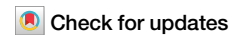


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Mapping forest-based natural climate solutions



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Natural climate solutions are critical actions of ecosystem stewardship to mitigate climate change. However, prioritizing locations and possible actions is challenging. We demonstrate a generalizable approach for identifying potential opportunities for natural climate solutions by creating a spatial hierarchy of land management restrictions. Global forest carbon stocks and flux models were then used to explore forest-based natural climate solutions in the high-carbon density coastal temperate rainforests of western North America. Our results show 13 million hectares are available for action, an area that holds $4,900 \pm 640$ megatonnes of carbon dioxide equivalent and represents 45% of regional and 0.5% of global aboveground forest carbon stocks. Based on historical trends, a 10% reduction in average annual forest carbon loss through improved forest management and conservation could reduce forest carbon emissions by 9.1 megatonnes of carbon dioxide equivalent per year, corresponding to 5.2% of the 2030 land-based climate commitments made by the United States and Canada. Large-scale implementation of natural climate solutions will require collaborative planning with forest-dependent communities, industry, governments, and Indigenous peoples.

To avoid some of the worst impacts of climate change, communities, governments, and businesses need to drastically reduce greenhouse gas emissions. The costs and challenges of mitigating climate change will be less the faster emissions are reduced¹. Although most climate mitigation efforts are appropriately focused on reduced emissions from fossil fuels, natural climate solutions (NCS) represent deployable and scalable options for additionally reducing emissions and sequestering CO₂^{2–4}. NCS are protection, restoration, and improved land management actions that increase carbon sequestration and avoid greenhouse gas emissions².

Forests currently sequester up to 20% of anthropogenic greenhouse gas emissions annually⁵, and can offer substantial potential for mitigation⁶. Indeed, the protection of threatened forest carbon stocks and implementation of conservation strategies such as improved forest management (e.g., variable retention harvesting, reduced timber harvest, and longer harvest rotation times⁷) are key actions identified as necessary to mitigate global climate change^{8–11}. However, estimates of the mitigation potential in forests hinge upon ambitious scenarios of forest protection and improved management¹². Currently, forest carbon management in many countries is constrained by a need to work with a multitude of landowners on land that varies in suitability and feasibility⁸ for different forest management and conservation strategies. Therefore, high-resolution, spatial-explicit approaches that incorporate landowner management restrictions are a critical information gap to identify appropriate NCS actions at an ecoregional scale.

A mapping approach can identify and prioritize NCS projects by highlighting the relationship between plausible carbon mitigation strategies, different landownership types, and the scale of opportunity¹³. This information can facilitate action planning with relevant communities, governments, and industries and advance policy-level interventions¹³. For example, coupling a cluster analysis with a spatial distribution of potential emissions reductions across different scales can characterize strategies of land management with high mitigation potential in different administrative regions¹⁴. This approach identified specific communities with rural economies closely tied to the forest industry and carbon mitigation potential, and thereby enable innovative financing to advance NCS implementation with community economic considerations in mind¹⁴. However, until recently, there have not been globally consistent data on forest carbon flux (i.e., emissions and sequestration)⁹ and aboveground forest carbon stocks with robust estimates of uncertainty¹⁵. This data paucity has hindered quantification of NCS opportunities at an ecoregional scale and at the resolution necessary for decision-making about how to implement NCS projects.

A diversity of global forest-based strategies is needed to mitigate climate change¹. Major disturbances, such as wildfire, are a concern for long-term, land-based climate mitigation^{16,17}. Wildfire risks to carbon durability (i.e., permanence) are especially relevant for boreal forests¹⁸, as well as drought-prone forests in western North America^{19,20} across California^{21,22} and southern Oregon, USA²³ (Fig. 1; Supplementary Table 1). To some extent, wet coastal forests where summer drought periods have become

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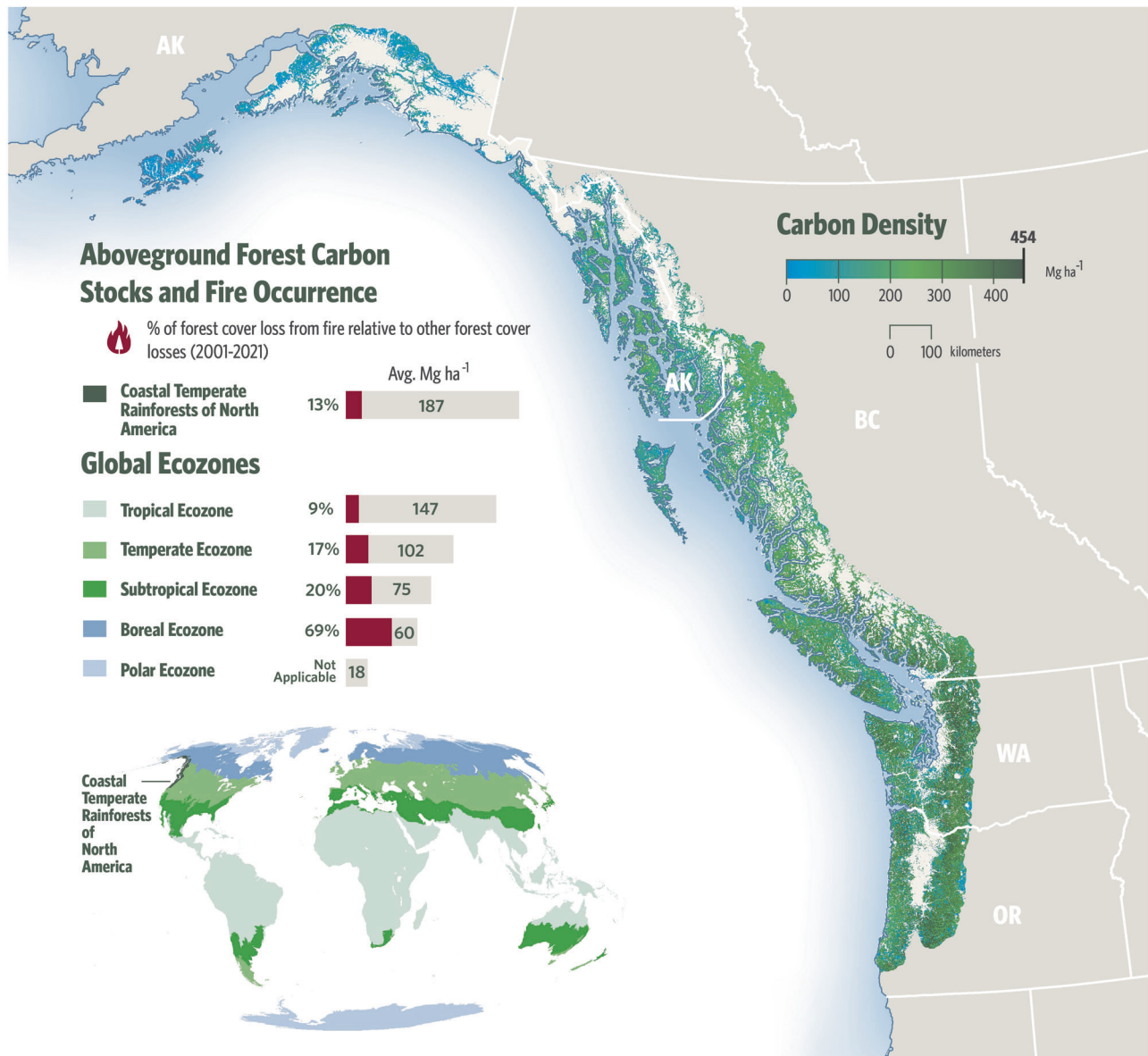


