the Suarez et al. 2019 updates for tropical forests, are based on chronosequenced data only and thus have coarser resolution, but are fit with log-linear models that result in more conservative rate estimates[40,41].

To test the sensitivity of our results, we use the equations reported in Appendix 2 of Suarez et al. to calculate sequestration in 30 years for tropical forests (combining sequestration rates for years 1-20 and years 20-100). Suarez et al. drew on GROA to create these equations but limited the inputs to the 712 sites in the tropics with chronosequenced measurements. For temperate and boreal ecosystems, we use the accumulation rates in Table 4.9: Aboveground Net Biomass Growth in Natural Forests, from *Chapter 4: Forest Land of the IPCC 2019 Refinement to the*

2006 IPCC Guidelines for National Greenhouse Gas Inventories[17]. For all forests, we use Table 4.4: Ratio of Belowground Biomass to Aboveground Biomass to estimate total biomass sequestration. Overall, the more conservative sequestration assumptions in IPCC/Suarez result in higher estimates of irrecoverable carbon.

In the main analysis, we use the publicly available input data in Cook-Patton et al. 2020 (2,741 georeferenced measurements) to model log-linear forest growth rates. This approach capitalizes on the greater spatial resolution in Cook-Patton et al. and the IPCC's more conservative assumptions of saturating growth. Our chosen approach using logarithmic equations is most appropriate for this analysis given our interest in understanding sequestration over the 30-year timeframe.

Alternate approach to land-use conversion and climate change risk

As an alternative to the metrics of vulnerability to climate change and land cover modification for irrecoverable summarized at an ecoregion level presented in the main text (**Figure 2**), we also explored an alternative approach that assess risk at a pixel basis. **Figure S14** shows the categorical risk of climate change and land cover change on irrecoverable carbon using the future risk of tree cover change through 2050 presented in Bastin et al. 2020[42] for the climate change axis and the future vulnerability to land cover change 2050 modeled through TerrSet land cover change modeler[43] (https://clarklabs.org/terrset/land-change-modeler/). Areas identified as higher risk due to climate change or land cover change in **Figure S14** represent the top quartile of pixels with >0 irrecoverable carbon within each data set. This corresponds to a projected tree cover decline due to climate change of >21% and a land cover vulnerability of >51%. These areas are mapped as blue and red respectively. Areas in the top quartile of both climate risk and land cover vulnerability are mapped as purple. This alternative approach is notable in that it highlights pervasive exposure to climate change for much of the lowland Amazon basin and dual threats of climate change and land cover change in Southeast Asia and Oceania.

Importance of Indigenous lands

At least 370 million people worldwide define themselves as Indigenous or descended from populations who inhabited a country before the time of conquest or colonization and who retain at least some of their own social, economic, cultural, and political institutions[44]. Indigenous Peoples often retain de facto influence over their ancestral lands, with varying degrees of legal land tenure and use rights. Garnett et al. 2018 estimate that Indigenous Peoples manage or have tenure rights over 38 million sq. km across 87 countries[44]. The type and security of tenure has been shown to matter for conservation outcomes: research in Peru finds that land titling for Indigenous Peoples significantly reduced forest clearing and disturbance[45]. Indigenous Peoples themselves are advocating for the recognition of their contributions to national climate plans, direct access to climate finance, and titling of unrecognized lands[46]. In addition to Indigenous Peoples, local communities, or "groupings of individuals and families that share common interests in a definable local land area within which they normally reside" (definition from LandMark) may represent de facto influence over certain land areas, whether or not they are formally recognized. For these reasons, it is relevant to assess the overlap between Indigenous Peoples' and Local Communities' (IPLC) lands and irrecoverable carbon.

Limitations to loss estimates

In the main text we calculate recent loss of irrecoverable carbon based on Hansen et al.'s tree cover loss dataset for the years 2011-2019[47], capturing an estimated 83% of irrecoverable carbon loss in the last decade (since most high irrecoverable carbon areas are tree-covered and thus captured in Hansen). However, many other natural ecosystems are not captured in the Hansen dataset. Of these, the largest source of uncertainty in terms of global irrecoverable carbon loss comes from freshwater wetlands, including peatlands. Currently, there are both bottom-up and top-down approaches to determine the extent and types of wetlands globally, but a global inventory of wetlands at high spatial resolution remains elusive[48]. One effort through the Freshwater Ecosystem Explorer for Sustainable Development Goal 6.6. aims to track changes in freshwater wetland areas over time at high resolution and has so far compiled baseline extents; this could be a means for tracking irrecoverable carbon loss in wetlands in the future. Loss of irrecoverable carbon from peatlands is of particular concern giving the centuries-long timescale to recover this carbon, if lost. From Leifeld & Menichetti 2018[49], we estimate that more than 50 million ha have been drained for agriculture or forestry, releasing 0.5 Gt C annually. However, the study is based on country-level estimates of degraded peatlands and is therefore inadequate for calculating a more precise value of irrecoverable carbon loss from peatlands. **Table S14** summarizes the loss of irrecoverable carbon by major ecosystem category.

Scenarios: Different land-use change assumptions

If agriculture moves North

As noted in **Table S5**, our vulnerable carbon map and calculations are based on logging/forestry being the primary driver of anthropogenic conversion in temperate and boreal forests. While this is true today[19] and conversion of temperate forests to cropland is relatively rare[50,51], models of where major global crops could expand based on shifting climatic suitability show that major new agricultural frontiers could open up by 2080, particularly in Canada and Russia, potentially putting temperate and boreal forests at risk of conversion[52]. While logging/forestry is not known to cause significant SOC loss[53-56], if agriculture were to become a significant driver of temperate and boreal forest loss, additional SOC in those ecosystems will be vulnerable to release. We therefore performed an analysis to understand how our assumption of logging/forestry as the primary driver affected the results.

For potential loss of SOC in temperate forests due to agriculture, we use the same CRF methodology based on Poeplau et al. 2011[23], as described above. Because this CRF is not calibrated for temperatures below 0 degrees Celsius, we use a simple % vulnerable assumption for boreal forests which are more likely to drop below this threshold. Our assumption of 31% is based on a global study that found this decrease in organic SOC stocks in boreal forests converted to agriculture, compiling data from 22 paired sites in this zone[57]. It is also aligned with a study of agricultural development in the Alaskan lowlands which tracked 34% SOC loss on non-permafrost soils several decades following the conversion (this study looks at a 100 cm depth profile)[58]. **Table S15** shows the results of the scenario analysis. Globally, an additional 18.38 Gt C is irrecoverable–both vulnerable to loss and irrecoverable within 30 years–if agriculture becomes a major driver of land-use change in temperate and boreal forests.

If rice is a larger driver of wetland loss

Certain drivers of wetlands loss, such as conversion to rice paddies[59], may lead to less soil carbon loss since this flooded agricultural system mimics the continuous inundation of the original wetland and does not require soil disturbance through tilling or altering hydrology through drainage[27]. Without spatial data on the drivers of wetland loss, we are not able to determine how much soil carbon might be spared by conversion to rice paddies versus other, more carbon-disruptive forms of agriculture. In Asia, where 90% of the world's rice is grown, 5.58 Gt of irrecoverable carbon are attributed to wetland/peatland soils. If rice is indeed the largest driver of wetlands conversion in this region, a smaller proportion of this soil carbon is likely vulnerable, so irrecoverable carbon numbers could be slightly overestimated.

Damming of rivers can also drive changes in wetlands, either by flooding additional areas or reducing waterflow downstream. Dams that keep areas flooded could prevent soil carbon disturbance, however this affects a relatively small area of wetlands in riverine floodplains and was beyond the scope of this analysis.

Other factors potentially affecting irrecoverable carbon but not included in this study

Our irrecoverable carbon estimate may be conservative because we assume restoration is initiated immediately after clearance, while in practice lands are often used for multiple years after disturbance (e.g., for shifting cultivation) or experience conditions that inhibit successful full recovery (e.g., degraded soils). We also do not account for the forgone sequestration that would result from forest loss[60]. Conversely, we are unable to account for potential land use legacies[61] on our estimates of initial carbon stocks and their trajectories, which could overestimate the realized effects. The effects of climate change[62] and CO_2 fertilization on biomass recovery[63] and SOC loss and gain[64] are presently unclear and may ultimately influence realized irrecoverability.

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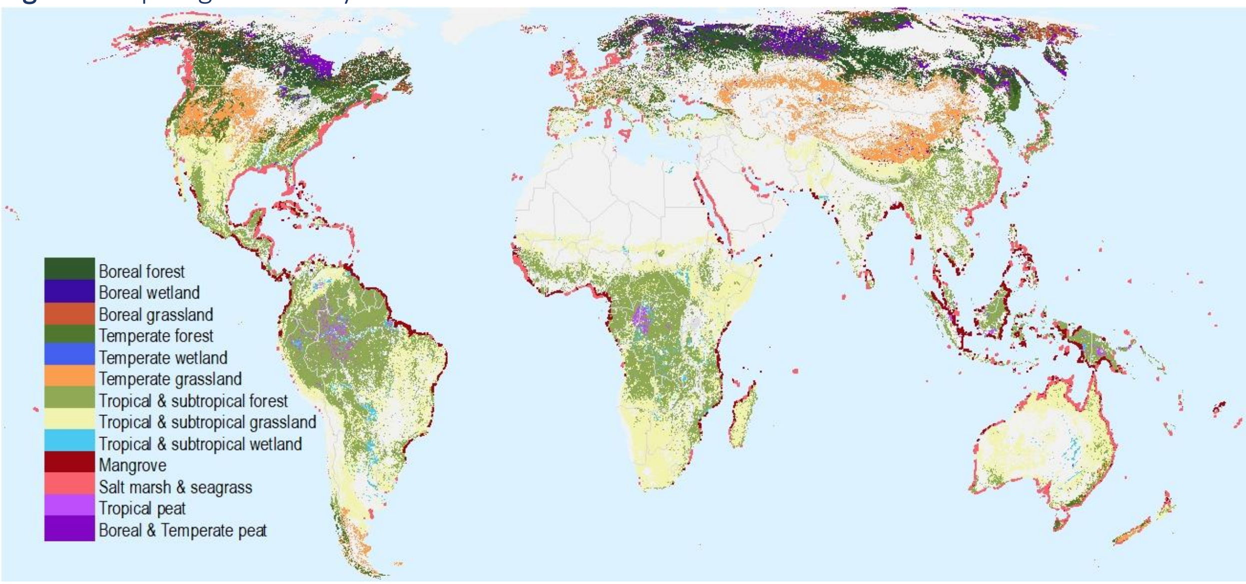
Supplementary Figures and Tables

Fig. S1. Map of global ecosystem extents



***Notes**:* Coastal ecosystem extents (mangrove, salt marsh and seagrass) are exaggerated on this map to be made visible at global scale.

