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Southern Alaska's Forest Landscape Integrity, Habitat, and Carbon Are Critical for Meeting Climate and Conservation Goals

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Key Points:

- The Tongass and Chugach are the largest and most intact of all US National Forests, with key bald eagle, brown bear, and gray wolf habitat
- The Tongass and Chugach are cool and wet with forest carbon stocks minimally impacted by wildfire and likely to increase with climate change
- The Tongass, Chugach and Pacific Northwest's National Forests are high priority for protection to meet climate and biodiversity goals

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract

The interdependent crises of climate change and biodiversity losses require strategic policies to protect, manage, and restore essential ecosystems. Here, we evaluate the relative importance of US national forests (NFs) for protection and conservation as natural climate and biodiversity solutions. We compared landscape integrity (degree of modification by humans), habitat for three keystone species, forest carbon density, accumulation, and total biomass carbon stocks across 154 NFs in the United States. Southern Alaska's Tongass and Chugach NFs hold disproportionally large amounts of high landscape integrity area among all NFs with 25.3% and 5.6% (total 30.9%) of all high (≥9.6) landscape integrity found on NF lands. The Tongass and Chugach store approximately 33% and 3% of all biomass carbon stocks that occur in NFs with high landscape integrity. These two NFs together account for about 49%, 37%, and 18% of all bald eagle, brown bear, and gray wolf habitat found on NF lands. Gray wolf habitat extent was 4% of the total or less on remaining NFs. The Tongass and Chugach were historically wetter and cooler among NFs, and are projected to experience much larger increases in precipitation and much lower increases in maximum temperatures over the coming century. Combined with relatively low recent occurrence of wildfire, this makes permanence more likely. The Tongass and Chugach forests, along with the Pacific Northwest's high carbon density forests should be a high priority for protection and conservation to meet climate and biodiversity goals given their landscape-scale scarcity and high value.

Plain Language Summary

Permanent protection of forests with relatively high carbon stocks, landscape integrity, and habitat extent would contribute substantially to climate mitigation and species adaptation. The Tongass and Chugach National Forests in southern Alaska rank highest among U.S. National Forests in all three areas. These forests also have relatively low near-term vulnerability to wildfire and climate, higher connectivity for animal movement, and lower human impacts, making permanence more likely.

1. Introduction

Forests play crucial roles for mitigating climate change and supporting biodiversity, thus making it important to identify and protect the most vital forests (IPCC, 2022; Law et al., 2021). Terrestrial ecosystems have been removing about 30% of global anthropogenic CO_2 emissions from the atmosphere each year for the past 60 years and most of the removal is by forests (Friedlingstein et al., 2022). Climate impacts would be even more severe without this ecosystem service. Yet intact forests with high carbon density and biodiversity are disappearing at an alarming rate (Potapov et al., 2017), such as in the Brazilian Amazon and Canadian British Columbia, which have become net carbon sources (Gatti et al., 2021; Government of British Columbia, 2022; Harris et al., 2021; Qin et al., 2021). Concerningly, current national climate pledges will increase greenhouse gas emissions by 16% from 2010 to 2030, indicating that the planned emissions reductions and increased removals from the atmosphere by the biosphere need to be much more aggressive (UNFCCC, 2021).

Nature-based Climate Solutions (NbCSs) are essential for protecting interdependent forest carbon and biodiversity (Dinerstein et al., 2020), leading to calls for conservation of 30%–50% of Earth's surface in the coming decades (IPCC, 2022). NbCSs allow ecosystems to continue to store and accumulate carbon from the atmosphere, provide habitat for plant and animal species, and protect watersheds. Intact forests are crucial for supporting wildlife, fish, clean water, carbon sequestration, and other ecosystem services (Grantham et al., 2020; Watson et al., 2018). Protected public lands (e.g., Wilderness Areas, National Parks) provide important NbCSs (Law

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et al., 2021, 2022), in part because they likely afford greater permanence of carbon storage than private lands (Anderegg, 2021). In the United States (US), there are 154 National Forests (NFs) that account for 76% of all federal forest land (590,240 km^2 of 773,620 km^2) (Smith et al., 2019). Logging and other extractive activities are allowed throughout most NF forest lands, with only about 19% classified as "reserved" from timber production (Smith et al., 2019), albeit with varying levels of biodiversity and logging protection. Consequently, there is a substantial gap between current conservation of NF forest lands and conservation targets focused on protecting biodiversity and carbon stocks.

Federal lands managed by the U.S. Forest Service (FS), the National Forest System (NFS), and the Bureau of Land Management are managed under a multiple use—sustained yield model (US Congress, 1960, 1976). The statute directs the agencies to "balance multiple uses of their lands and ensure a sustained yield of those uses in perpetuity" (Riddle, 2022). The balance of multiple uses on federal lands has been an ongoing point of contention (Riddle, 2022), with many concerned that conservation isn't a higher priority given the critical need for meeting conservation targets for climate mitigation and adaptation. Forest management activities, particularly harvest, appear to be in conflict with the intertwined goals of protecting forest carbon and biodiversity for climate mitigation and adaptation. NFs in the conterminous US particularly in the West have experienced increasing incidence of wildfire, insects, and drought, yet still represent the majority of late mature and old-growth forest area remaining, which imparts a unique role in protecting these areas for biodiversity and climate change. Research studies have shown that older forests containing large trees are more resilient and have greater ecosystem integrity than younger forests (Rogers et al., 2022).

The coastal rainforests of southern Alaska are unique ecosystems that could help fill the conservation gap on NF forest lands (DellaSala et al., 2022; Vynne et al., 2021). Two NFs in the region are the Tongass and Chugach NFs (Figure 1). In addition to storing a large amount of carbon (Barrett, 2014; DellaSala et al., 2022), these coastal rainforests have extensive intact forests, complete wildlife assemblages, and are strongholds for wild salmon and other fish (Vynne et al., 2021). Unlike much of the conterminous US, this region still has substantial populations of large carnivores including bald eagle (*Haliaeetus leucocephalus*), brown bear (*Ursus arctos*), and gray wolf (*Canis lupus*). Therefore, to guide conservation planning it is important to understand current forest integrity and protection status in these coastal rainforests, as well as how they compare with other US NFs.

Recently developed spatial data sets can provide valuable insights into current forest integrity and other forest bioclimatic characteristics that are important to consider in conservation planning. For instance, the new forest landscape integrity index (FLII) characterizes the level of forest landscape degradation from human activities in a consistent manner worldwide (Grantham et al., 2020). Other large-scale spatial data sets provide detailed information on forest biomass carbon stocks (Spawn et al., 2020), wildlife habitat (USGS GAP, 2022), and fire activity (Giglio et al., 2018), as well as current and potential future climate (Brun et al., 2022a, 2022b). Forest carbon stocks and wildlife habitat can be eroded by high fire activity and climatic changes that lead to hotter and drier conditions (Buotte et al., 2019). Together, these data sets provide new opportunities to characterize forest bioclimatic conditions across coastal rainforests in southern Alaska and to understand how these rainforests compare with forest lands in other US NFs.