Fig. 1 | Study area map with relative forest cover loss from fire. Aboveground carbon density (AGB Mg ha⁻¹) in the coastal temperate rainforests of western North America. The bar chart indicates average aboveground forest carbon stocks (AGB Mg ha⁻¹) overlaid with historical (2001–2021; >30% tree cover) forest cover

lost to fire (red bars)¹⁸ compared to the total forest cover loss⁹² for the coastal temperate rainforests of western North America (13%) and other global ecozones (9–69%)⁹³ (Supplementary Table 1). Figure by Erica Sloniker using publicly available data.

longer and drier²⁴ are also experiencing an increased threat of forest carbon loss due to wildfire²⁵. However, the cool, wet, and high-carbon density coastal temperate rainforests of western North America (Fig. 1; Supplementary Table 1) have high sequestration rates²⁶, high risk of disturbance due to timber harvest¹⁰, and relatively low risk of reversal from wildfire^{27,28}. Thus, this region represents a globally important opportunity to invest in forest conservation and improved forest management for NCS^{17,29}.

This paper demonstrates a generalizable approach that leverages recently available global datasets on aboveground forest carbon stocks and fluxes alongside landownership data, synthesized into NCS Action Categories based on locations where timber harvest is permissible and NCS actions may feasibly deliver an atmospheric benefit under appropriate project conditions, e.g., landowner support, Indigenous consent, and an applicable protocol for project-level carbon accounting (Table 1; Supplementary Table 2 and 3). Using these data, we conduct an assessment of forest-based NCS opportunities in the 51 Mha coastal temperate rainforest ecoregion of western North America (Fig. 1). We then estimate the potential contribution from an

increase in improved forest management and conservation (consistent with the historical range of variation for timber harvest in the region; see Supplementary Table 4) toward the 175 MtCO₂e yr⁻¹ land-based climate commitments made by the United States and Canada for 2030^{30,31}.

We define sequestration as carbon absorbed from the atmosphere by forest growth³² while carbon losses³³ are defined as forest carbon lost from ecosystem carbon pools due to disturbances. In this region, the primary forest disturbance has historically been commercial timber harvest^{34–36}. Regional and national estimates show, under current practices, approximately 43–54% of forest carbon stocks removed by timber harvest is lost to the atmosphere within the first 20 years following harvest^{3,23}. Forest carbon losses in this paper do not reflect carbon transfers from ecosystem carbon pools to harvested wood products (i.e., forest carbon loss ≠ emissions). From a carbon accounting perspective, these estimates also do not include the highly variable carbon emissions from logging operations, milling, and transportation of durable wood products³⁷. Therefore, we present the forest carbon emissions due to forest loss using a globally consistent model⁹ as a

Table 1 | Action categories for natural climate solutions (NCS)

NCS Action Category	Description	Definition	Examples
1	Available for action	Development and forest land management areas	Private industrial forests, public timber tenures, National Forest adaptive management areas
2	Not currently available for action	Administratively protected areas	Habitat protections such as wildlife reserves, riparian or wetland buffers
3	Not available for action	Protected areas	National parks, provincial parks, wilderness areas

See Supplementary Table 2 for specific categorizations by jurisdiction and designation ($n = 305$)

starting place for more localized analyses to explore and refine the carbon accounting of NCS projects.

Results

Opportunity for forest-based natural climate solutions

Our forest-based NCS mapping found 40% of the coastal temperate rainforests in western North America (13 Mha; $4,900 \pm 640$ MtCO₂e; Table 2; Fig. 2; Fig. 3) are potentially available for NCS action (NCS Action Category 1; NCS1) (Table 1), which represents 45% of regional and 0.5% of global aboveground forest carbon stocks¹⁵ (Table 2; Fig. 2). Administratively protected areas (NCS Action Category 2; NCS2) covered 30% of land area (Fig. 3; Supplementary Table 3) while permanently protected areas (NCS Action Category 3; NCS3) covered 29% (Fig. 3; Supplementary Table 3). All the carbon results are presented in CO₂e or CO₂ for consistency and comparability in Table 2.

The average carbon density of these NCS1 forests (370 MgCO₂e ha⁻¹, inclusive of harvested areas), is higher than 90% of the world's forests¹⁵. Between 2001 and 2021, these NCS1 forests had an average net carbon sequestration of 36 MtCO₂ yr⁻¹ (Table 2; Fig. 2). We conservatively estimate that a 10% reduction of average annual forest carbon losses (within the historical range of variability in timber harvest; Supplementary Table 4) through improved forest management and conservation could reduce emissions by as much as 9.1 MtCO₂e yr⁻¹, equivalent to 5.2% of the 2030 land-based climate commitments made by the United States and Canada combined.

Across the coastal temperate rainforests in western North American, 61% of carbon stocks available for NCS action are publicly owned (Federal, Provincial, State and local government). Most of these forests have higher density carbon stocks compared to other ownerships (Table 2). Private forest lands comprise 32% of the carbon stocks available for NCS action, and Indigenous ownerships contain 7% of the carbon stocks available for NCS action. However, extensive old-growth forest carbon stocks and growing Indigenous land ownership in British Columbia, Canada, and Alaska, USA, also represent a substantial opportunity for forest-based climate mitigation that can readily incorporate equity, a critical principle of NCS (e.g., access and authority in management decisions)³⁸.

Assuming historical carbon losses predict future trends, Oregon and Washington may represent the largest regionally important opportunities to transition towards additional carbon storage and sequestration through improved forest carbon management and conservation (Supplementary Fig. 3, 4). In forest lands available for NCS action, forest carbon losses are driven by emissions due to forestry between 2001 and 2021 in Oregon, USA, (45 MtCO₂e yr⁻¹) and Washington, USA, (27 MtCO₂e yr⁻¹) (Table 2).