Fig. S2. Map of total manageable carbon in biomass

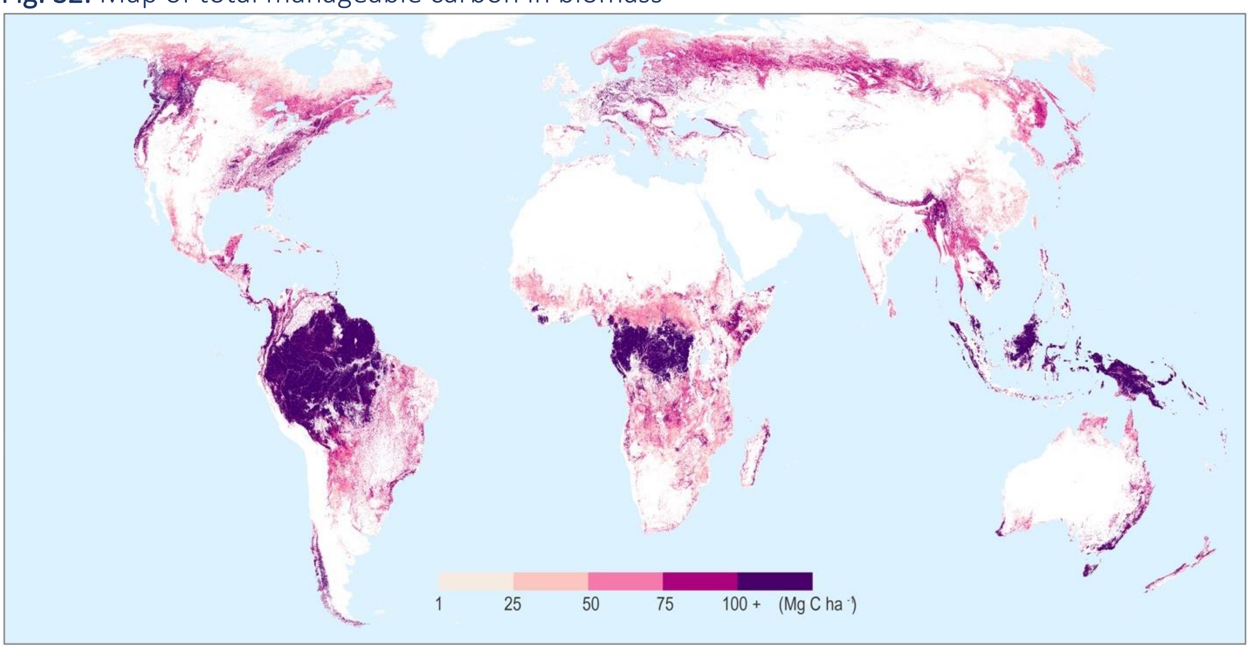


Fig. S3. Map of total manageable carbon in soils

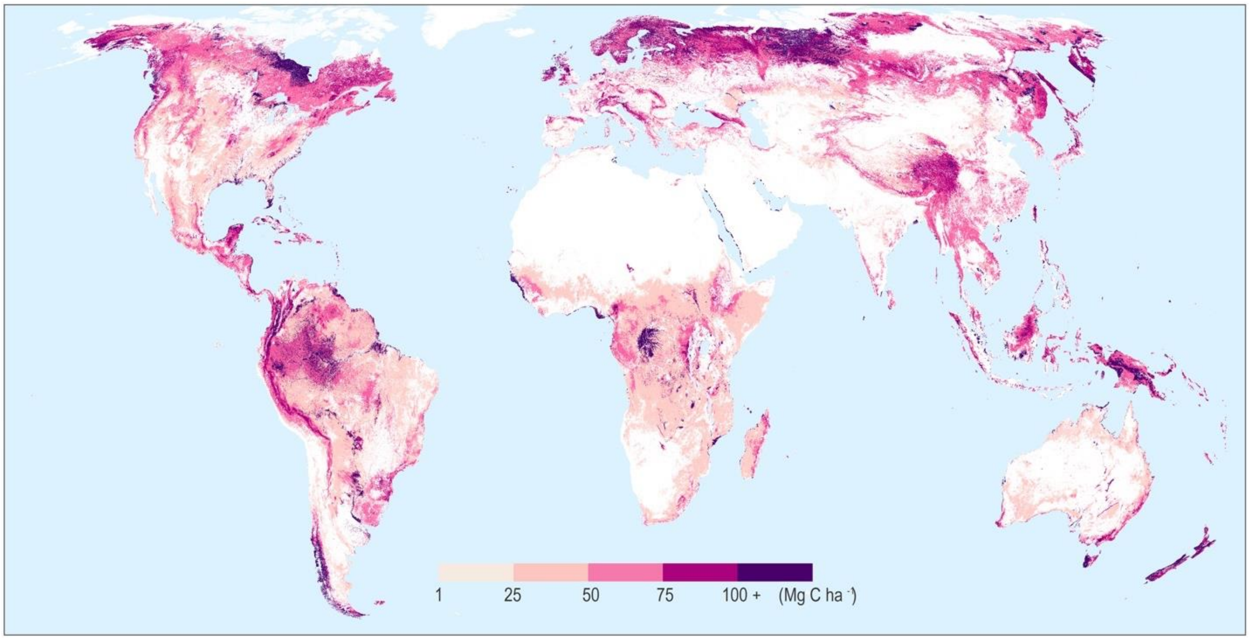
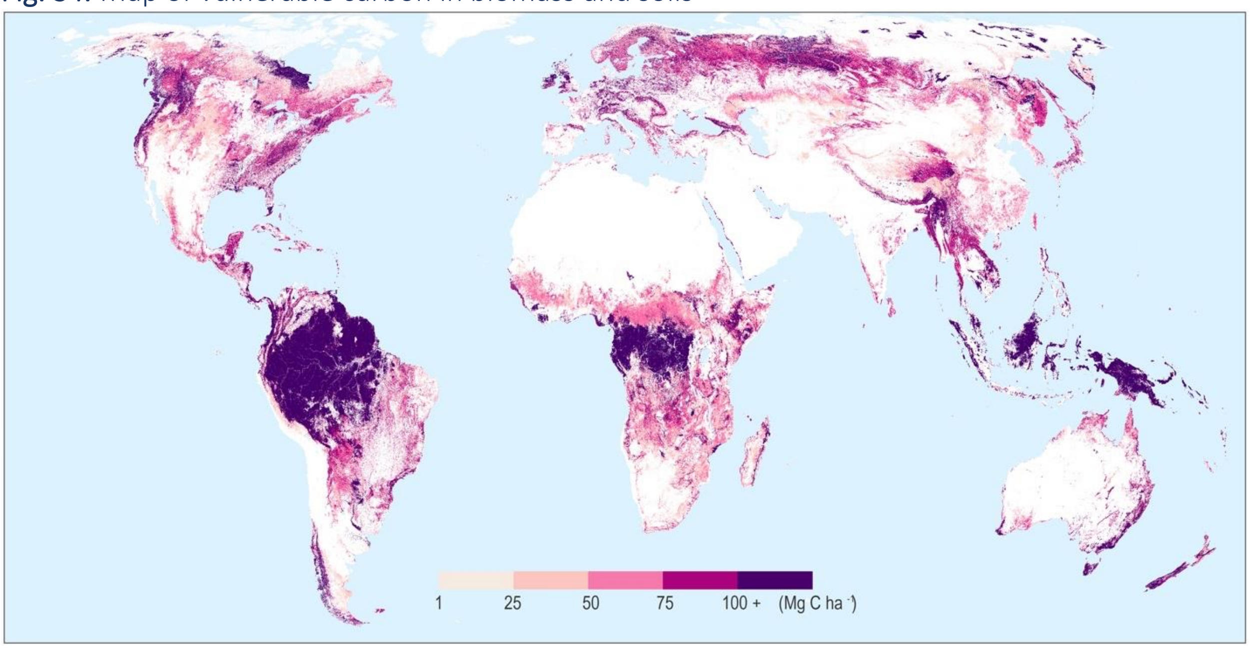
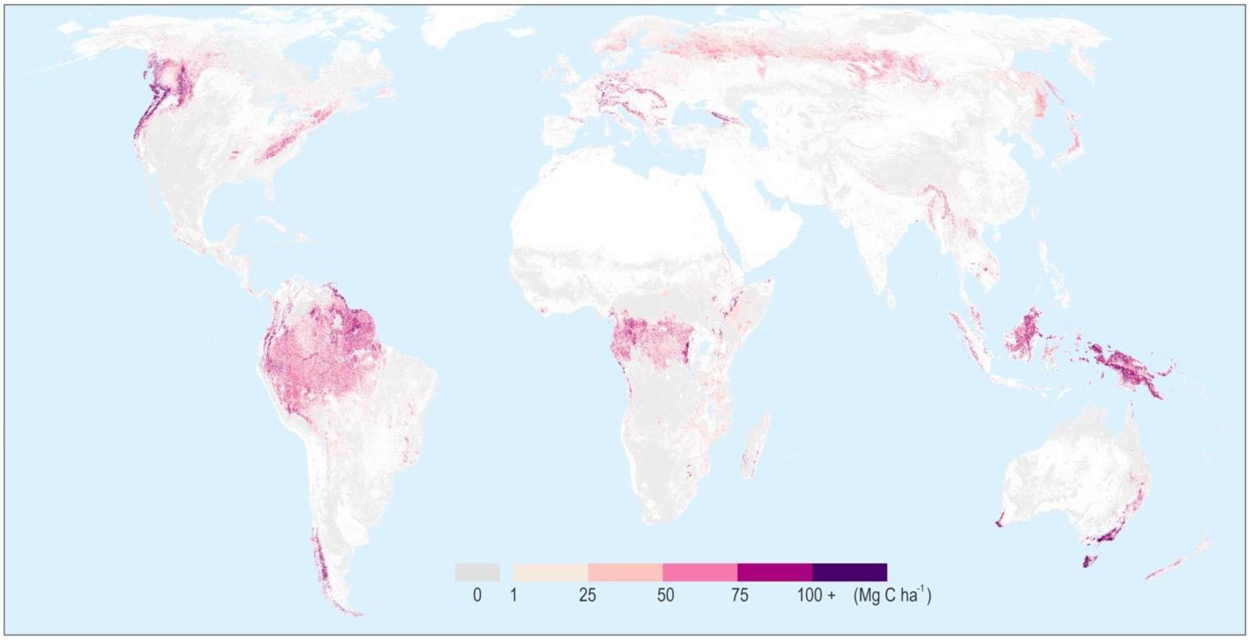