To better understand potential conservation benefits of preserving forest lands in the Tongass and Chugach NFs (Figure 1), we compared forest bioclimatic attributes of these NFs with all other NFs in the conterminous US. We focus on the need to retain large tracts of intact forest landscapes that help mitigate climate change and protect biodiversity as part of a "Strategic Forest Reserve" system emphasizing NbCSs on federal lands in the US. Our objectives are:

1. Compare forest area, landscape integrity, and biomass carbon among NFs;
2. Determine and compare the areal extent of habitat for bald eagle (*Haliaeetus leucocephalus*), brown bear (*Ursus arctos*), and gray wolf (*Canis lupus*) among NFs;
3. Compare recent and projected climate conditions and wildfire occurrence among NFs to determine risk.

Our analysis was based on spatial data sets primarily derived from satellite remote sensing and geospatial modeling (Giglio et al., 2018; Grantham et al., 2020; Hansen et al., 2013; Spawn et al., 2020), though also included future climate projections from CMIP6 (Brun et al., 2022a, 2022b) and current preservation status from the Protected Areas Database of the United States (PAD-US version 3) produced by the US Geological Survey (USGS) Gap Analysis Project (GAP; USGS GAP, 2018). These spatial data sets enable consistent analysis of

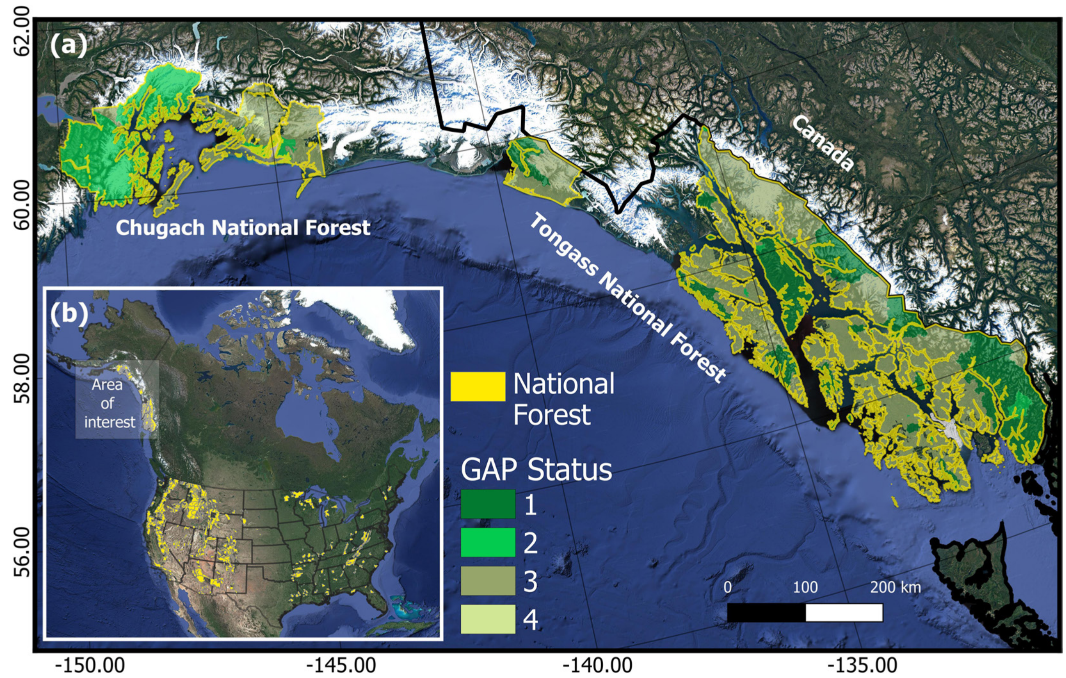

Figure 1. Administrative boundaries of the (a) Tongass and Chugach National Forests in southern Alaska and (b) National Forests throughout the USA. Also shown (a) are the current GAP Status of lands in the Tongass and Chugach National Forests. GAP 1 and GAP 2 lands are managed for biodiversity, GAP 3 lands are managed for multiple uses including mining, logging, and off highway vehicle use, and GAP 4 lands are those with no known mandate for protection. GAP Status data were from the Protected Area Database of the US (PAD-US version 3; USGS GAP, 2022). Basemap from Google Satellite © 2021 Google.

forest attributes across all US NFs. Our analysis highlights unique bioclimatic characteristics of coastal rainforests in southern Alaska that prioritize increased protection for forests in the region.

2. Materials and Methods

2.1. General Approach

We analyzed and ranked forest attributes among NFs using existing spatial data sets related to forest extent, landscape integrity, carbon, biodiversity, wildfires, and climate. Specifically, we focused on federally managed lands within the administrative boundary of each NF, with management type determined based on a spatial overlay with the PAD-US (USGS, 2022). Therefore, our analysis does not include inholdings within NF administrative boundaries, such as lands managed by local or state governments or Alaska Native Corporations. Our analysis also does not include the El Yunque National Forest in Puerto Rico due to data limitations. Most of the spatial data sets had a spatial resolution of ~300 m, therefore we chose to conduct the analysis using a common 300 m resolution grid in an Albers Equal Area projection. We reprojected categorical data sets using nearest neighbor resampling and continuous numeric data sets using bilinear interpolation. We analyzed and visualized data using the R software (version 4.2) (R Core Team, 2021) with the libraries *terra* (Hijmans, 2022), *raster* (Hijmans, 2019), *sf* (Pebesma, 2018), *data.table* (Dowle & Srinivasan, 2021), and *ggplot2* (Wickham, 2016). We created the maps using open-source software QGIS (v3.20; QGIS.org, 2021).

2.1.1. Forest Extent

We quantified the areal extent of forest within each NF using a global tree canopy cover data set (Hansen et al., 2013). This spatial data set provides per pixel estimates of tree canopy cover (0%–100%) at 30 m resolution for peak growing season circa 2010 based on Landsat 7 satellite imagery and regression tree modeling. We mean resampled these data from 30 to 300 m spatial resolution and then identified forestlands as areas with tree canopy cover ≥10%. We determined the total area of forestlands within each NF and used this layer to mask other spatial data sets to forestlands. Supplemental analysis showed a strong linear relationship between estimates of total forest area at 30 versus 300 m spatial resolution across NFs ($r^2 = 0.996$, $y = -219 + 0.946\,x$).

2.1.2. Forest Landscape Integrity

We assessed forest ecological integrity across each NF using the forest landscape integrity index (FLII; Grantham et al., 2020). This spatial data set describes the degree of modification of forests by humans and is derived from observed human pressures (infrastructure, agriculture, tree cover loss), inferred human pressure based on proximity to the observed pressures, and loss of forest connectivity (ratio of current to potential connectivity) (Grantham et al., 2020). The anthropogenically disturbed nature of many areas with temporary tree cover loss and recovery is reflected in scoring within the index, because temporary tree cover loss in the categories of shifting cultivation or rotational forestry is treated as an observed pressure. It does not treat tree cover loss associated with wildfire as an observed pressure because fires are often the result of natural processes. The FLII ranges from 0 to 10, with higher scores describing more intact forest landscapes that have ecosystem functions (e.g., carbon storage, biodiversity, watershed protection) closer to natural levels barring potential impacts of climate change. Scores are divided into three levels of integrity, low (≤6.0), medium (>6.0 and <9.6), and high (≥9.6) and were identified by the data creators (Grantham et al., 2020). Forests with scores ≥9.6 are considered to have high integrity based on inspection of benchmark locations (Grantham et al., 2020). The FLII was mapped globally at 300 m resolution using spatial data from 2000 to 2019 and can be applied at subnational to global scales. We computed the average and standard deviation of the FLII across each NF, as well as the total areal extent of high integrity forest (FLII ≥ 9.6) within each NF.