Private forest lands (1.7 Mha), in particular, contributed 82% of the average annual carbon losses from NCS1 lands in Oregon (Table 2). Private forests similarly drove average annual carbon losses on NCS1 lands in Washington, accounting for 78% of total carbon losses between 2001 and 2021. Of those carbon losses in Washington, the vast majority occur in industrial forests for net carbon losses of 3.8 MtCO₂e yr⁻¹, while private non-industrial forest lands saw a net gain of 5.7 MtCO₂e yr⁻¹ (Supplementary Table 6). State lands in Washington also represent an important NCS opportunity with carbon losses of 4.6 MtCO₂e yr⁻¹.

While historical emissions based on past forest loss provide a baseline understanding of flux trends for the region, the spatial approach presented

here also allows for a complementary analysis of standing carbon stocks within these same NCS1 forest lands. This analysis shows where high-density carbon stocks remain and may be at risk of loss, indicating opportunities for improved forest management and conservation.

In Washington and Oregon, private forest lands have the largest remaining carbon stocks available for NCS action by ownership type (640 ± 8 MtCO₂e and 630 ± 31 MtCO₂e, respectively; Table 2). Collectively, these forests account for 26% of the NCS1 carbon stocks within the study area. Publicly owned forest lands in Washington and Oregon comprise a further 18% of the carbon stocks available for NCS action in the region. In both states, the carbon density of privately owned forests is lower than publicly owned forests, further indicating opportunities to increase net carbon sequestration through active carbon management (Table 2).

The Province of British Columbia is the single largest forest manager in the coastal temperate rainforests of western North America (5.1 Mha), which manages 40% of the total aboveground forest carbon stocks available for NCS action in the region (2000 ± 610 MtCO₂e with an average annual carbon loss of 11 MtCO₂e yr⁻¹) (Table 2). Privately managed forest lands ($920,000$ ha; 280 ± 130 MtCO₂e) in British Columbia, which comprise 6% of carbon stocks available for NCS action, are the next largest opportunity in the province with an average annual carbon loss of 7.0 MtCO₂e yr⁻¹. However, lands owned or managed by Indigenous Nations ($660,000$ ha; 190 ± 100 MtCO₂e) will continue to expand, as many treaties are still under negotiation and a legislated requirement for respecting Indigenous rights and obtaining free, prior and informed consent in land and resource management is now being implemented³⁸.

Alaska forest lands within the study area comprise 5% of the carbon stocks available for NCS action. Federal lands with an active timber harvest program in Alaska (i.e., the Tongass National Forest) have the highest carbon densities (360 MgCO₂e ha⁻¹, inclusive of harvested areas) in the state with the most abundant remaining old-growth forest with associated ecosystem co-benefits^{35,39}. The majority of land classified as available for NCS action ($710,000$ ha), as well as the majority of the aboveground forest carbon stocks (110 ± 15 MtCO₂e), is owned and managed by Indigenous landowners (e.g., Alaska Native Corporations and tribal organizations). Cumulatively, these Indigenous owned and managed forest lands also have the highest average annual forest carbon losses in the state (0.6 MtCO₂e yr⁻¹). However, forests owned and managed by Alaska state agencies have the highest rates of carbon loss (0.1 MtCO₂e yr⁻¹) per unit area ($110,000$ ha).

Comparison across global, national, and regional forest carbon maps

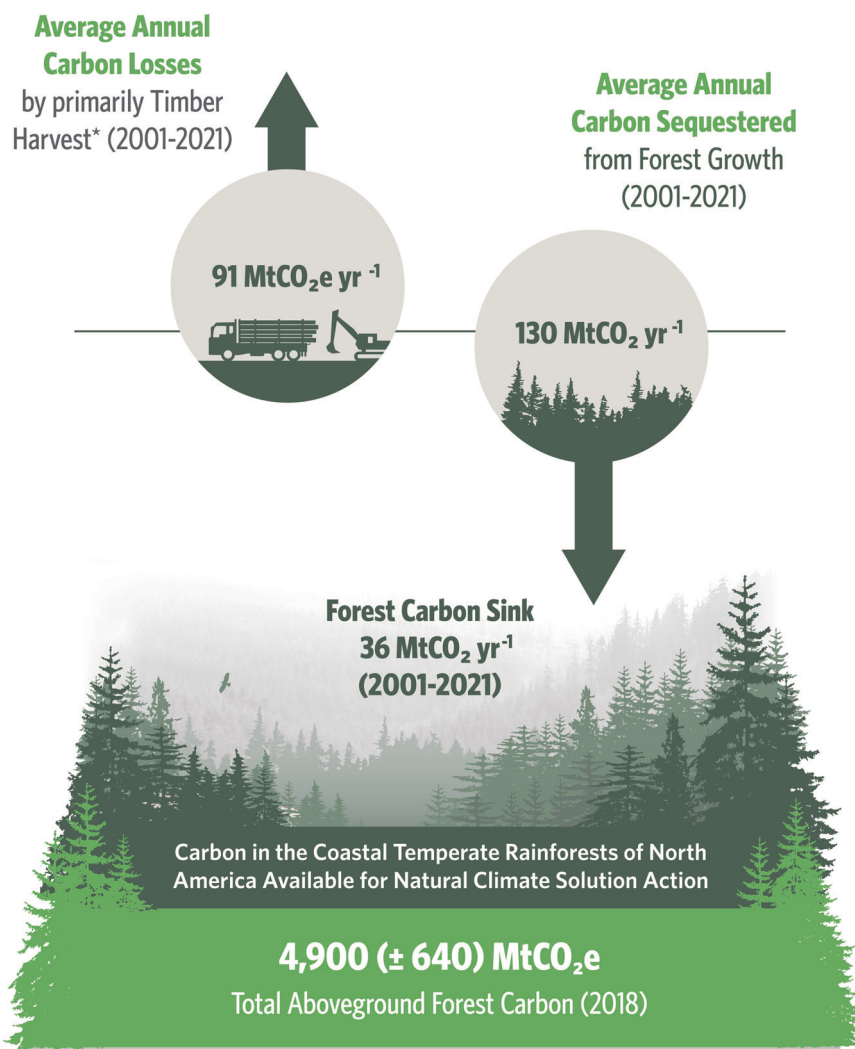
Estimates of carbon density were similar across global¹⁵, national^{40,41}, and regional⁴² data sources. The global map generally identifies higher aboveground forest carbon stocks than the national and regional models, with stronger model convergence at more southern latitudes in this region. There is no similar high resolution (≤ 100 m) aboveground forest carbon model available for comparison in Alaska at the time of publication. At the jurisdictional scale for British Columbia, Washington, and Oregon, the global model¹⁵ predicts 23%, 15%, and 7% higher aboveground carbon than the national models^{40,41} and 13% and 2% higher than the Pacific Northwest regional model for Washington and Oregon respectively⁴².