Fig. S4. Map of vulnerable carbon in biomass and soils



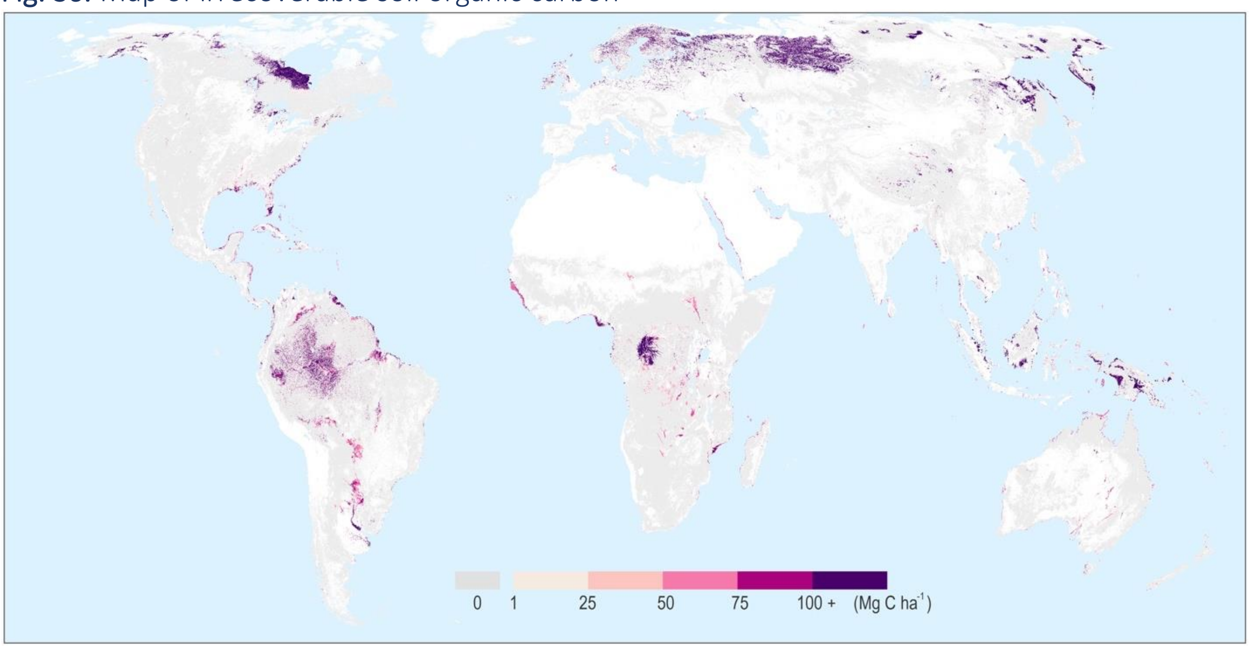
Note: The figure shows both biomass carbon and soil carbon that is vulnerable to loss in a typical conversion event (a portion of the total manageable carbon is vulnerable).

Fig. S5. Map of irrecoverable carbon in biomass



***Note**:* Areas with zero irrecoverable carbon are displayed in grey to demonstrate the footprint of total manageable carbon.

Fig. S6. Map of irrecoverable soil organic carbon



Note: Areas with zero irrecoverable carbon are displayed in grey to demonstrate the footprint of total manageable carbon.

Fig. S7. Global amounts of irrecoverable, vulnerable but recoverable, and not vulnerable carbon in biomass and soils, by ecosystem