2.1.3. Forest Carbon

We quantified tree carbon stocks using harmonized global maps of above and belowground biomass carbon density in the year 2010 at 300 m spatial resolution (Spawn et al., 2020). The data set provides estimates of carbon storage in live tree aboveground (i.e., stems, branches, twigs, and bark) and belowground (i.e., roots) biomass for stems greater than 10 cm diameter at breast height. The data set was derived from remotely sensed measurements of tree aboveground biomass density combined with measurements of biomass carbon content and root to shoot ratios (Spawn et al., 2020). An accuracy assessment showed that estimates of total state-wide tree carbon stocks for states in the conterminous USA were very similar whether derived from the harmonized maps or independent USFS forest inventory data ($r^2 = 0.96$, slope = 1.17, $n = 48$; Spawn et al., 2020). We masked this data set to forestlands and then computed average and standard deviation of tree carbon density (Mg C ha^{-1}) for each NF, as well as total tree carbon stock (Tg C) in each NF.

2.1.4. Forest Wildlife Habitat for Keystone Species

We assessed the current areal extent of habitat for bald eagle (*Haliaeetus leucocephalus*), brown bear (*Ursus arctos*), and gray wolf (*Canis lupus*) across each NF using species distribution data sets produced by the USGS Gap Analysis Project (GAP) (Gotthardt et al., 2014; USGS, 2018). These species are important apex predators that can trigger trophic cascades (Ripple et al., 2014) and were historically ubiquitous in much of North America. Moreover, these top predators may function as umbrella species, hence conserving them could offer broader biodiversity benefits (Sergio et al., 2006). The GAP project produced separate species distribution models for Alaska (Gotthardt et al., 2014) and the continental US (USGS, 2018) at 60 and 30 m spatial resolution, respectively. Each species' distribution was predicted using models that linked occurrence records with geospatial data sets related to soil, hydrologic, topographic, land cover, development, disturbance climate, and ecological conditions. For each species, we reprojected data sets onto the common 60 m resolution grid and then quantified the areal extent of contemporary habitat that occurred within the boundaries of each NF.

2.1.5. Climate Data

We characterized historical climate conditions and potential future climate change across forestlands in each NF using two bioclimatic variables from the CHELSA-BIOCLIM + data set (Brun et al., 2022a, 2022b). This data set included climatologies for historical (1981–2010) and future (2071–2100) periods that were mechanistically downscaled to 1 km spatial resolution. For future conditions, we examined climatic changes predicted by an ensemble of five earth system models (ESMs) that were run as part of the Coupled Model Intercomparison Project Phase 6 (CMIP6) following a high-carbon emission shared socioeconomic pathway scenario (SSPS585). We focused on mean daily maximum temperature of the warmest month (hereafter *maximum temperature*, °C) and annual precipitation (mm), which are derived bioclimate variables that provide insight into ecosystem energy and moisture limitations. We reprojected these data onto the common 300 m resolution grid and masked out non-forest areas (e.g., icefields in the Tongass NF). For each grid cell, we computed the projected climatic changes from historical to future periods (i.e., 2071–2100 minus 1981–2010) using each climatology from the five ESMs. Next, we calculated the spatial average and standard deviation of historical and future climate and climatic changes for forestlands in each NF. For each NF, we focused on the ensemble median change predicted in spatially-averaged climate across the five ESMs, and also computed the minimum and maximum changes across the ensemble.

2.1.6. Wildfire Data

We quantified forest area burned in recent decades across each NF using the MODIS satellite burned area data set (MCD64A1 version 6; Giglio et al., 2018). This data set provides burned area extent every month across the world at 500 m spatial resolution. We accessed these data using Google Earth Engine (GEE; Gorelick et al., 2017) and for each grid cell determined whether it had burned from 2001 through 2020. We exported these data from GEE, resampled them to 300 m resolution to match the forest cover data set, and then computed total forest area burned for each NF, as well as the percentage of forest area that burned during these two decades.

2.1.7. Protected Area Data

We identified federally managed lands and evaluated the current extent of forest protection in the Tongass and Chugach NFs using the Protected Area Database of the United States (PAD-US version 3.0) produced by the United States Geological Survey Gap Analysis Project (USGS GAP, 2022). This spatial data set is the official inventory of protected areas across the nation (USGS GAP, 2022). Protected status is characterized by GAP status codes that describe management intent to preserve biodiversity following guidelines from the International Union for the Conservation of Nature (IUCN). GAP 1 and GAP 2 lands are managed for biodiversity, GAP 3 lands are managed for multiple uses including mining, logging, and off highway vehicle use, and GAP 4 lands are those with no known mandate for protection. GAP 1 typically aligns with IUCN Categories Ia, Ib, and II and is the only designation that protects all ecological functions and limits firefighting yet does allow hunting in Alaska. GAP 2 typically aligns with IUCN Categories III through VI and aims to maintain a "primarily" natural state but may receive uses or management that degrades the quality of existing natural communities, including suppression of natural disturbance. We rasterized land ownership and GAP status codes at 300 m spatial resolution, selecting the lowest GAP status if a land had multiple designations. We then masked all analyses to federally managed lands (i.e., excluded inholdings) and calculated total area and carbon stocks of forestlands falling under each GAP status code.

3. Results

3.1. Forest Area and Landscape Integrity

The Tongass and Chugach are among the few national forests (NFs) with high landscape integrity, and the Tongass has by far the largest forest area of all 154 NFs in the country (Figure 2). The Tongass and Chugach comprise 9.4% and 2.0% (total 11.4%) of all federally managed forest area on NF lands (~539,850 km^2 total) and are ranked first and second out of all NFs in terms of their forest area. Moreover, the Tongass and Chugach have mean (±1SD) FLII values of 9.8 ± 0.5 out of 10, respectively comprising 25.3% and 5.6% (total 30.9%) of all high (≥9.6) integrity forest landscapes found in the NFS, where FLII averages 8.0 ± 2.3. Other NFs with high mean forest landscape integrity (≥9.6) but less area include Challis NF in Idaho and Humboldt NF in California, which comprise 0.8% and 0.5% of all forest area on NF lands (Table S1 in Supporting Information S1). Compared to other NFs, the Tongass and Chugach are thus unique not only because of their extensive forest area but also their high forest landscape integrity.

3.2. Forest Carbon

Mean tree carbon densities are higher-than-average on the Tongass NF, but quite low on the Chugach NF (Figure 3a). The mean (±1SD) tree carbon density on the Tongass (88 ± 45 Mg C ha^{-1}) and Chugach (35 ± 25 Mg C ha^{-1}) are about ~10% higher and ~56% lower, respectively, than that of all forestlands in the National Forest System (61 ± 46 Mg C ha^{-1}; Figure 3a). The top 5 NFs with the highest mean tree carbon density (141–170 Mg C ha^{-1})