Table 2 | Total and average aboveground forest carbon stocks and average annual carbon flux in the coastal temperate rainforests of western North America available for Natural Climate Solution (NCS) action (NCS Action Category 1), summarized by jurisdiction, landowner type, and carbon model

Jurisdiction	Global forest carbon model				National and regional forest carbon models			Global forest carbon flux models		
	Resolution	100 m	Santoro et al. ¹⁵	Total Aboveground Forest Carbon Stock and Standard Error (SE) (MtCO ₂ e)	Canada	U.S. Pacific Northwest	Contiguous U.S.	Harris et al. ⁹	Harris et al. ⁹	Harris et al. ⁹
	Model year(s)	2018			30 m	30 m	30 m			
	Reference				2015	2016	2010			
	Forest available for NCS (ha)	Average Aboveground Forest Carbon Stock (MgCO ₂ e/ha)			Matasci et al. ⁴⁰	Hudak et al. ⁴²	Williams et al. ⁴¹	Average Annual Carbon Sequestration (MtCO ₂ /yr)	Average Annual Carbon Lost (MtCO ₂ e/yr)	Average Annual Net Balance (MtCO ₂ e/yr)
<i>Alaska</i>										
Federal	210,000	360	76 (± 2)	–	–	–	–	1.9	–0.1	1.8
State	110,000	200	21 (± 3)	–	–	–	–	0.8	–0.1	0.7
Indigenous	710,000	150	110 (± 15)	–	–	–	–	4.7	–0.6	4.1
Local government	51,000	200	10 (± 3)	–	–	–	–	0.4	0.0	0.5
Private	42,000	210	9 (± 1)	–	–	–	–	0.4	0.0	0.4
Other	–	–	–	–	–	–	–	–	–	–
Subtotal	1,100,000	200	230 (±16)	–	–	–	–	8.2	–0.8	7.4
<i>British Columbia</i>										
Federal	–	–	–	–	–	–	–	–	–	–
Provincial	5,100,000	390	2,000 (± 610)	1500	–	–	–	42	–11	31
Indigenous	660,000	290	190 (± 100)	150	–	–	–	5.0	–0.3	4.6
Local government	–	–	–	–	–	–	–	–	–	–
Private	920,000	310	280 (± 130)	290	–	–	–	7.7	–7.0	0.7
Other	38,000	450	17 (± 3)	16	–	–	–	0.3	–0.2	0.2
Subtotal	6,700,000	370	2500 (±630)	1900	–	–	–	55	–18	73
<i>Washington</i>										
Federal	400,000	550	220 (± 52)	–	200	200	200	4.4	–0.6	3.8
State	520,000	480	240 (± 9)	–	230	230	230	5.7	–4.6	1.1
Indigenous	100,000	380	37 (± 2)	–	36	33	33	1.3	–0.6	0.7
Local government	60,000	400	24 (± 1)	–	23	24	24	0.9	–0.3	0.6
Private	1,700,000	370	640 (± 8)	–	530	510	510	23	–21	2.2
Other	–	–	–	–	–	–	–	–	–	–
Subtotal	2,800,000	410	1200 (±53)	–	1000	1000	1000	36	–27	8.2
<i>Oregon</i>										
Federal	620,000	520	320 (± 32)	–	350	320	320	6.2	–5.1	1.1
State	240,000	470	110 (± 29)	–	130	110	110	2.7	–2.5	0.2
Indigenous	8700	430	4 (± 1)	–	4	4	4	0.1	–0.1	0.0
Local government	19	580	0 (± 0)	–	0	0	0	0.0	0.0	0.0
Private	1,700,000	360	630 (± 31)	–	560	550	550	20	–37	–17.0
Other	–	–	–	–	–	–	–	–	–	–
Subtotal	2,600,000	410	1100 (±53)	–	1000	990	990	29	–45	–16
Total	13,000,000	370	4900 (±640)	–	–	–	–	130	–91	36

All the carbon units are in CO₂e or CO₂ for consistency and comparability. The results were converted to two significant digits and may not sum exactly.

Fig. 2 | Forest carbon flux illustration. The forest carbon balance of the coastal temperate rainforests of western North America available for action by Natural Climate Solutions (NCS) (Table 1; NCS 1). Total aboveground forest carbon and Standard Error (SE) was calculated using a global carbon model¹⁵ for the year 2018 (Table 2). Average annual carbon losses were calculated from a global flux model⁹ for the 2001–2021 time period (Table 2). Average annual carbon sequestered was calculated with a global sequestration model⁹ for the 2001–2021 time period (Table 2). The results were converted to two significant digits and therefore do not sum exactly. *Average annual carbon losses are primarily driven by timber harvest (estimated to be 78% using an independent course scale model; see Supplementary Table 5), but also include other disturbances⁹. A portion of carbon losses due to timber harvest are captured in durable wood products^{3,9,23}. Figure by Erica Sloniker using publicly available data.



Discussion

We developed a generalizable approach that leverages a spatial framework to identify forest-based NCS opportunities by combining land management restrictions with high-resolution aboveground forest carbon stocks and flux models. Our study improves upon the growing body of NCS assessments^{2–4,14,23} with a mapping approach that uses fine-resolution land use information, and offers a guide for assessments in globally important forest landscapes, such as the 51 Mha high-carbon density coastal temperate rainforests of western North America^{9,10,26}.

Identifying where interventions aimed at forest carbon storage and sequestration are suitable and feasible can improve planning, implementation, and ecoregional assessments of NCS potential by allowing the exploration of approaches, such as policy interventions, voluntary carbon markets, or economic incentive programs⁴³ that can influence improved forest management and conservation¹⁰. A spatial approach, as demonstrated in this paper, can reduce the likelihood of overestimating NCS opportunities as compared to approaches which do not include this information. For example, NCS opportunities would be inflated by not accounting for extensive administrative protections (i.e., fish, wildlife, and wetland protections) within otherwise development designations for managed forests (e.g., National Forests). Indeed, this analysis showed 30% (Fig. 3; Supplementary Table 3; Supplementary Figs. 1–4) of the forest within the study area is administratively protected by timber harvest restrictions, most of which are not captured in global^{44,45} and national^{46,47} spatial databases for protected areas.