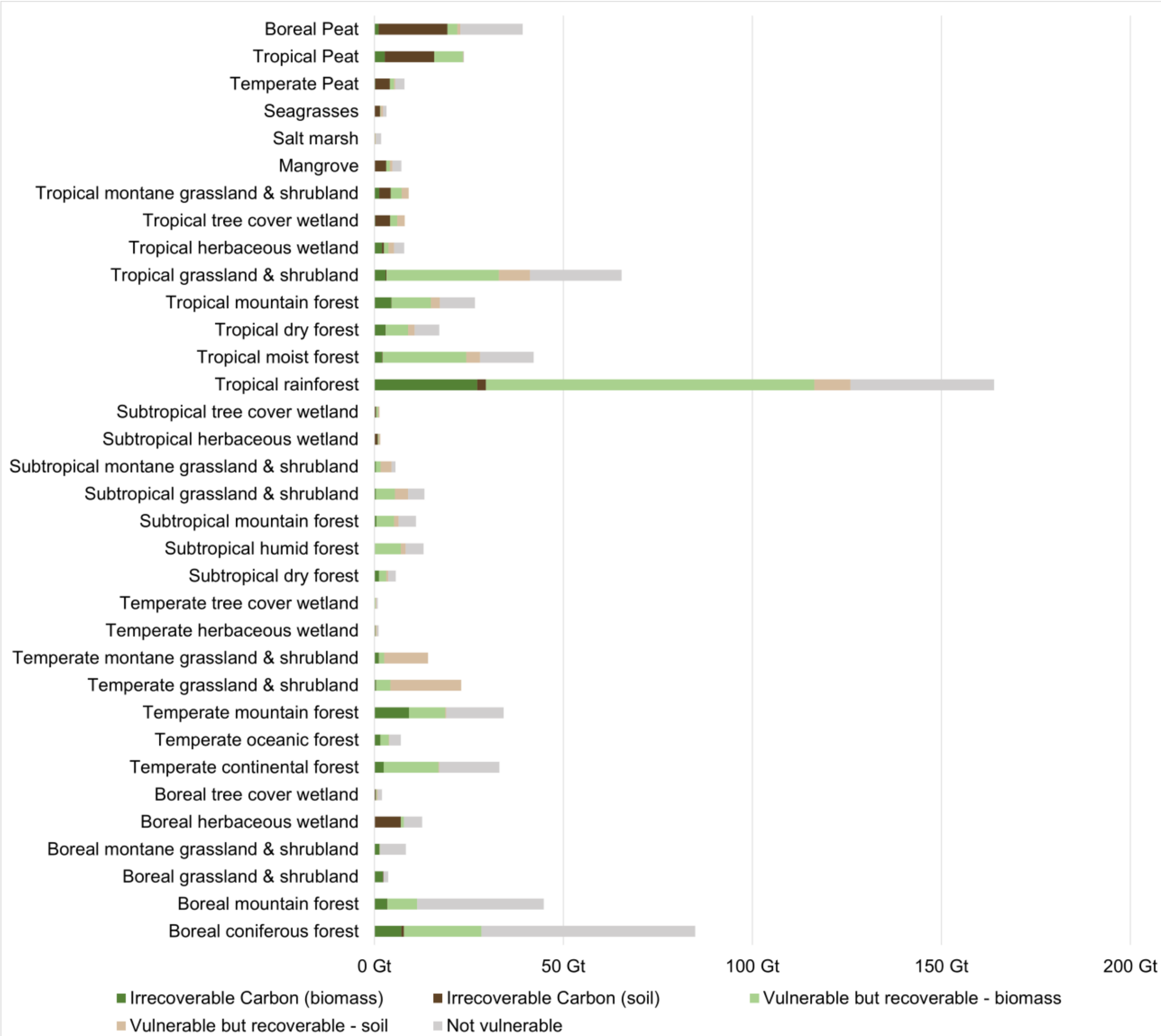


Fig. S8. Uncertainty layer for total manageable biomass carbon

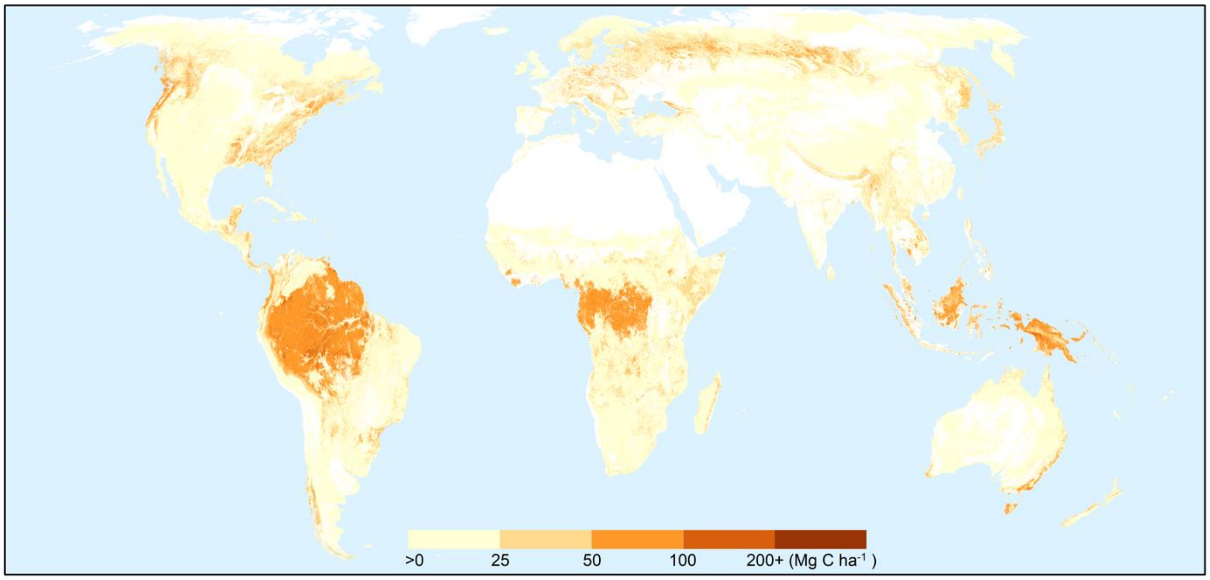


Fig. S9. Uncertainty layer for total manageable soil organic carbon

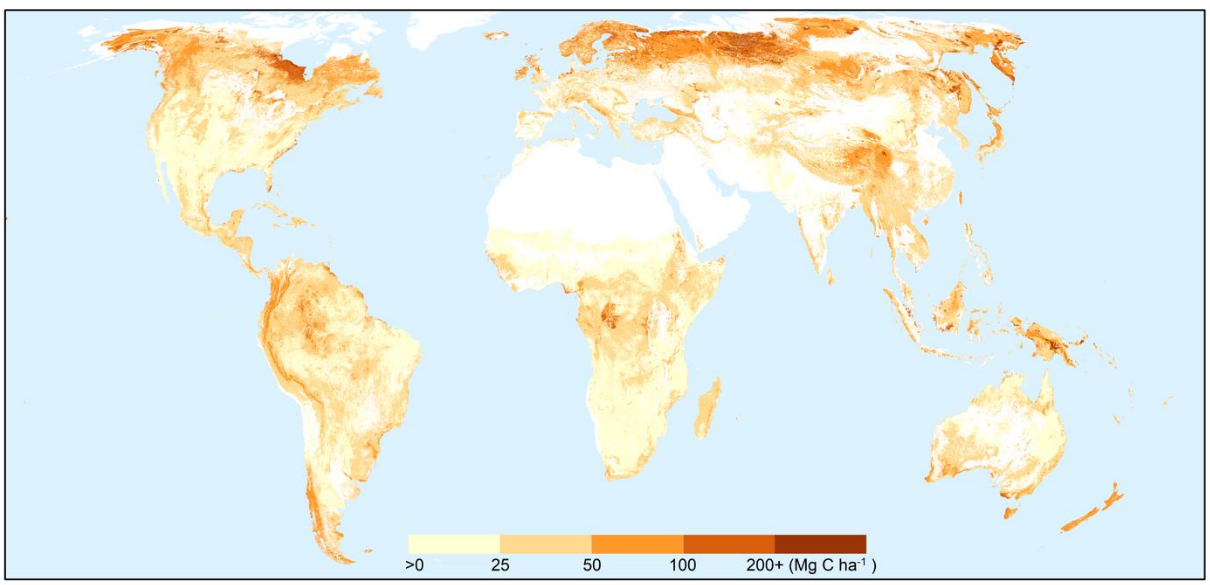


Fig. S10. Uncertainty layer for vulnerable soil organic carbon

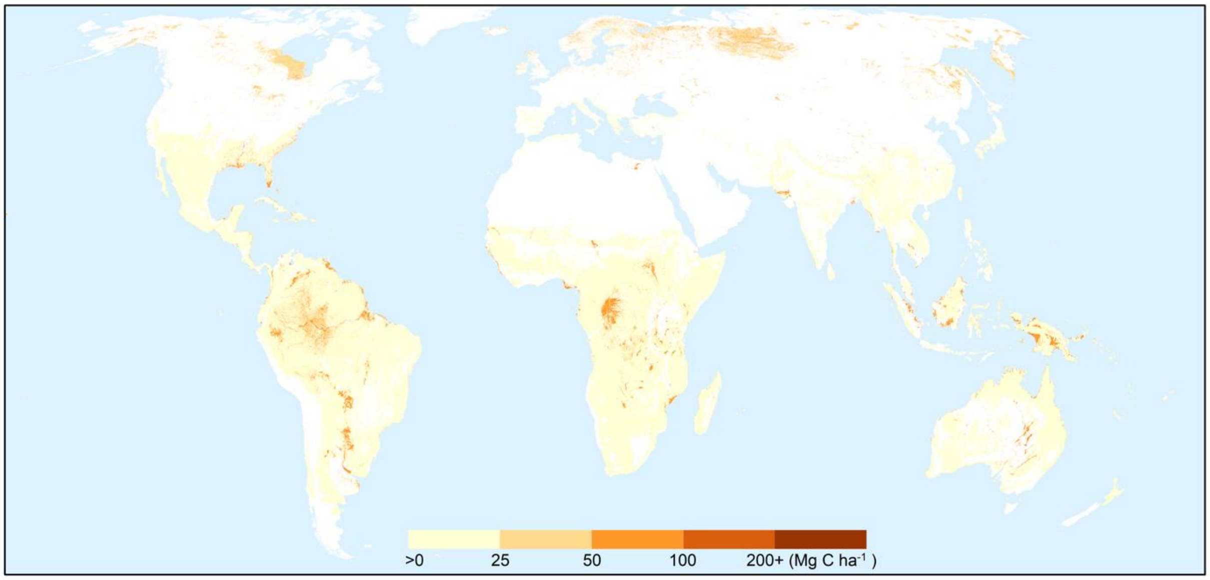


Fig. S11. Uncertainty layer for irrecoverable biomass carbon

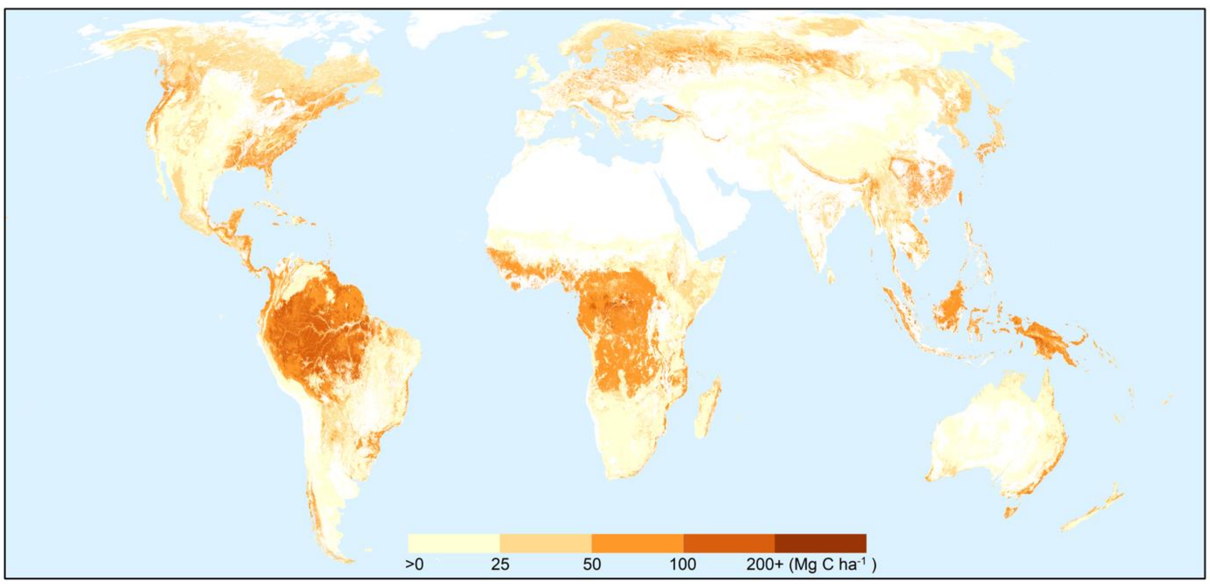


Fig. S12. Uncertainty layer for irrecoverable soil organic carbon

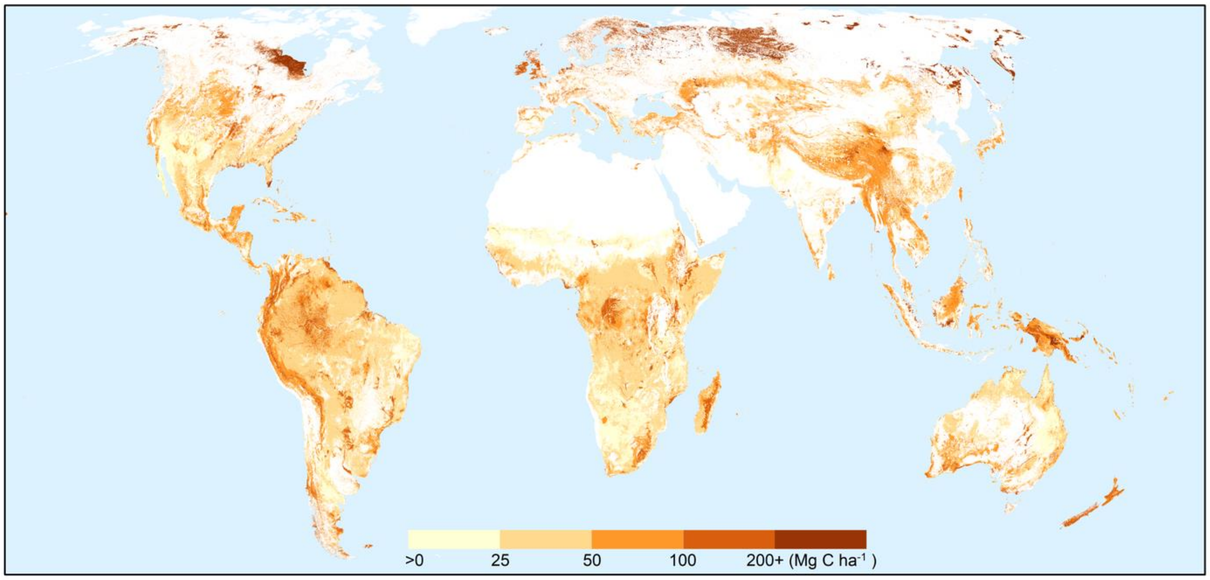
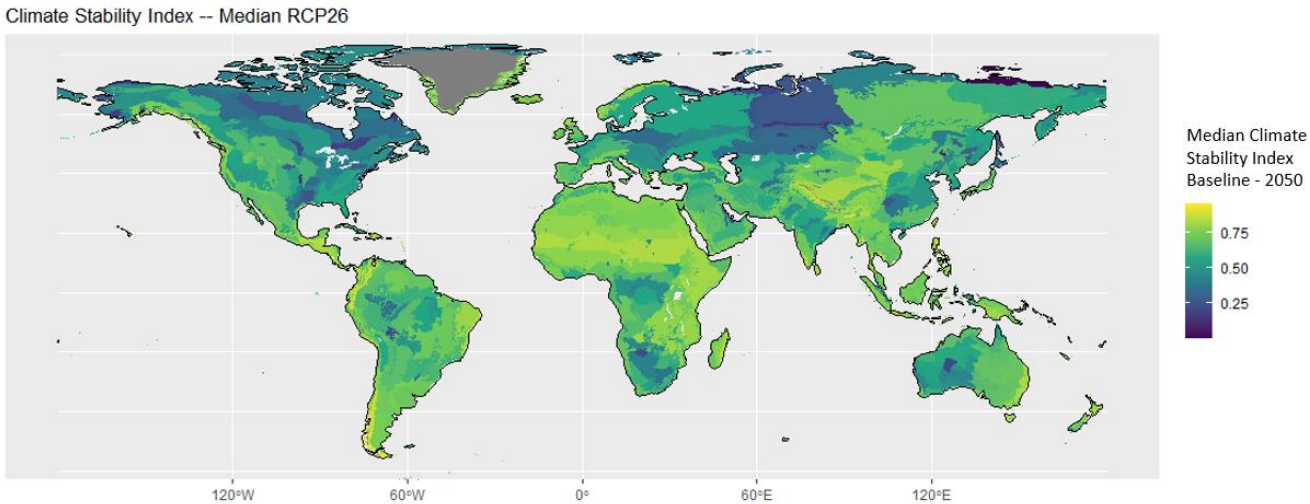