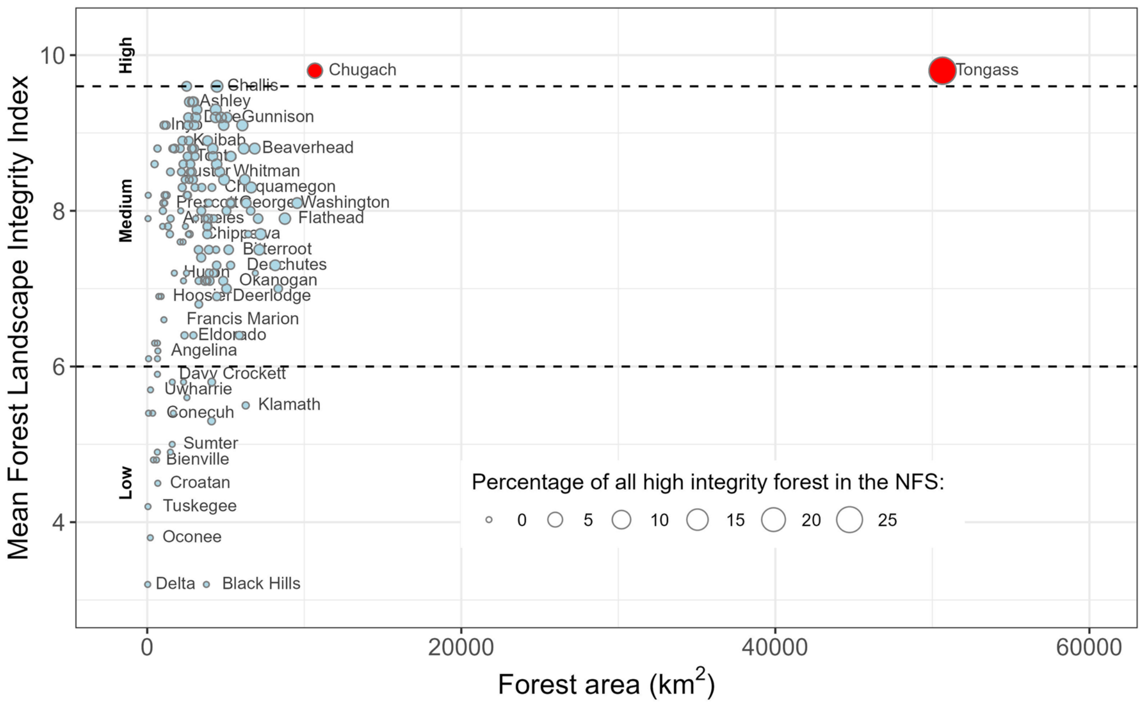

Figure 2. Forest area (km^2) and mean forest landscape integrity (unitless) for each national forest in the US National Forest System. The forest landscape integrity index ranges from 0 (lowest integrity) to 10 (highest integrity). Low (≤6.0), medium (>6.0 and <9.6), and high (≥9.6) forest integrity are identified using thresholds from the data creators (Grantham et al., 2020). The plotting character for each national forest is scaled by its relative holding of all high integrity forest in the National Forest System. Note the exceptional forest area and integrity of the Tongass and Chugach National Forests (red points).

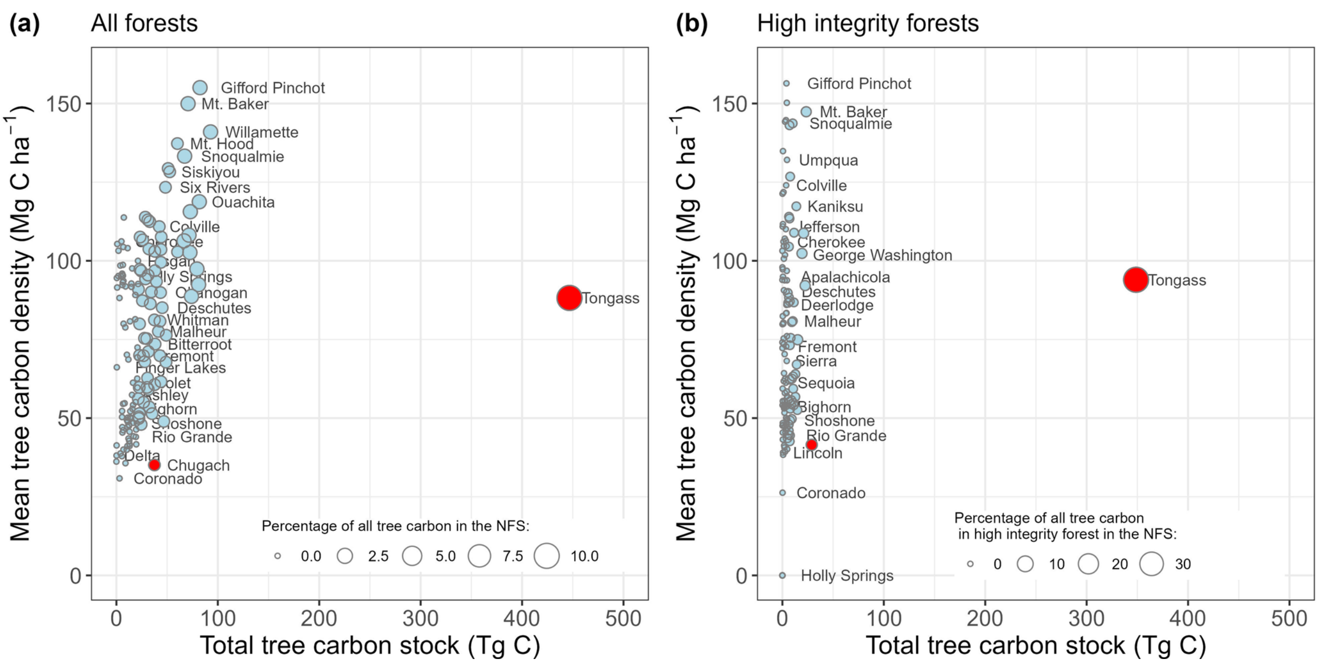

Figure 3. Mean tree carbon density (Mg C ha^{-1}) and total tree carbon stock (Tg C) for each national forest in the National Forest System (NFS). Summaries are provided for (a) all forests and (b) high integrity forests within each national forest. Tree carbon includes live aboveground and belowground biomass. The plotting character for each national forest is scaled by its overall contribution to total tree carbon stocks across (a) all forests and (b) high integrity forests in the NFS. Forests were considered high integrity if the forest landscape integrity index was ≥9.6 out of 10 (Grantham et al., 2020). There were 25 national forests without any high integrity forest, so in (b) these are plotted at the origin (0,0). The Tongass and Chugach National Forests are plotted as red points. Note the exceptionally large tree carbon stock of the Tongass and the much smaller carbon stock on the Chugach (red points).