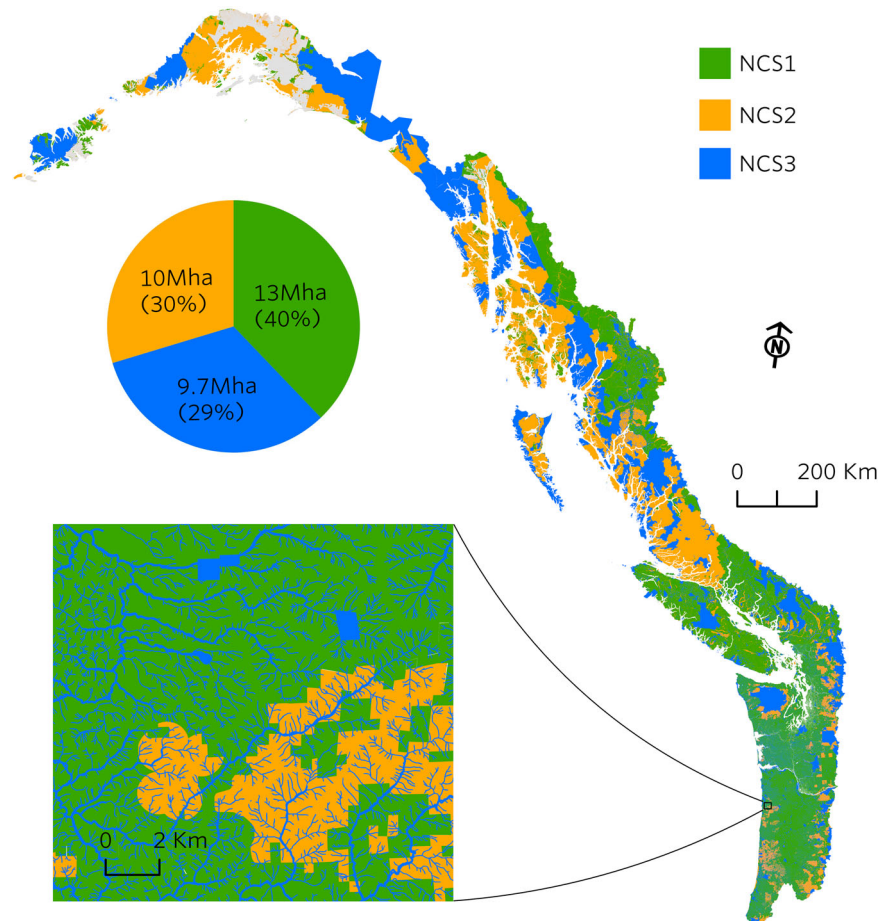
Available data for forest carbon stocks with estimates of uncertainty (i.e., Standard Error) and flux are now at an adequate spatial resolution and

temporal frequency (semi-annually) that carbon accounting tools that combine these data with land management restrictions should be the new standard for assessments of annual NCS opportunity at ecoregional scales. As exemplified in this paper, forest landscapes with spatial information on land use restrictions provide excellent opportunities to improve estimates of climate mitigation potential. However, this type of assessment may not be possible in regions without information on land use restrictions or land tenure. In these cases, incorporating Indigenous and local knowledge may improve regional-scale assessments of NCS potential⁴⁸. Our land use mapping approach may also be complicated or not appropriate where there is weak governance, lax enforcement of land use restrictions, or complex tenure arrangements with complicated decision-making processes or unclear authority.

The technology and science around forest carbon and flux estimates are constantly evolving^{9,12}. Therefore, the results presented in this paper should be considered iterative. We found that a global map of aboveground forest carbon stocks¹⁵ corresponded well with regional⁴² and national^{40,41} maps produced at finer spatial resolutions with higher plot densities and more localized training datasets. This correspondence gives increased confidence to regions without localized carbon maps (e.g., Alaska in this study) to utilize global maps where consistent comparisons can be made.

We used forest carbon sequestration and emission estimates (that do not account for durable wood products) based on a globally consistent spatial model⁹ in order to provide comparisons across jurisdictions within the coastal temperate rainforests of western North America. However, more

Fig. 3 | Mapped natural climate solutions action categories. Action categories for Natural Climate Solutions (NCS) in the coastal temperate rainforests of western North America. NCS1 is available for action. NCS2 is not currently available for action. NCS3 is protected. Inset shows spatial details of categories, such as administrative protections (NCS2) and riparian buffers (NCS3). Gray areas are either non-forested or have unknown forest management plans.



robust flux estimates may exist at regional scales^{17,49}. For example, state-specific measurements of forest carbon pools by the US Forest Service Forest Inventory and Analysis (USFS FIA) program are available for Oregon, Washington, and Alaska but mismatches in data availability, spatial and temporal coverage, and accounting methodologies complicate summarizing these inventories for use in ecoregional analyses⁵⁰. Comparisons between the spatially explicit carbon flux presented here and state-level forest carbon inventories highlight similar patterns, where private ownerships are driving forest carbon emissions, although the magnitude of the flux varies (Supplementary Table 7). Both the global emissions data and the USFS FIA inventories follow IPCC guidelines for forest greenhouse gas flux estimates, and neither account for transfers to harvested wood products⁵¹. Indeed, the results of our analysis show similar trends to other published forest carbon and flux assessments⁵² but the results vary by geography, likely due to different analytical methods (e.g., plot-based versus remote sensing), compounding uncertainties with each approach, and different assumptions. Furthermore, older datasets on aboveground forest carbon stocks may not be accurate in areas with recent timber harvest. Therefore, we present our analysis as a starting place for strategizing NCS actions at an ecoregional scale and understanding their contribution to global and regional 2030 climate commitments, rather than as a replacement for localized carbon accounting of NCS projects. FIA datasets provide the opportunity to ground truth the remote sensing techniques and better understand the uncertainty associated with these techniques.

Using the approach presented in this study, we demonstrate that at the ecoregional scale, a 10% reduction in annual forest loss due to timber harvest (within the historical range of variation) could result in a meaningful average annual reduction in carbon emissions (9.1 MtCO₂e yr⁻¹). However, improved forest management actions are implemented at stand and local scales and can include multiple silvicultural approaches⁷. As policymakers

and land managers work to incorporate climate change mitigation strategies into forest management decisions, additional analyses which assess specific forest management actions at local and stand scales will help determine which actions are most appropriate in which areas. Furthermore, by working with local communities, policymakers and land managers will be better positioned to identify which of the potential forest management actions are most likely to be successful in their jurisdictional or local contexts.