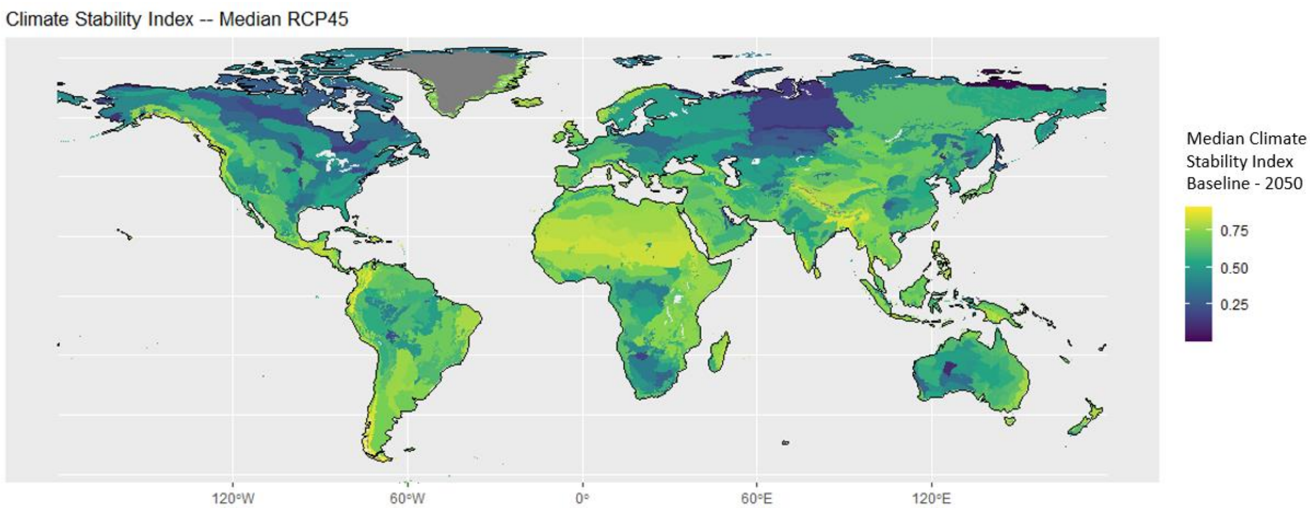


Fig. S13. Risks from climate change under alternate CSI scenarios





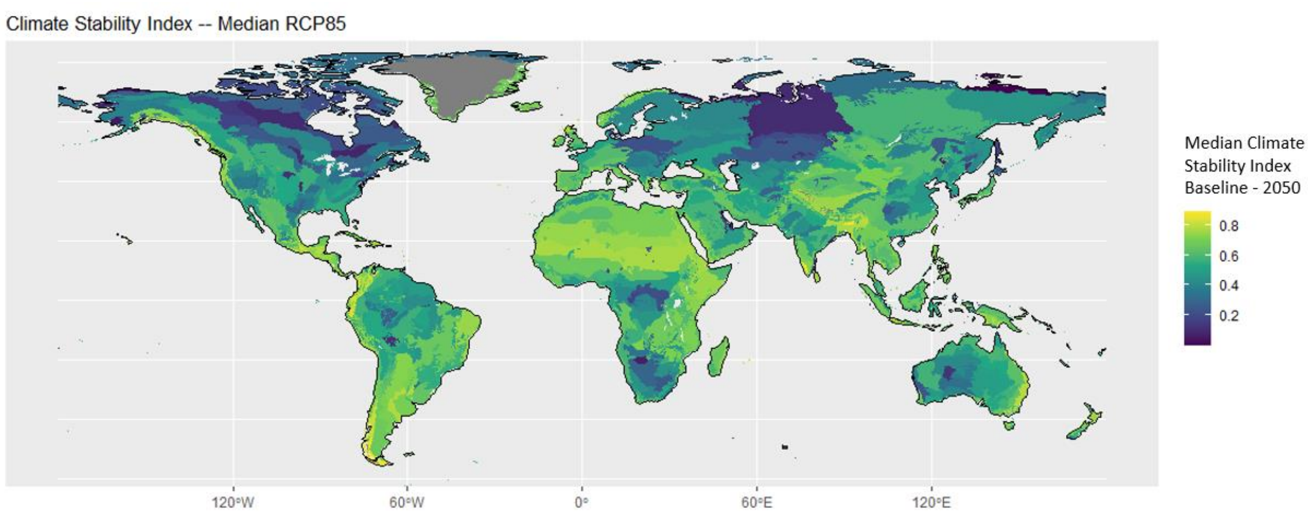
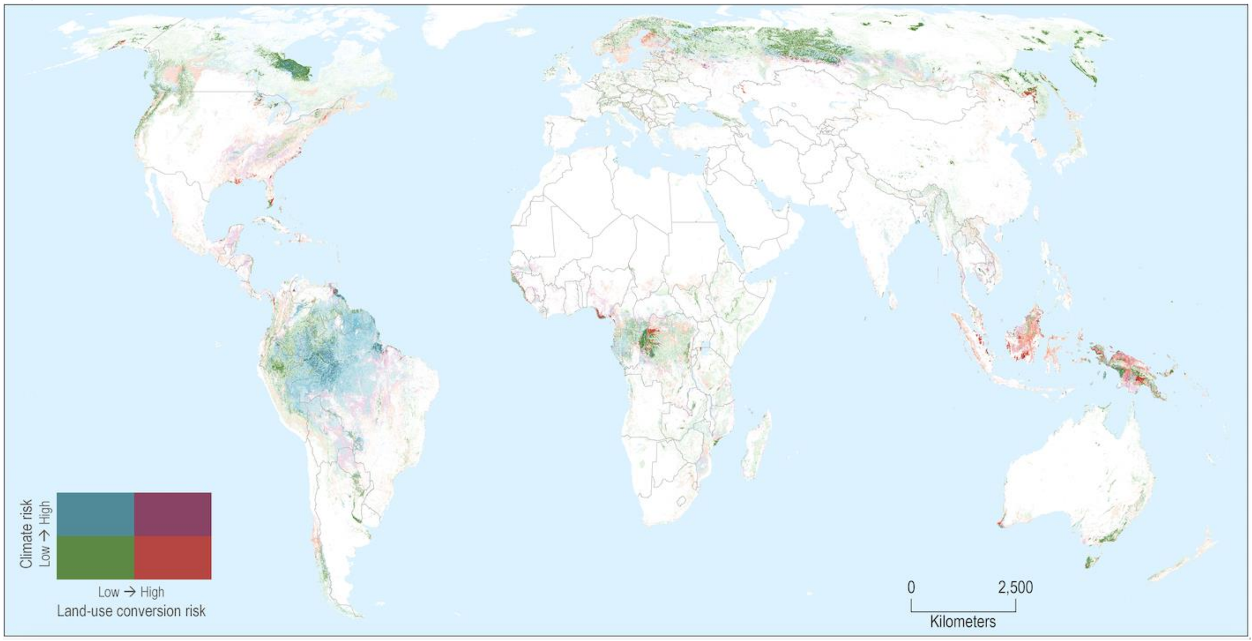


Fig. S14. Alternate map of climate and land-use risks to irrecoverable carbon



Notes: This is an alternate approach to Fig. 2 in the Main Text, using future risk of tree cover change due to climate change through 2050 (Bastin et al. 2020) as the climate risk axis and TerrSet's land cover change modeler (Clark Labs 2020) as the land-use conversion risk axis. It is pixel-based rather than the ecoregion-based approach in the Main Text.