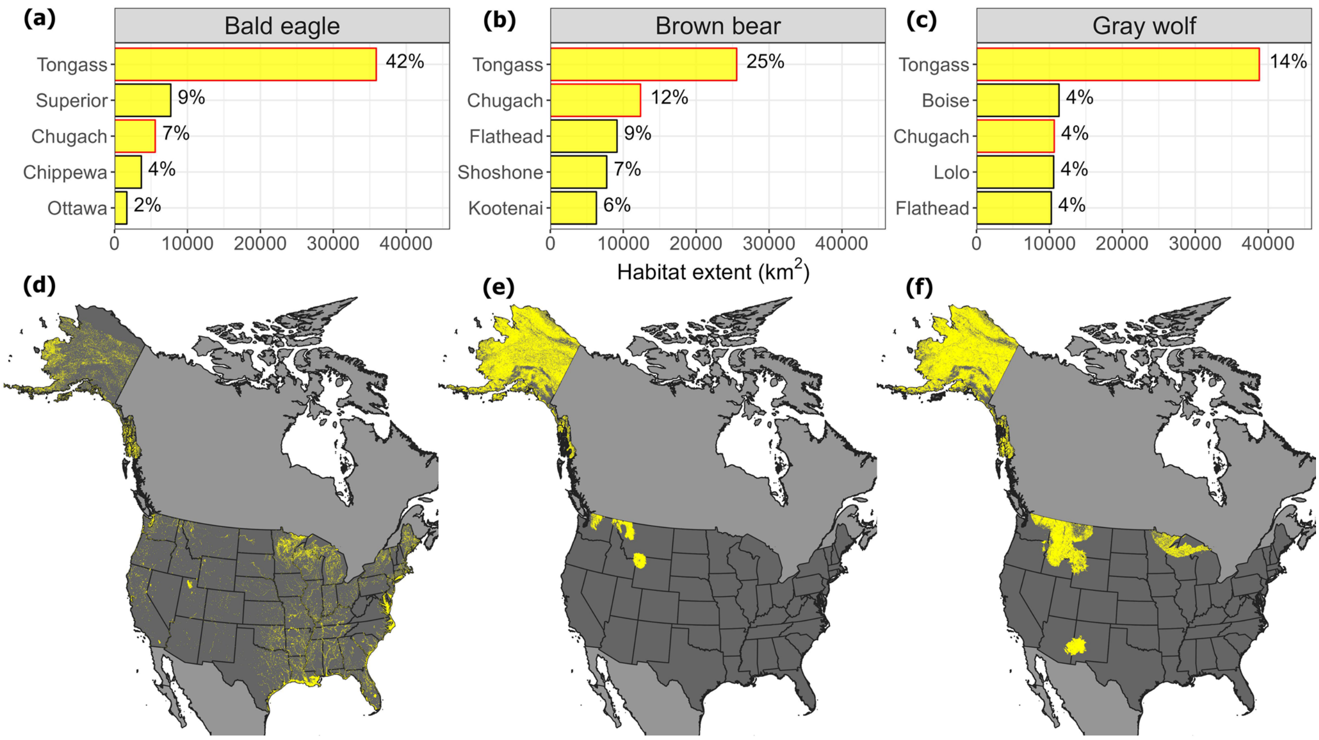

Figure 4. Current areal extent of bald eagle, brown bear, and gray wolf habitat in the (a–c) five national forests with the most habitat for each species and (d–f) the overall USA. In panels (a–c), the percentages denote the extent of species habitat within each national forest relative to the total extent of species habitat on all national forest lands. Species habitat distribution data sets generated as part of the USGS GAP (Gotthardt et al., 2014; USGS, 2018).

are the Siuslaw, Olympic, Gifford Pinchot, Mt. Baker, and Willamette, which all occur in either the Coast Range or Cascade Range of western Oregon and Washington (Table S2 in Supporting Information S1).

The Tongass and Chugach store approximately 10.4% and 0.9% (total 11.3%) of all tree carbon stocks that occur on NF lands (~4,305 Tg C total) and are ranked 1st and 40th out of all NFs in terms of their total tree carbon stocks (Figure 3a). Furthermore, the Tongass and Chugach store approximately 33% and 3% of all tree carbon stocks that occur in forests with high landscape integrity (FLII ≥9.6), placing them first and second among all NFs in this regard (Figure 3b; Table S2 in Supporting Information S1). Notably, the Tongass tree carbon stock (~447 Tg C) is nearly five time larger than that of the second ranked NF (Willamette). The top 5 NFs with the highest tree carbon stocks also include Ouachita, Flathead, and Gifford Pinchot, which is the only NF that also makes the top 5 for highest tree carbon densities.

3.3. Forest Wildlife Habitat

The Tongass provides substantially more habitat for bald eagles, brown bears, and gray wolves than any other NF, while the Chugach provides the second or third most habitat depending on species (Figure 4a). These two NFs together account for about 49%, 37%, and 18% of all bald eagle, brown bear, and gray wolf habitat found on NF lands, respectively. Other NFs important for bald eagles include Superior, Chippewa, and Ottawa in the upper Midwest (Figure 5), though the Tongass provides nearly three times as much habitat as all of these combined. While brown bears and gray wolves are found throughout much of Alaska, their current distributions in the continental US are restricted to the Northwest and, in case of gray wolves, to small areas in the Southwest and upper Midwest (Figure 4b).

3.4. Climate and Wildfire Risk

The Tongass and Chugach historically (i.e., 1981–2010) had the highest annual precipitation and lowest maximum temperature of all NFs (Figure 5a), as well as the largest projected increases in annual precipitation and among

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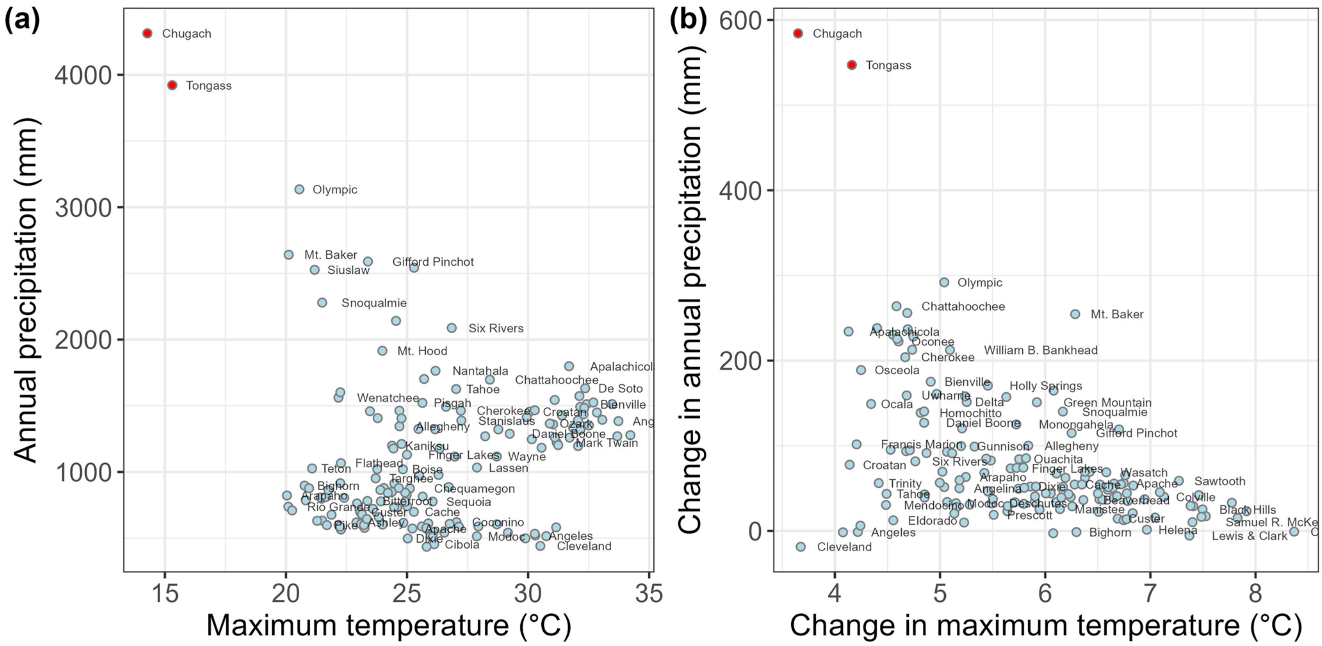