Our mapping approach highlights the key role for rural and Indigenous communities for implementing NCS projects that can meet carbon alongside other community-defined objectives³⁸. The coastal temperate rainforests of western North America are home to many communities with traditional territories not accurately represented in current designations of land ownership. Regional spatial approaches, as demonstrated here, provide a starting point from which to intentionally co-produce NCS strategies with communities⁵³. Integrating spatial data with traditional knowledge through conversations and utilization of social science will be critical to developing well-informed and socially responsible NCS projects. Our current analysis was limited to governmentally recognized ownership designations for tribes, reservations, and Indigenous corporations. As such, it is not representative of the influence and authority that Indigenous communities are working to re-establish over their traditional territories⁵⁴.

We recommend governments, businesses, and conservation organizations invest in a globally diverse portfolio of NCS projects in collaboration with local communities as a buffer to climate change, disturbances, and support political change in collaboration with local and Indigenous communities. While the coastal temperate rainforests of western North America are less prone to fire than most other forest types, they are not immune to disturbance from insect outbreaks or wind, and still require addressing land management needs of local economies. The realization of mitigation

potential is site-specific and will depend on a variety of legal and regulatory frameworks (e.g., atmospheric benefit sharing agreements), alongside the right economic incentives for voluntary measures (e.g., carbon market projects on private lands)³⁸.

For comparison, a coarse scale (10 km²) predictive global model of drivers of forest loss²⁸ suggests that 78% of forest loss in areas mapped as available for NCS is driven by forestry (6% was attributed to other drivers and 15% was unattributed to a single driver), suggesting relative agreement between the two different mapping approaches (Supplementary Table 5). Our assumption that an increase in improved forest management and conservation can yield substantial mitigation potential rests on the premise that it will not be counteracted by forest carbon losses in other geographies (i.e., leakage) and that project implementation on this large scale is feasible. The climate benefit of different types of forest-based NCS will also vary on a per-hectare and site-productivity basis and were beyond the scope of this study. Local information and community discussions will be needed to inform these assumptions and set the stage for an equitable and iterative process. Lastly, while this study was focused on improved forest management, additional NCS pathways such as restoration of forest cover or interventions to enhance growth of regenerating forests should also be considered²⁹. Further research should explore how frameworks such as the one presented here can be used to explore synergies and trade-offs among NCS²⁶.

NCS are critical for mitigating climate change in the near term, and although they are not a substitute for decarbonizing the economy, they offer a meaningful opportunity to achieve carbon emission reductions now. The generalizable spatial approach that incorporates land ownership, designations, and high-resolution forest carbon stocks and flux models demonstrated in this paper provides a clear path to build upon past NCS assessments and guide future assessments in globally important forests.

Methods

Ecoregion boundary

The coastal temperate rainforests of western North America are defined by a cool and wet maritime climate. Subnational ecoregion datasets were compiled to define the most accurate boundaries. In Alaska, USA, the extent was defined by Nowacki et al. 2001⁵⁵ Level 2 Coastal Rainforests. In British Columbia, Canada, the extent was defined by the Cool Hypermaritime and Highlands Ecodivision⁵⁶. The Washington and Oregon extent was defined by combining ecoregional data with fire regime groups⁵⁷. Fire regime groups were used to identify areas least susceptible to frequent, high-severity fires due to climate change. We included fire regime groups with long fire return intervals as well as those with shorter return intervals but with low-mixed severity. Specifically, we included five ecoregions across Oregon and Washington—Pacific Northwest Coast, Willamette Valley / Puget Trough, West Cascades, North Cascades and the portions of the East Cascades and Okanogan Ecoregions with a high density of fire regime groups V-A, V-B, I-C and III-B. The Washington and Oregon extent was further refined by combining data on forest productivity^{58,59}, and Biophysical Settings (BPS) / Potential Vegetation Types (PVT)⁶⁰ to identify areas that have high carbon potential but which may currently be in agricultural or other human modified land uses. We resampled the forest productivity data, which provides estimates of bolewood productivity (gC/m²/yr) based on climate data and site index, from 800 m to 30 m and calculated the mean productivity for each BPS/PVT type across the region^{58,59}. Within the area defined by ecoregions and fire regime group, we retained BPS/PVT cells with a mean productivity GTE 175 gC/m²/yr as well as any cells where forest productivity was within the upper 50% of productivity values (>136 C/m²/yr). These productivity/BPS/PVT data were overlaid with NRCS 6th level (12-digit) Hydrologic units and any watersheds overlapping the retained productivity/BPS/PVT cells were selected to form the final Washington and Oregon extent boundaries.

Spatial data hierarchy

A spatial data hierarchy was developed to consistently compare opportunities for forest carbon conservation with a jurisdictionally nested database

structure by country, state/province, landowner type, and land management designations that define the scope of NCS actions available in a given project location. Recent and publicly available subnational land ownership and land designation spatial datasets were synthesized starting with the most authoritative government datasets that are publicly available online. These data were supplemented, verified, and augmented with finer scale datasets obtained directly from local agencies. In cases where spatial data were not readily available, as was the case with some administratively protected areas (e.g., riparian buffers), the regulations were mapped using GIS analysis.

We developed a classification framework based on existing land use designations for assigning categories of action related to implementation of forest-based NCS (Table 1; Fig. 4). Areas available for NCS action were classified as NCS Action Category 1 (NCS1). In general, NCS1 areas are open to timber harvesting or other extractive activities where conservation and management actions related to enhanced carbon storage or sequestration are additional to the status quo. Examples include private forest lands, public lands held under forest management licenses to corporations, State Forests, National Forests, or woodlots. This category also includes Indigenous reserves, settlement areas for Indigenous land claims, or private lands held by Indigenous communities. NCS Action Category 2 (NCS2; Not currently available for action) include lands with administrative but not necessarily permanent protections that preclude additional measures for carbon conservation, such as riparian buffers in public lands that exclude timber harvest, special management zones such as wildlife reserves, and recreation areas. NCS Action Category 3 (NCS3; Not available for action) include permanently protected areas, such as National Parks, Wilderness Areas, and private lands protected by non-governmental organizations or land trusts. Each of these is derived from publicly available data so that potential users can further refine NCS actions to the specific circumstances and management constraints relevant to each designation. A detailed table of NCS Categories and land use designations can be found in Supplementary Table 2.