Table S1. Datasets combined to create the ecosystem extent

Major ecosystem extent for irrecoverable carbon map	COMBINATIONS FOR TERRESTRIAL ECOSYSTEMS		
	ESA land cover class		**Ecozone**
Boreal coniferous forest	Any forest class	∩	Boreal coniferous forest or Boreal tundra woodland
Boreal mountain forest	Any forest class	∩	Boreal mountain system
Boreal herbaceous wetland	Herbaceous wetlands	∩	Any Boreal ecozone
Boreal tree-covered wetland	Tree-covered wetlands	∩	Any Boreal ecozone
Temperate continental forest	Any forest class	∩	Temperate continental forest, Temperate steppe, or Temperate desert
Temperate oceanic forest	Any forest class	∩	Temperate oceanic forest
Temperate mountain forest	Any forest class	∩	Temperate mountain system
Temperate shrubland and grassland	Grassland or shrubland class	∩	Any Temperate ecozone *except* Temperate mountain forest
Temperate herbaceous wetland	Herbaceous wetlands	∩	Any Temperate ecozone
Temperate tree-covered wetland	Tree-covered wetlands	∩	Any Temperate ecozone
Subtropical humid forest	Any forest class	∩	Subtropical humid forest ecozone
Subtropical dry forest	Any forest class	∩	Subtropical dry forest, Subtropical desert, or Subtropical steppe
Subtropical mountain forest	Any forest class	∩	Subtropical mountain system
Subtropical shrubland and grassland	Grassland or shrubland class	∩	Any Subtropical ecozone *except* Subtropical mountain forest
Subtropical herbaceous wetland	Herbaceous wetlands	∩	Any Subtropical ecozone
Subtropical tree-covered wetland	Tree-covered wetlands	∩	Any Subtropical ecozone
Tropical rainforest	Any forest class	∩	Tropical rainforest
Tropical moist forest	Any forest class	∩	Tropical moist forest
Tropical dry forest	Any forest class	∩	Tropical dry forest or Tropical desert
Tropical mountain forest	Any forest class	∩	Tropical mountain system
Tropical shrubland and grassland	Grassland or shrubland class	∩	Any Tropical ecozone *except* Tropical mountain forest
Tropical herbaceous wetland	Herbaceous wetlands	∩	Any Tropical ecozone
Tropical tree-covered wetland	Tree-covered wetlands	∩	Any Tropical ecozone
Montane shrubland and grassland	Grassland or shrubland class	∩	Boreal mountain forest, Temperate mountain forest, Subtropical mountain forest, or Tropical mountain forest
	COMBINATIONS FOR COASTAL ECOSYSTEMS AND PEATLANDS		
	Additional ecosystem extent		**Ecozone**
Mangroves	Global Mangrove Watch 2010[8]		Not applicable (coastal ecosystem)
Seagrasses	UNEP-WCMC 2018[10]		Not applicable (coastal ecosystem)
Salt Marshes	McOwen et al 2017[11]		Not applicable (coastal ecosystem)
Boreal & temperate peat	PEATMAP 2018[12] and histosols[7]		Any Boreal or Temperate
Tropical peat	PEATMAP 2018[12]		Any Tropical

Note: Peat layers are applied to soil carbon only.

Table S2. Spatial and temporal resolutions for datasets used in this analysis

	Dataset	Spatial Resolution	Year	Data type	Date accessed	Source/Dataset
Biomass	Aboveground biomass carbon (AGC)	300 m	2010	Raster	3/19/2020	Spawn and Gibbs 2020[65,66]
	Belowground biomass carbon (BGC)	300 m	2010	Raster	3/19/2020	Spawn and Gibbs 2020[65,66]
	Mangrove AGB	30 m	2000	Raster	5/14/2019	Simard et al. 2019[15]
Soil	Mangrove soil carbon	30 m	2000	Raster	1/29/2019	Sanderman et al. 2018[18]
	Soil organic carbon (SOC)	250 m	1980 - 2020	Raster	6/5/2020	ISRIC 2020[13]
	WorldClim v2	30 second	1970 - 2000	Raster	3/19/2020	Fick & Hijmans 2017[22]
Extent	Mangrove extent	0.8 arc seconds	2010	Vector	6/13/2020	Bunting et al. 2010[8]
	Seagrass extent	1:1,000,000	2000	Vector	9/27/2018	UNEP-WCMC 2018[10]
	Salt marsh extent	Between 1:10,000 to 1:4,000	2000	Vector	9/27/2018	McOwen et al. 2017[11]
	Peatland extent (Peatmap; Histosols)	0.5 x 0.5 degree	2019	Raster	1/21/2020	Xu et al. 2018[12]
	SoilGrids Most Probably Class	250m	2006	Raster	9/21/2020	ISRIC 2020[7]
Land cover	FAO Global Ecological Zones (GEZ)	1km	2010	Raster	4/22/2020	FAO 2010[1]
	Land Cover (ESA CCI)	300 m	2010	Raster	2/20/2020	ESA 2010[3]
	Land Cover (ESA CCI)	300 m	2018	Raster	2/20/2020	ESA 2018[3]
	Plantations	Varies by source	2015	Vector	5/16/2020	Harris et al 2019[5]
	Cryosols	250m	2006	Raster	9/21/2020	ISRIC 2020[7]
Sequest-ration	GROA database	NA	NA	Data - base	7/9/2020	Cook-Patton et al. 2020[39]
Risk and Loss	Forest loss	30m	2011 - 2019	Raster	6/16/2020	Hansen et al. 2013[67]
	Human Footprint	1km	2009	Raster	4/21/2020	Venter et al. 2016[68]
Protect ion	World Database of Protected Areas		2020	Vector	5/8/2020	UNEP-WCMC and IUCN 2020[69]
	Indigenous People, Lands, Communities		2020	Vector	9/23/2020	Garnett et al. 2018 (modified dataset available from UNEP-WCMC)[44]

Table S3. Default biomass carbon values for seagrasses and salt marshes

Ecosystem	AGC ($MgC\ ha^{-1}$)	Standard Error AGC	BGC ($MgC\ ha^{-1}$)	Standard Error BGC	Source
Seagrasses	0.755	0.065	1.756	0.191	Fourqurean et al. 2012[70]
Salt marshes	5.0	0.26	5.5	0.286	Byrd et al. 2018[71] *Applied same ratio of Standard Error for AGC to BGC.

Table S4. Summary of 2018 ecosystem extents and total manageable carbon values

Ecosystem	Extent (M sq. km)	Manageable carbon in biomass (Gt C)	Manageable carbon in soils (Gt C)	Total manageable carbon (Gt C)
Boreal coniferous forest	5.80	27.93	40.58	68.48
Boreal mountain forest	2.52	11.22	17.71	29.02
Boreal grassland and shrubland	1.17	2.44	8.24	10.71
Boreal montane grassland & shrubland	0.87	1.41	5.95	7.43
Boreal herbaceous wetland	0.40	0.97	7.32	8.45
Boreal tree-covered wetland	0.11	0.30	1.57	1.90
Temperate continental forest	2.79	16.90	16.46	33.47
Temperate oceanic forest	0.46	3.83	3.22	7.08
Temperate mountain forest	2.43	18.74	15.47	34.25
Temperate grassland and shrublands	4.47	4.21	18.76	23.35
Temperate montane grassland & shrubland	2.36	2.61	11.62	14.46
Temperate herbaceous wetland	0.08	0.20	1.04	1.28
Temperate tree-covered wetland	0.05	0.27	0.65	0.94
Subtropical dry forest	0.60	3.11	2.68	5.82
Subtropical humid forest	1.51	6.93	6.24	13.26
Subtropical mountain forest	1.07	5.18	5.94	11.17
Subtropical grassland and shrublands	4.88	5.41	14.87	20.58
Subtropical montane grassland and shrublands	1.77	1.68	8.25	10.09
Subtropical herbaceous wetland	0.14	0.21	1.32	1.59
Subtropical tree-covered wetland	0.09	0.53	0.82	1.37
Tropical rainforest	9.38	114.12	50.19	163.83
Tropical moist forest	4.30	24.17	18.05	42.29
Tropical dry forest	2.22	8.91	8.24	17.22
Tropical mountain forest	1.60	14.91	11.86	26.85
Tropical grassland and shrublands	11.39	32.76	35.33	68.62
Tropical montane grassland and shrubland	1.12	3.22	5.75	9.09
Tropical herbaceous wetland	0.62	2.10	5.85	8.16
Tropical tree-covered wetland	0.42	4.18	4.87	9.26
Mangroves	0.14	1.10	4.24	5.59
Salt marsh	0.05	0.08	0.49	0.58
Seagrass	0.29	0.09	3.09	3.20
Temperate peat	0.37	1.35	6.85	8.31
Tropical peat	0.82	10.33	12.93	23.97
Boreal peat	1.82	4.04	35.82	40.00
Total	**68.12**	**335.44 (+/- 152.98)**	**392.31 (+/- 268.95)**	**731.66 (+/- 340.22)**

Notes: The error is summed in quadrature. The biomass carbon listed for peatlands is the sum of the aboveground biomass vegetation type (e.g., tropical rainforest biomass, tropical moist forest biomass, tropical herbaceous wetland, etc.) and biomass carbon values listed for other ecosystem are specifically for the non-peat areas of those ecosystems. Soil organic carbon was considered down to 100 cm for inundated soils (wetlands, peatlands, and coastal ecosystems) and down to 30 cm for all other soils, based on our manageability criterion.