Figure 5. Historical climate (1981–2010) and future climate changes (2071–2100 minus 1981–2010) for each National Forest. (a) Climate variables include annual precipitation and mean daily maximum temperature of the warmest month (i.e., maximum temperature, °C). Climate data were spatially averaged across forestlands in each NF. (b) Climatic changes were derived from the ensemble median of predictions from five CMIP6 Earth system models driven by a high-carbon emission shared socioeconomic pathway scenario (SSPS585). Climate data were from the CHELSA-BIOCLIM + data set (Brun et al., 2022a, 2022b).

the lowest projected increases in maximum temperature over the coming century (i.e., 2071–2100; Figure 5b). Across forestlands in the Tongass and Chugach, annual precipitation historically averaged 3,920 ± 890 mm and 4,310 ± 1,390 mm, respectively, and is projected to increase 547 [195, 700] mm and 584 [413, 855] mm by the end of 21st century. Not only have the Tongass and Chugach historically been far wetter than any other NF, but future changes in annual precipitation are projected to be nearly two times larger than any other NF. Similarly, across forestlands in the Tongass and Chugach, maximum temperatures historically averaged 15.3 ± 2.1°C and 14.3 ± 1.6°C, respectively, and are projected to increase by 4.2 [3.5, 9.9] °C and 3.6 [2.5, 11.5] °C by the end of the century. The Tongass and Chugach historically had maximum temperatures that were about 5°C lower than any other NF, with rates of future warming that are the lowest to sixth lowest of any NF. Overall, the Tongass and Chugach were historically much colder and wetter than any other NF and are projected to experience much larger increases in precipitation and much lower increases in maximum temperatures over the coming century.

Satellite data showed fires burned a minuscule amount of forest area in the Tongass and Chugach from 2001 through 2020 (Figure 6). In total, forest fires burned about 70,251 km^2 (13.0%) of NF lands during the last two decades. The Tongass and Chugach together accounted for merely 0.1% of total forest burn area on NF lands but comprised about 11.4% of total forest area. During this period, forest fires burned a total of 61 km^2 (0.1%) and 27 km^2 (0.2%) in the Tongass and Chugach, respectively. These two NFs ranked near the bottom (144th and 140th) of all NFs in terms of their percent of forest area that burned in recent decades, in contrast with Mendocino and Angeles NFs where 66%–90% of forest area burned. Forests that burned multiple times (i.e., reburns) during this period are only counted once. Overall, forest fires were very uncommon during recent decades in Alaska's coastal rainforests.

3.5. Protected Areas

The forest area currently protected at GAP 1 or 2 levels sums to 17,983 km^2 on the Tongass (35.5% of the NF area) and 6,150 km^2 on the Chugach (57.6% of the NF area) (Figure 1, Table 1). The Tongass protected area is primarily GAP 1 status, mostly due to the six wilderness areas. The Chugach has no GAP 1 protected areas, with most protected areas designated as GAP 2 because of wilderness study and national heritage areas designated within its boundaries. GAP 3 areas are managed for multiple uses but also contain roadless areas which would be good candidates for higher levels of protection.

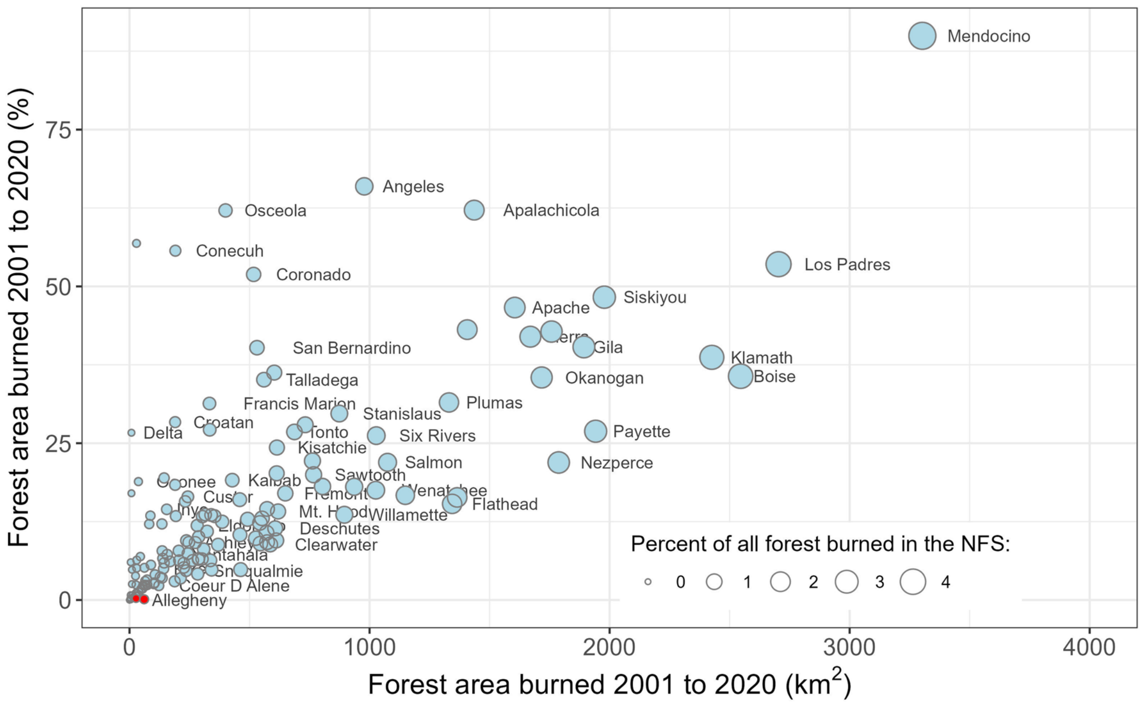

Figure 6. Absolute and relative forest area burned from 2001 to 2020 for each national forest in the US National Forest System. The plotting character for each national forest is scaled by its overall contribution to total forest burned area across all national forests. Note the exceptionally low absolute and relative forest burned areas of the Tongass and Chugach (small red points in bottom left). Burn area was derived from MODIS satellite data (Giglio et al., 2018).

4. Discussion

Severe ecological disruption is expected to occur over the next 10–30 years as the climate rapidly warms, hence immediate actions are needed to mitigate climate change and protect biodiversity (IPCC, 2018, 2021). These actions include effective conservation of 30%–50% of Earth's land, freshwater and ocean areas, including current near-natural ecosystems (IPCC, 2022). To better understand potential conservation benefits of preserving forestlands in the Tongass and Chugach NFs, we compared forest bioclimatic attributes of these NFs with all other NFs in the conterminous US. We focus on forests because of their significant carbon storage and accumulation of carbon over decades to centuries. Actions that support biodiversity also support ecosystem resilience in the long term (Oliver et al., 2015). Thus, our analysis compares landscape integrity among national forests, as well as tree biomass carbon stocks and habitat extent for keystone species while accounting for projected climate conditions that may impact some forests more than others. Current protected areas at GAP 1 and 2 levels can help to identify NFs where additional areas could be moved into these levels of protection with some changes in management, although there are some preexisting stipulations and allowances for other uses in Alaska. Our analysis highlights the Tongass and Chugach are exceptionally large and intact forests that provide important habitat and carbon sequestration that are buffered against fires and future climate disturbance.