Alaska, USA- The primary ownership dataset used for Alaska was the Bureau of Land Management (BLM) National Surface Management Agency Area Polygons - National Geospatial Data Asset (NGDA)⁶¹. The areas available for NCS action (NCS1) were defined as privately owned (e.g., Alaska Native Corporation lands), have a timber management program, or are a local municipality. The Tongass National Forest harvestable land base (NCS1) was defined by the suitable and available stands dataset⁶². The Haines State Forest harvestable land base (NCS1) was defined by the commercially viable vegetation polygons⁶³. The Southeast Alaska State Forest (NCS1) was defined by the Alaska State Forest boundaries⁶⁴. Similarly, the University of Alaska Land Grant Trust and Alaska Mental Health Trust Authority investment lands (NCS1) were defined with their parcel database⁶⁵. Administratively protected harvest exclusions (NCS2) on non-Federal lands were approximated with a 30-m buffer on all perennial streams, lakes, and coastlines using the National Hydrography Dataset (NHD)⁶⁶ in accordance with the Alaska Forest Resources and Practice Act⁶⁷. Forest carbon projects (NCS2) on the American Carbon Registry, Climate Action Reserve, and the University of Alaska Land Management Carbon Credit Program⁶⁸ were also excluded from potentially harvestable lands. Lastly, we mapped permanently protected areas (NCS3) with the Protected Areas Database (PAD-US) 2.1 Vector Analysis File⁶⁹ GAP 1 lands; GAP 2 lands were classified as administratively protected (NCS2). Lands with an unclear forest management plan (e.g., NGDA “Alaska-Other” designation) were designated as unknown.

British Columbia, Canada- The primary ownership dataset used for British Columbia was the Generalized Forest Cover Ownership⁷⁰. This dataset was supplemented with Aboriginal Lands of Canada Legislative Boundaries⁷¹, Tree Farm Licenses⁷², and Timber Supply Areas⁷³. The areas available for NCS action (NCS1) were defined by private ownership or by Crown Tenure—Forest Management Unit, Timber License, Woodlot License Schedule A, Timber License in a TFL, Christmas Tree License and Crown Lease – Miscellaneous Leases. Indian Reserves, Land Claim Settlement Areas and Municipal Parcels were also classed as NCS1. Riparian

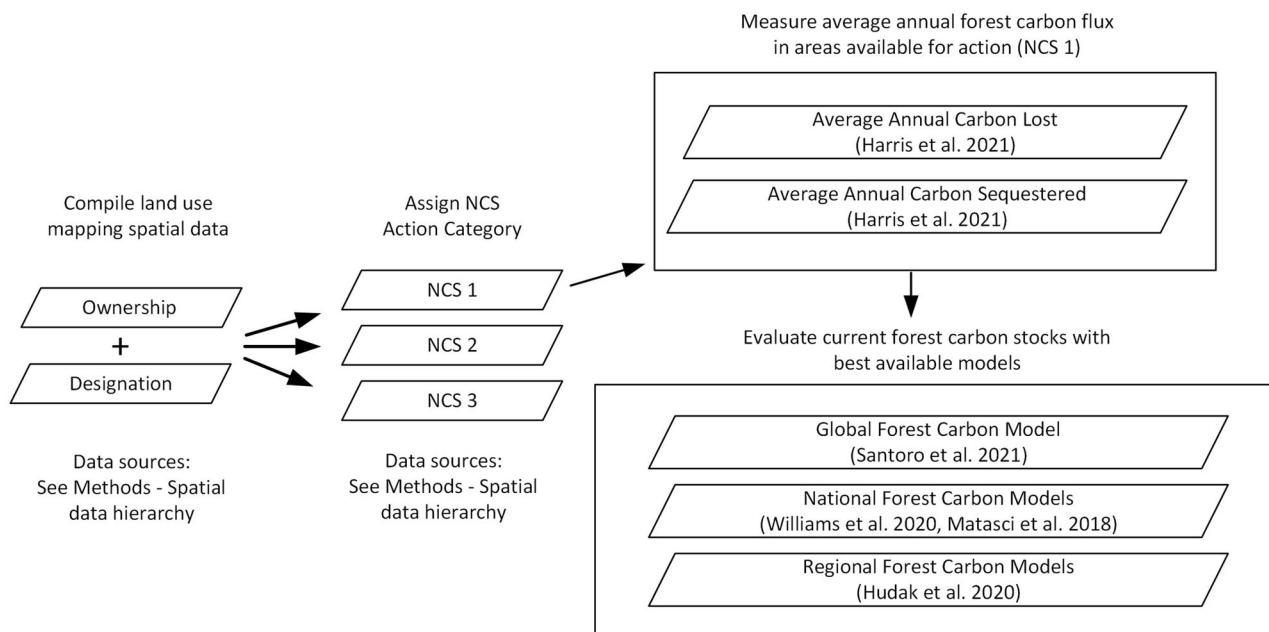


Fig. 4 | Mapping forest-based natural climate solutions workflow diagram. The generalizable framework developed to identify areas available for Natural Climate Solution (NCS) action and quantify the average annual flux and standing forest carbon stocks in the coastal temperate rainforests of western North America.

harvest exclusions (NCS2) were approximated with a 30-m buffer on watercourse hydrographic features using the Topographic Data of Canada—CanVec Series⁷⁴, freshwater lakes⁷⁵, and coasts⁷⁰ in accordance with the Fish Protection Act⁷⁶. Additional administratively protected areas (NCS2) included Forest Recreation Reserves, Wildlife Management Areas, Military Reserves, Recreation Areas, Federal Reserves, and Heritage Sites. NCS2 areas also included all non-private land inside the Great Bear Rainforest agreement area. Permanently protected areas (NCS3) were defined by the Canadian Protected and Conserved Areas Database IUCN Categories I–III⁴⁶.

Washington, USA- A suite of ownership datasets was combined for Washington. These included the NGDA⁶¹, PAD-US⁴⁷, Northwest Forest Plan (NWFP)⁷⁷, and county tax parcels⁷⁸. The areas available for NCS action (NCS1) were defined by private ownership, Indigenous treaty lands and tribal ownership, NGO, or NWFP Primary Land Use Allocations (LUAs): Adaptive Management Areas, No NWFP Designation, and Others (Supplementary Table 2). From the NWFP, administratively protected areas (NCS2) were defined by the LUAs: Administratively withdrawn, Adaptive management areas in reserves, Late-successional Reserve, Late-successional reserves for marbled murrelet and the northern spotted owl, Managed late-successional reserves. Congressionally Reserved areas in the NWFP were mapped as permanently protected (NCS3). The PAD-US GAP 2 (NCS2) was mapped as administratively protected and GAP 1 (NCS3) as permanently protected. From each data source, we prioritized the most limiting land use category. Lastly, we mapped permanent protections (NCS3) on riparian zones and wetlands with a 30-m buffer around all fish-bearing streams and state shorelines and a 15-m buffer around all other streams based on stream typing for fish-bearing designations. Stream, wetland, and waterbody data sources include Washington watercourses and waterbodies⁷⁹, salmon fish distributions⁸⁰, and the National Wetlands Inventory⁸¹. We designed these buffer widths as simplified representations of those described for the Washington Forest Practice Rules⁸².