Table S5. Approaches for calculating vulnerable SOC by ecosystem

Ecosystem	Primary driver of anthropogenic conversion (assumption)	Vulnerable SOC: how calculated (standard error in parentheses)	Source / explanation
Tropical & subtropical forests (all types)	Agriculture	Initial C x 21.3% (+/- 4.1%)	Emissions factor from Don et al 2011, normalized to 30 cm based on Sanderman methodology.
Tropical & subtropical grasslands	Agriculture	Initial C x 25.2% (+/- 3.3%)	
Montane grasslands	Agriculture	Modeled	In the absence of montane grassland-specific data, we used a Carbon Response Function (CRF) for temperate grasslands from Poeplau et al. 2011 [23].
Tropical & subtropical wetlands (non-peat, both forested and herbaceous)	Agriculture/ development	Initial C x 100% or 450 (+/- 67) MgC ha^{-1} (whichever is smaller)	Sjogersten et al 2014[31] find no significant difference in CO2 fluxes between tropical wetlands on organic (peat) and mineral soils; we therefore treat non-peat tropical wetlands the same as tropical peatlands.
Temperate forests (all types)	Forestry	Initial C x 0%	In a meta-analysis of 75 studies reporting 432 SOC response ratios for harvested temperate forests, Nave et al. (2010) report no significant SOC change in forest mineral soils[53].
Temperate grasslands	Agriculture	Modeled	We used a Carbon Response Function (CRF) for temperate ecosystems' conversion to cropland from Poeplau et al. 2011 to model the SOC response of this transition[23].
Temperate wetlands (non-peat, both forested and herbaceous)	Agriculture/development	Initial C x 42% (+/- 16.8%)	Estimate from Nahlik & Fennessy 2016[30].
Boreal forests (all types)	Forestry	Initial C x 0%	Studies suggest that forestry/ timber has no meaningful effect on mineral SOC stocks in boreal forests, therefore we assumed 0% change[55,56].
Boreal grasslands and shrublands	Agriculture/development	Initial C x 0%	We assumed the same CRF as for temperate grasslands.
Boreal wetlands (non-peat, both forested and herbaceous)	Agriculture/development	Initial C x 42% (+/- 16.8%)	In absence of a boreal-specific study, we applied the same loss as temperate wetlands.
Mangroves	Aquaculture/development	Initial C x 81% (+/- 15.7%)	Estimate from Kauffman et al. 2017[35]
Seagrasses	Aquaculture/development	Initial C x 72% (standard error not available)	Estimate from Macreadie et al. 2014[37]
Salt marshes	Aquaculture/development	Initial C x 60% (+/- 8%)	Estimate from Van de Broek et al. 2019[38]
Tropical peatlands	Agriculture	Initial C x 100% or 450 (+/- 67) Mg C ha^{-1} (whichever is smaller)	Estimate based on IPCC emissions factors.
Temperate & boreal peatlands	Agriculture	Initial C x 100% or 135 (+/- 33) Mg C ha^{-1} (whichever is smaller)	

Table S6. Summary of vulnerable carbon by ecosystem extent

Ecosystem	Vulnerable carbon in biomass (Gt C)	Vulnerable carbon in soil (Gt C)	Total vulnerable carbon (Gt C)	Mean vulnerable Mg C ha^{-1}
Boreal coniferous forest	27.66	0.53	28.19	48.87
Boreal mountain forest	11.21	0.04	11.26	44.86
Boreal grassland and shrubland	0.23	0.14	0.37	10.05
Boreal montane grassland and shrubland	1.41	0.04	1.44	16.58
Boreal herbaceous wetland	0.95	3.04	3.99	99.10
Boreal tree-covered wetland	0.29	0.63	0.92	86.71
Temperate continental forest	16.89	0.28	17.17	62.93
Temperate oceanic forest	3.83	0.11	3.93	101.85
Temperate mountain forest	18.74	0.30	19.03	82.18
Temperate grassland and shrubland	4.21	18.78	22.98	52.31
Temperate montane grassland and shrubland	2.61	11.57	14.17	61.25
Temperate herbaceous wetland	0.20	0.46	0.66	82.91
Temperate tree-covered wetland	0.27	0.28	0.55	110.36
Subtropical dry forest	3.11	0.55	3.66	66.14
Subtropical humid forest	6.93	1.32	8.25	65.35
Subtropical mountain forest	5.18	1.22	6.40	62.79
Subtropical grassland and shrubland	5.41	3.51	8.93	18.56
Subtropical montane grassland and shrubland	1.68	2.84	4.52	25.73
Subtropical herbaceous wetland	0.21	1.36	1.57	114.54
Subtropical tree-covered wetland	0.53	0.82	1.36	167.82
Tropical rainforest	114.11	11.90	126.02	136.02
Tropical moist forest	24.17	3.78	27.95	65.42
Tropical dry forest	8.90	1.70	10.61	48.23
Tropical mountain forest	14.91	2.46	17.36	109.28
Tropical grassland and shrubland	32.75	8.43	41.19	36.31
Tropical montane grassland and shrubland	3.22	1.98	5.20	46.74
Tropical herbaceous wetland	2.10	5.95	8.05	132.16
Tropical tree-covered wetland	4.18	4.91	9.09	220.74
Mangroves	1.10	3.66	4.72	326.69
Salt marsh	0.08	0.31	0.40	80.23
Seagrass	0.09	2.25	2.34	79.89
Temperate peat	1.35	4.17	5.52	159.79
Tropical peat	10.33	13.22	23.55	297.03
Boreal peat	3.70	19.02	22.73	150.93
Total	**332.54 (+/- 152.98)**	**131.56 (+/- 49.02)**	**464.07 (+/- 176.98)**	

Note: The error is summed in quadrature. The biomass carbon listed for peatlands is the sum of the aboveground biomass vegetation type (e.g., tropical rainforest biomass, tropical moist forest biomass, tropical herbaceous wetland, etc.) and biomass carbon values listed for other ecosystem are specifically for the non-peat areas of those ecosystems. Soil organic carbon was considered down to 100 cm for inundated soils (wetlands, peatlands, and coastal ecosystems) and down to 30 cm for all other soils, based on our manageability criterion.

Table S7. Biomass sequestration rates in tropical forests, delineated by region

Ecosystem (and region)	Number of measurements	Sequestration equation for year X	Sequestration in 30 years (MgC ha^{-1})	R^2	Mean value (MgC ha^{-1}) for 25-35 yr old stands (Number of measurements)	+/- Root mean of squared error	Low-end sequestration	High-end sequestration
Boreal coniferous forest (America)	30	44.06*ln(X) - 87.534	62.3	0.5534	NED	33.9	28.4	96.2
Boreal coniferous forest (Eurasia)	31	25.933*ln(X) - 44.159	44.0	0.4812	NED	28.1	15.9	72.1
Temperate continental forest (America)	59	33.285*ln(X) - 47.147	66.1	0.3982	82.8 (7)	40.5	25.6	106.6
Temperate continental forest (Eurasia)	127	36.328*ln(X) - 50.393	73.2	0.4346	94.1 (12)	37.1	36.1	110.3
Temperate mountain forest (America)	98	21.973*ln(X) - 23.6	51.1	0.5349	49.1 (11)	24.9	26.2	76.0
Temperate mountain forest (Eurasia)	37	15.755*ln(X) - 13.162	40.4	0.1418	54.1 (12)	18.4	22.0	58.8
Tropical moist forest (America)	942	38.223*ln(X) - 45.368	84.6	0.3672	84.4 (135)	41.2	43.4	125.8
Tropical rainforest (America)	670	37.186*ln(X) - 15.446	111.0	0.2274	119.2 (104)	62.4	48.6	173.4
Tropical moist forest & Tropical rainforest (Africa)	51	39.076*ln(x) - 18.642	114.3	0.2178	NED	60.3	54.0	174.6
Tropical moist forest & Tropical rainforest (Asia)	301	36.79*ln(x) - 26.777	98.4	0.4647	NED	42.3	56.1	140.7
Subtropical humid forest (All regions)	131	102.92*ln(X) - 228.09	122.0	0.4572	114.2 (19)	74.6	47.4	196.6
Tropical/subtropical mountain forest (America)	85	36.494*ln(X) - 40.427	83.7	0.4304	82.9 (6)	31.5	52.2	115.2
Tropical/ subtropical mountain forest (Asia)	41	28.859*ln(X) - 20.3	77.9	0.6437	79.6 (6)	22.5	55.4	100.4
Tropical/ subtropical mountain forest (All regions - for Africa proxy)	126	31.774*ln(x) - 29.447	78.6	0.4876	NED	29.1	49.5	107.7
Tropical dry forest (Africa)	42	4.3663*ln(X) + 6.3543	21.2	0.1272	NED	10.4	10.8	31.6
Tropical dry forest (America)	96	21.804*ln(X) - 23.841	50.3	0.3260	52.6 (10)	28.6	21.7	78.9
Tropical dry forest (All regions – for Asia proxy)	138	18.628*ln(x) - 17.398	46.0	0.3324	NED	26.0	20.0	72.0

Note: NED = Not enough data. Values are only included where there are at least five measurements from stands between 25-35 years old.

Table S8. Biomass sequestration rates in non-forest ecosystems

Ecosystem	Sequestration rate (Mg C ha^{-1} yr^{-1})	Source or assumption
Tropical grassland	2.36	From Xia et al 2014 & Gill & Jackson 2000[72,73]. Tropical grasslands were assumed to recover all of their biomass within 30 years.
Montane grassland	0.5	From Xia et al 2014 & Gill & Jackson 2000[72,73]. Montane grasslands were assumed to recover all of their biomass within 30 years.
Subtropical grassland	2.36	Assumed same as tropical grasslands
Temperate grassland	1.95	From Xia et al 2014 & Gill & Jackson 2000[72,73]. Temperate grasslands were assumed to recover all of their biomass within 30 years.
Mangroves	5.15 +/- 0.38 (standard error)	From Bernal et al. 2018[74].
Seagrasses	Not applicable	Assumed full recovery of biomass carbon for seagrasses and salt marshes given small initial value (most seagrass and salt marsh carbon is in their soils).
Salt marshes	Not applicable	
Tree-covered wetlands (non-peat)	See assumption	In the absence of differentiated biomass sequestration rates for wetlands, and because the biomass in forested wetlands would behave similarly to a forest, we applied the rate for tropical moist forests in the tropics, temperate continental forests in the temperate zone, and boreal coniferous forests in the boreal zone.
Herbaceous wetlands (non-peat)	See assumption	In the absence of differentiated biomass sequestration rates for wetlands, and because the biomass in herbaceous wetlands would behave similarly to grasslands, we applied the biomass sequestration rates for grasslands in the relevant zone (tropical, temperate, or boreal).
Tropical peatlands	Not applicable	Peatlands are characterized by high-carbon soils and can underlie other aboveground land-use classes on our map. We therefore adopted the biomass sequestration rate of whatever the aboveground land-use class was.
Temperate peatlands		
Boreal peatlands		
Notes: Grasslands would typically achieve their maximum biomass potential within 2-4 years. On our map, we look at sequestration over 30 years but cap biomass carbon recovery to the original value.		