Table 1
Current Extent of Land and Forest Protection Under Federal Management in the Chugach and Tongass National Forests in Southern Alaska

National Forest	GAP status	All lands		Forest lands		Forest carbon	
		km^2	%	km^2	%	Tg C	%
Chugach	1	0	0	0	0	0	0
	2	13,733	60.9	6,150	57.6	353	58.4
	3	8,821	39.1	4,520	42.3	251	41.6
	4	12	0.1	11	0.1	0	0
Tongass	1	23,421	34.3	17,267	34.1	1,005	33.3
	2	836	1.2	716	1.4	42	1.4
	3	43,986	64.5	32,667	64.5	1,974	65.3
	4	1	0	1	0	0	0

4.1. Forest Landscape Integrity

We found the Tongass and Chugach NFs have the highest forest landscape integrity of all NFs, and are ranked first and second in their forest area, making them high priority areas for protecting forest landscape integrity. Large contiguous tracks of intact forest landscape are important for biodiversity, carbon sequestration, water regulation, indigenous culture, and human health (Grantham et al., 2020; Potapov et al., 2017; Watson et al., 2018). However, globally, the extent of intact forest landscapes declined ~7% from

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Table 2
Estimated Accumulation Rate of CO_2 by National Forest Region

National Forest region	Net change in stock (Mg CO_2/yr)	Area (ha)	Accumulation (MgCO_2/ha/yr)
Alaska	4.0	3,057,631	1.3
Eastern	11.5	4,767,960	2.4
Intermountain	−11.5	9,051,830	−1.3
Northern	−0.9	8,889,956	−0.1
Pacific Northwest	28.3	9,041,109	3.1
Pacific Southwest	5.7	5,994,752	1.0
Rocky Mountain	−12.2	6,118,661	−2.0
Southern	25.5	5,321,390	4.8
Southwestern	−6.9	6,164,438	−1.1
All Regions	43.5	58,407,728	0.7

Note. Net change in C stock from Domke et al. (2023). Area estimates are from the FIA database. Negative numbers mean CO_2 stocks are declining.

2000 to 2013 (Potapov et al., 2017), with overall forest landscape integrity also declining such that now only ~40% of forest area has high landscape integrity (Grantham et al., 2020). Moreover, just 27% of high-integrity forestland is designated as protected and, within the protected areas, slightly more than half of forestlands are considered high integrity (Grantham et al., 2020). Therefore, there is a pressing need to conserve the remaining large tracts of forest with high landscape integrity. There was extensive industrial logging in parts of southeastern Alaska during the second half of the twentieth century (DellaSala et al., 2022), yet our analysis underscores that the Tongass and Chugach NFs still have exceptionally large and intact forests compared to other NFs. Nevertheless, most NFs (83%) have at least some high integrity forests. Future analyses could identify conservation priorities within individual NFs by determining where contiguous tracts of intact forests occur using existing spatial data sets (e.g., Grantham et al., 2020).

4.2. Forest Carbon

Alaska's coastal rainforests have accumulated vast amounts of carbon for hundreds to thousands of years, keeping it out of the atmosphere (Smith et al., 2019). Drawing on a satellite-derived data set (Spawn et al., 2020), our results showed that the Tongass had higher and the Chugach had lower than average biomass density over all NFs. But because of the large area of these two forests, we estimated that the total live tree biomass in the Tongass and Chugach amounted to ~484 Tg C of the ~4,305 Tg C (i.e., 11.3%) found in the National Forest System, with tree biomass carbon stocks on the Tongass ~12 times greater than the Chugach. This is generally consistent with estimates derived from forest inventory data that indicate tree biomass in the broader Alaskan coastal rainforest region stores 464–557 Tg C (Barrett, 2014; Smith et al., 2019; Yatskov et al., 2019; Zhu & McGuire, 2016) and that regional tree biomass carbon stocks account for ~10.7% of the ~4,330 Tg C found in forests in the National Forest System that are managed by the Forest Service (Smith et al., 2019). In these coastal rainforests, live tree biomass comprises ~31% of forest ecosystem carbon stocks, which also includes understory vegetation, snags, woody debris, litter, and especially soil organic matter (Yatskov et al., 2019). Regional forest ecosystem carbon stocks have been estimated at 1,385 based on inventory data across nine NFs in Alaska (Smith et al., 2019), while a recent query of the FIA data shows 783 Tg C for Tongass and 154 Tg C for Chugach, 937 Tg C total, which is closer to Smith et al. (2019). However, the forest ecosystem carbon stocks in the Tongass alone have been estimated at 2,679–2,800 Tg C (DellaSala et al., 2022; Leighty et al., 2006). Our analysis further underscores that Alaska's coastal rainforests, particularly the Tongass, are a carbon reservoir of national importance that should be protected to help mitigate climate change. Nevertheless, discrepancies in regional carbon stock estimates emphasize that additional efforts are needed to improve understanding of current forest ecosystem carbon stocks across the region.

Estimates of annual net C accumulation for the Tongass and Chugach National Forests are becoming available as repeated forest inventories expand in these areas. A recent report by Domke et al. (2023) estimates that the annual net change in C stocks for these two forests is about 4 Mg CO_2/yr. Converting to CO_2 density, this represents 1.3 Mg CO_2/ha/yr or nearly twice the average for all FS national forests combined (Table 2). Several regions in the Western U.S. are losing C stocks because of increases in natural disturbances, but this is not the case for southern Alaska public forests which are protected from fire and drought by ample rainfall. The net annual accumulation of CO_2 in the two Alaska national forests is about half the average for private forest lands in the U.S. of 2.7 Mg CO_2/ha/yr, most of which occurs in Eastern regenerating forests (Domke et al., 2023). Thus, besides the value of protecting the vast accumulated C stocks in southern Alaska, these forests are also accumulating additional CO_2 each year and do not appear to be affected by increasing threats to the long-term sustainability of this accumulation rate. Some proposed policies advocate conversion of older forests with large C stocks to younger and faster growing forests rather than letting them grow, but this argument ignores the huge C debt that must be covered before there would be any net additional C accumulation because it would take many decades to centuries to re-stock the C emissions from harvesting mature and old-growth forests (Birdsey et al., 2023; Harmon et al., 1990; Law et al., 2021).

4.3. Forest Wildlife Habitat

Our analysis showed the Tongass and Chugach NFs provide important habitat for bald eagles, brown bears, and wolves. These keystone species used to occur widely in northern North America but have been extirpated from much of their historical ranges. Historically, bald eagles occurred throughout the contiguous United States and Alaska (Buehler, 2000). Brown bears were native to the western half of North America, and those in California and Mexico are extinct (Haroldson et al., 2022). The historical range of gray wolves was coast to coast and north of 20° latitude over North America—they are second only to humans in adapting to climate extremes (Laliberte & Ripple, 2004).

The Tongass and Chugach forests have relatively abundant populations of animals that have become uncommon in other parts of the U.S. Alaska has over 98% of the US brown bear population, and the largest North American breeding populations of bald eagles are in Alaska and Canada. Gray wolf distribution covers about 85% of Alaska (total 7,000–11,000 wolves), with the highest densities in the Southeast. However, brown bears, and gray wolf have been impacted by hunting and predator control programs that reduced their numbers, leading to local declines and extirpations (Crupi et al., 2017; Ripple et al., 2019).