Oregon, USA- The primary ownership dataset used on Oregon federal lands was the BLM Oregon Management Ownership Dissolve Polygon⁶¹. State managed lands were delineated with Oregon Department of Forestry (ODF) ownership land management data⁸³. These datasets were augmented with the USFS Region 6 boundaries⁸⁴. Private and tribal land boundaries were compiled directly from tax lot information ParcelPoint Tax Lot

Database⁸⁵, Regrid⁸⁶ and the U.S. Census Tigerlines for U.S. American Indian, Alaska Native, and Native Hawaiian Areas⁸⁷. Management status of lands in Oregon were determined from the PAD-US⁴⁷ and Northwest Forest Plan LUAs⁷⁷. The areas available for NCS action (NCS1) were defined by private ownership, NWFP LUAs, BLM multiple-use public land, USFS multiple-use public land, and Indigenous lands (Supplementary Table 2). Additional administratively protected areas (NCS2) included BLM wilderness areas, FWS study areas, NWFP LUAs, and USFS reserves. Permanently protected areas (NCS3) were defined by US-PAD GAP 1 lands and riparian buffers on the NHD⁶⁶ defined by the Oregon Forest Practices Act Private Forest Accord⁸⁸.

Forest carbon and flux models

The best available high-resolution aboveground forest carbon stock and flux (emissions and sequestration) maps at global, national, and regional scales were analyzed to compare the resulting patterns of climate mitigation benefits from improved forest management and conservation. To start, a forest vegetation mask was generated from the 30-m North America Land Change Monitoring System (NALCMS) Classes 1–10 for the year 2015⁸⁹. These data were also resampled to a 90-m resolution using the nearest neighbor technique to match the global forest carbon model. This mask included forest, shrubland, and grassland classes because recently harvested clearcuts important to our analysis were classified as shrubland and grassland. The excluded classes included: snow and ice, water, urban, barren islands, cropland, wetland, and sub-polar and polar lichen-moss classes.

The global AGB model for 2018 v3^{15,90} was downloaded in WGS84 tiles of average Mg ha^{-1} , mosaiced, projected to BC Albers with a 90-m cell using bilinear interpolation, and masked/snapped to the NALCMS mask. The AGB Mg ha^{-1} were converted into AGB Mg/pixel by multiplying by 0.81 corresponding with the cell area ($8,100 \text{ m}^2$). The AGB Mg/pixel were converted to MgC/pixel by multiplying by 0.47. Lastly, the MgC/pixel was converted to $\text{MgCO}_2\text{e/pixel}$ by multiplying by 3.67 for summing totals by ownership polygons. The corresponding AGB Standard Error (SE) rasters^{15,90} were processed the same as the AGB data. To summarize carbon stocks at the level of State/Provincial ownership types, the MgCO_2e SE was summed and then squared by individual parcels before taking the square root of the resulting totals for each subnational ownership type categories. To

obtain 95% confidence intervals around the mean, the SE was multiplied by 1.96 on either side of the mean.

The Canada⁴⁰, U.S. Pacific Northwest^{42,91}, and contiguous U.S.⁴¹ AGB models in average Mg ha⁻¹ were downloaded with 30-m cells that were projected into BC Albers and masked/snapped to the NALCMS mask. Data for AGB Mg ha⁻¹ were converted into AGB Mg/pixel by multiplying by 0.09 corresponding with pixel area (900 m²). The AGB Mg/pixel were converted to MgC/pixel by multiplying by 0.47. Lastly, the MgC/pixel was converted to MgCO₂e/pixel by multiplying by 3.67 and used to sum total biomass by ownership polygons. For calculating the forested area (ha) available for NCS action and average MgCO₂e ha⁻¹, the spatial hierarchy ownership polygons were clipped to the 30-m NALCMS mask.

We estimated forest carbon sequestration and losses for 2001–2021 based on a global map of carbon flux⁹. This map includes emissions from all biological carbon pools for stand-replacing disturbances and removals into aboveground and belowground biomass by standing and new forest. It spatializes estimates of flux based on Intergovernmental Panel on Climate Change national greenhouse gas inventory rules by overlaying forest extent, loss and gain maps with emission and removal factors from the literature. Sequestration³² and emission³³ rasters were downloaded in WGS84 tiles of average MgCO₂e pixel⁻¹, mosaiced, and left unprojected for calculating zonal statistics. The feature class data was unprojected into WGS84 for calculating zonal statistics. For the purposes of this analysis, the gross forest greenhouse gas emissions and gross carbon loss data were used. The MgCO₂e/pixel was converted to the average MgCO₂e pixel⁻¹ yr⁻¹ by dividing the 21-year time period for summing totals by ownership polygons. These historical fluxes are assumed to apply to future trends, and we assume that historical patterns and causes of disturbances will continue through 2030. Uncertainty estimates for these flux estimates are not available for this data at this level of analysis.

2030 natural climate solutions opportunity

To demonstrate the scale of potential NCS opportunity from an increase in improved forest management and conservation⁷ in the coastal temperate rainforests of western North America, we compared the historical range of variability in timber harvest³ (Supplementary Table 4) to the 175 MtCO₂e yr⁻¹ 2030 land-based climate commitments made by the United States and Canada^{30,31}. The 10% coefficient of variation (CV) in historical timber harvest (harvested roundwood only represents a portion of the emissions detected with the flux model used in this study⁹) was then used as a conservative emissions reduction target based on the average annual carbon emissions for the study region (91 MtCO₂e yr⁻¹).

Data availability

A web-based mapping tool was developed for this publication to explore Natural Climate Solution (NCS) project ideas: <https://maps.tnc.org/emerald-edge-carbon-map>. The raw spatial data for this mapping tool and publication are available for download on the Harvard Dataverse: <https://doi.org/10.7910/DVN/D3XUHZ>.

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Author contributions

C.S.S. led the conceptualization, analysis and writing. R.A.G. contributed to the conceptualization and writing. C.R.D. contributed to the conceptualization, analysis and writing. M.S. contributed to the conceptualization, analysis and writing. J.C.R. contributed to the conceptualization, analysis and writing. M.J.C. contributed to the conceptualization and writing. T. B. contributed to the conceptualization and writing. This project was funded by the Bezos Earth Fund.

Competing interests

The authors declare no competing interests.

Additional information

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