Table S9. SOC recovery factors for tropical forests and grasslands

Ecosystems	Median % SOC that could be recovered with restoration (standard deviation)
Tropical and Subtropical forests (all types)	50.3 (±11.9)
Tropical and Subtropical grasslands (non-mountainous)	50.3 (±11.9)
Montane grasslands	25 (±16)

Table S10. SOC sequestration rates in wetlands

Ecosystem	SOC sequestration rate (Mg C ha^{-1} yr^{-1})	Min (Mg C ha^{-1} yr^{-1})	Max (Mg C ha^{-1} yr^{-1})	Standard Error (Mg C ha^{-1} yr^{-1})	Source & notes
Forested wetlands (non-peat)	1.76	0.895	5.633	1.209	Rate is based on a meta-analysis of SOC recovery in 110 studies. The average for freshwater tree-dominated wetlands was applied here[75]. Min-max range is Q1-Q3. Standard error was calculated assuming normal distribution of the data.
Herbaceous wetlands (non-peat)	1.226	0.865	2.093	0.313	Rate is based on a meta-analysis of SOC recovery in 110 studies. The average for freshwater marshes was applied here[75]. Min-max range is Q1-Q3. Standard error was calculated assuming normal distribution of the data.
Tropical peatlands	0	NA	NA	NA	There are no effective examples of tropical peatland restoration[28,76].
Temperate peatlands	0.28	0.10	0.46	0.092	Rate is the midpoint of the range (0.10 - 0.46 Mg C ha^{-1} yr^{-1}) from a study of peatlands in Finland[77,78]. Standard error was calculated assuming normal distribution of the data.
Boreal peatlands	0.21	0.15	0.26	0.028	Rate is the midpoint of the range (0.15 - 0.26 Mg C ha^{-1} yr^{-1}) from a study of peatlands in Finland[77,78]. Standard error was calculated assuming normal distribution of the data.

Table S11. SOC sequestration rates in coastal ecosystems

Ecosystem	SOC sequestration rate (Mg C ha^{-1} yr^{-1})	Standard error (Mg C ha^{-1} yr^{-1})
Mangroves	1.68	+/- 0.36
Seagrasses	0.83	No uncertainty available
Salt marshes	2.42	+/- 0.26

Notes: The averages are from Taillardat et al 2018.[79] We assumed a linear rate of SOC sequestration over 30 years to calculate the 'recoverable' carbon.

Table S12. Summary of irrecoverable carbon by ecosystem type

Ecosystem	Irrecoverable carbon (IrrC) in biomass (Gt C)	IrrC in soil (Gt C)	Total IrrC (Gt C)	Mean Irr Mg C ha^{-1}
Boreal coniferous forest	7.13	0.68	7.81	13.47
Boreal mountain forest	3.37	0.07	3.44	13.67
Boreal grassland and shrubland	2.22	0.19	2.41	20.61
Boreal montane grassland and shrubland	1.29	0.06	1.36	15.52
Boreal herbaceous wetland	0.17	6.83	7.00	172.99
Boreal tree-covered wetland	0.02	0.34	0.36	33.82
Temperate continental forest	2.45	0.05	2.49	8.93
Temperate oceanic forest	1.56	0.01	1.56	33.97
Temperate mountain forest	9.14	0.02	9.15	37.74
Temperate grassland and shrublands	0.41	0.04	0.45	1.01
Temperate montane grassland and shrubland	1.15	0.02	1.17	4.98
Temperate herbaceous wetland	0.03	0.20	0.23	27.22
Temperate tree-covered wetland	0.05	0.05	0.10	19.79
Subtropical dry forest	1.22	0.00	1.23	20.45
Subtropical humid forest	0.12	0.04	0.16	1.06
Subtropical mountain forest	0.54	0.00	0.54	5.08
Subtropical grassland and shrublands	0.35	0.03	0.38	0.77
Subtropical montane grassland and shrublands	0.37	0.01	0.38	2.13
Subtropical herbaceous wetland	0.02	0.91	0.93	66.60
Subtropical tree-covered wetland	0.01	0.47	0.47	55.22
Tropical rainforest	27.22	2.27	29.49	31.44
Tropical moist forest	1.99	0.14	2.13	4.96
Tropical dry forest	2.93	0.02	2.95	13.28
Tropical mountain forest	4.49	0.06	4.55	28.46
Tropical grassland and shrubland	3.02	0.20	3.22	2.83
Tropical montane grassland and shrubland	1.99	0.52	2.51	22.49
Tropical herbaceous wetland	0.26	3.91	4.17	67.75
Tropical tree-covered wetland	1.25	3.04	4.29	101.74
Mangroves	0.15	3.01	3.15	217.87
Salt marsh	0.03	0.12	0.15	29.55
Seagrass	0.00	1.53	1.53	52.25
Temperate peat	0.21	3.88	4.09	110.40
Tropical peat	2.77	13.07	15.84	192.73
Boreal peat	1.11	18.24	19.35	106.07
Total	**79.04 (+/- 227.05)**	**60.02 (+/- 303.81)**	**139.06 (+/- 443.58)**	

Note: The error is summed in quadrature. Irrecoverable carbon cannot be less than 0, so 0 is reported as the lower bound of the range in the Main Text. The biomass carbon listed for peatlands is the sum of the aboveground biomass vegetation type (e.g., tropical rainforest biomass, tropical moist forest biomass, tropical herbaceous wetland, etc.) and biomass carbon values listed for other ecosystem are specifically for the non-peat areas of those ecosystems. Soil organic carbon was considered down to 100 cm for inundated soils (wetlands, peatlands, and coastal ecosystems) and down to 30 cm for all other soils, based on our manageability criterion.

Table S13. Irrecoverable carbon in IPLC lands and Protected Areas, by ecosystem

Ecosystem	Total Irrecoverable Carbon (Gt)	In IPLC lands	In Protected Areas	In Both IPLC lands and Protected Areas	In Neither IPLC lands nor Protected Areas
Boreal forest	11.25	2.95	0.41	3.28	7.98
Boreal wetland	7.36	4.76	0.45	4.87	2.49
Boreal grassland	3.76	1.46	0.32	1.74	2.03
Temperate forest	13.21	0.74	3.16	3.70	9.51
Temperate wetland	0.33	0.03	0.08	0.11	0.22
Temperate grassland	1.62	0.14	0.39	0.50	1.12
Tropical & subtropical forest	41.07	16.24	13.79	23.54	17.52
Tropical & subtropical wetland	9.86	2.60	2.86	4.62	5.23
Tropical & subtropical grassland	6.48	2.77	1.09	3.29	3.19
Mangrove	3.15	0.45	1.15	1.42	1.74
Salt marsh & seagrass	1.68	0.02	0.41	0.42	1.26
Tropical peat	15.84	5.15	5.74	8.61	7.23
Boreal & Temperate peat	23.44	9.39	2.12	11.01	12.43
Total Irrecoverable Carbon	**139.06**	**46.69**	**31.98**	**67.11**	**71.95**

Note: Soil organic carbon was considered down to 100 cm for inundated soils (wetlands, peatlands, and coastal ecosystems) and down to 30 cm for all other soils, based on our manageability criterion.

Table S14. Loss of irrecoverable carbon by major ecosystem category

	Irrecoverable carbon loss 2011-2019	
Ecosystem	**Gt C**	**%**
Boreal coniferous forest	0.52	6.64%
Boreal mountain forest	0.16	4.58%
Boreal grassland and shrubland	0.06	2.39%
Boreal montane grassland and shrubland	0.01	0.88%
Boreal herbaceous wetland	0.08	1.18%
Boreal tree-covered wetland	0.01	2.36%
Temperate continental forest	0.12	4.93%
Temperate oceanic forest	0.06	4.15%
Temperate mountain forest	0.43	4.73%
Temperate grassland and shrubland	0.01	2.61%
Temperate montane grassland and shrubland	0.03	2.31%
Temperate herbaceous wetland	0.00	0.72%
Temperate tree-covered wetland	0.00	2.01%
Subtropical dry forest	0.11	9.03%
Subtropical humid forest	0.02	10.76%
Subtropical mountain forest	0.02	3.73%
Subtropical grassland and shrubland	0.02	4.25%
Subtropical montane grassland and shrublands	0.01	2.63%
Subtropical herbaceous wetland	0.01	0.62%
Subtropical tree-covered wetland	0.02	4.83%
Tropical rainforest	0.68	2.29%
Tropical moist forest	0.07	3.22%
Tropical dry forest	0.11	3.82%
Tropical mountain forest	0.08	1.80%
Tropical grassland and shrubland	0.11	3.57%
Tropical montane grassland and shrubland	0.08	3.10%
Tropical herbaceous wetland	0.04	1.03%
Tropical tree-covered wetland	0.11	2.64%
Mangroves	0.08	2.39%
Seagrasses	0.00	0.26%
Salt Marshes	0.00	0.02%
Temperate peat	0.11	2.74%
Tropical peat	0.34	2.18%
Boreal peat	0.51	2.65%
Total	**4.04**	**2.90%**

Note: The numbers in Table S14 are based on Hansen et al.'s tree cover loss dataset and therefore reflect only the loss of forested pixels. Loss in grasslands, herbaceous wetlands, and peatlands without tree cover is largely not accounted for. Soil organic carbon was considered down to 100 cm for inundated soils (wetlands, peatlands, and coastal ecosystems) and down to 30 cm for all other soils, based on our manageability criterion.

Table S15. Irrecoverable SOC in the 'agriculture moves North' scenario

Ecosystem	**Total additional irrecoverable SOC (Gt C)**	**Irrecoverable SOC (mean)**
Boreal coniferous forest	10.33	18.18
Boreal mountain forest	6.55	26.38
Temperate continental forest	0.74	6.84
Temperate oceanic forest	<0.01	2.57
Temperate mountain forest	0.76	7.57