There are three species of special concern in the coastal forests of southern Alaska: The Alexander Archipelago wolf (*Canis lupus ligoni*), the marbled murrelet (*Brachyramphus marmoratus*), and the yellow cedar (*Callitropsis nootkatensis*). The Alexander Archipelago wolf is a subspecies of the gray wolf that is found in the coastal rainforests of Alaska and British Columbia (Schoen et al., 2014). These wolves have been impacted by logging as they rely heavily on old-growth forests for their habitat, cover, den sites, and prey (Gilbert et al., 2022). The marbled murrelet is a small seabird that nests in old-growth forests along the coast of Alaska and the Pacific Northwest. These birds are particularly vulnerable to habitat loss because they rely on mature trees for nesting sites (Carter et al., 2009; Piatt & Naslund, 1995). The logging of old-growth forest in coastal Alaska has led to a decline in the marbled murrelet population. Yellow cedar in the coastal rainforests of southeast Alaska has been listed as a species of concern under the Endangered Species Act, with population declines due to logging and climate change (Hennon et al., 2018).

In the Tongass, five species of salmon with a diversity of spawning periods provide food for a high concentration of bears, eagles, and other animals over a prolonged period each year. Brown bears are the dominant predator of salmon (Levi et al., 2015). Wolves in the region obtain about 20% of their diet from actively fishing salmon, which appears to contribute to the high survival rate of pups (90% compared with 50% in Minnesota). Where other prey is low, wolves are extremely reliant on a marine diet compared to coastal bears (Szepanski et al., 1999). After spawning, the salmon carcasses provide nutrients for forests.

Extinction risk is most acute for the largest and smallest vertebrates, and the largest vertebrates, for example, bears, are most vulnerable to direct killing by humans (Ripple et al., 2019). Thus, stronger protections and reduction of harvest of both trees and animals will give them a better chance of survival and resilience to the dual crises of climate change and biodiversity loss.

4.4. Climate and Wildfire Risk

We found the Tongass and Chugach historically had the highest annual precipitation and lowest maximum temperature of all NFs, as well as the largest projected increases in annual precipitation and among the lowest projected increases in maximum temperature over the coming century. The cool, wet conditions contribute to there being little wildfire activity in the region, with future increases in wildfires likely mitigated by increases in annual precipitation.

While much attention has been paid to climate change in northern Alaska, southern Alaska is expected to experience changes that are moderate by comparison. For example, temperature extremes in southeast Alaska are expected to be small compared to the rest of Alaska (Gray et al., 2018; Lader et al., 2022), and the length of warm and dry spells is not expected to change much. Nevertheless, climate risks for forests in southern Alaska include increased frequency and severity of forest disturbances and changes in hydrology. Such risks can affect forest sustainability and resilience both inside and outside protected areas and lead to shifts in suitable habitat boundaries for vegetation and wildlife communities (Shanley et al., 2015). For example, heavy rains and flooding are expected over coastal areas, as well as warmer water temperatures and warmer springs that have impacted

Alaska yellow cedar (Hennon et al., 2018). Yet projected warmer and wetter climate in southern Alaska probably will not destabilize forest carbon and biodiversity as much as in other NFs that are expected to become hotter and drier (Buotte et al., 2019; Law et al., 2021).

Ecosystem model simulations with climate projections indicated that this cool region with low forest fire risk is expected to remain a stable carbon sink or even increase in the future due to climate change (McGuire et al., 2018; Zhu & McGuire, 2016). Simulations under scenarios of climate change for southeast and south-central regions show that if these forests are allowed to grow without harvest, forest carbon could increase by 27% by 2100 (Zhu & McGuire, 2016). Furthermore, climate change could increase the importance of protection in this region since species may disproportionately favor protected areas as their ranges shift poleward and appropriate management could slow climate-related declines (Thomas & Gillingham, 2015).

4.5. Forest Protection in Southern Alaska

We found that about 35.5% of the Tongass and 57.6% of the Chugach are preserved at GAP 1 or 2 levels of protection that meet IUCN standards for conservation. Much of the Chugach has been inventoried as roadless, but is still classified as GAP 3 status, meaning that multiple use management that may involve logging is still the priority in this forest. An initial step has been taken to limit timber harvest on a portion of the Tongass through reinstating the roadless rule. The Biden administration finalized the Alaska roadless rule in 2023 that restores roadless protection to more than 36,422 km^2 of the Tongass, keeping it free from road-building and extraction. However, other uses may still be allowed. Our results demonstrate that the priority areas for conservation of landscape-integrity over large areas include the Tongass and Chugach NFs.

4.6. Limitations

Forest inventory plot density is lower in southern Alaska than in the other NFs. Forest Service wilderness areas and interior Alaska have not been inventoried by FIA, but are in progress for inclusion in future inventories (USDA Forest Service, 2023). Observation-based forest carbon mapping combining satellite and field data could be improved and spatially derived using methods such as those of the Landscape Ecology Modeling Mapping and Analysis program (https://lemma.forestry.oregonstate.edu/data). Due to limitations with available spatial data sets, we did not assess carbon stocks in dead standing trees (i.e., snags), woody debris, trees smaller than 10 cm diameter, understory vegetation, or soil.

The analysis of habitat extent that can support apex species under future climate is limited by data availability (Gotthardt et al., 2014). Habitat and species distribution modeling based on the reference data needs improvement. Yet, these are the only consistent spatial data available. Although habitat extent in southern Alaska is likely underestimated, it is by far the largest among NFs. The results provide estimates of areas with the potential for protection of forest carbon and key species, and closer landscape analysis will refine estimates of candidate areas to protect for carbon, plant and animal species and ecological resilience under climate change.

Similarly, the ability to map human modification in Alaska is limited by data and accuracy issues, as well as pressures that are often unmapped because they differ from those experienced in lower latitudes (Reynolds et al., 2018). These unmapped pressures mean that forest integrity could be overestimated for some of these forests. Yet, these forests are experiencing tremendous pressures that demand additional protection (Trammell et al., 2022).

4.7. Policy and Management Implications

A recent United Nations proposal calls for national parks, marine sanctuaries and other protected areas to cover nearly one-third or more of the planet by 2030 as part of an effort to stop a sixth mass extinction and slow global warming (IUCN, 2021). Climate change and biodiversity loss are closely interconnected by human actions such that policies should simultaneously address synergies between mitigating climate change and biodiversity loss to maximize co-benefits (Pandit et al., 2021). NbCSs can be most effective when planning for longevity of carbon storage rather than rapid carbon sequestration. Avoiding and reversing the loss and degradation of carbon- and species-rich ecosystems of land and waters is of highest importance for combined biodiversity protection and climate change mitigation actions with large adaptation co-benefits.

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Key strategies emerging for mitigating climate change and preventing biodiversity losses include:

1. Establish national strategic reserves that protect existing mature and old forests from resource extraction, and expand wilderness areas. Forests with medium to high carbon density also tend to have high critical habitat and genetic diversity (Buotte et al., 2020; Dinerstein et al., 2020; Law et al., 2021).
2. Resilience-building strategies that address elements of biodiversity (preventing extinctions, ecoregion diversity) and facilitate animal movement by connectivity of protected areas, and new and expanded protected areas.
3. Implement measurement, reporting and verification from local to national levels that are consistent and meet international standards for tracking progress in protecting forest carbon and biodiversity.

Governments must establish and achieve NbCS targets in the Nationally Determined Contributions to meet Paris Agreement goals (Dinerstein et al., 2020; Griscom et al., 2017). Currently, there is a large gap between pledges and desired outcomes (UNEP, 2022). In the U.S., more public lands have been opened up for resource extraction since 2020 compared to the previous years while at the same time pledges were made to protect 30% of lands and waters by 2030. President Biden's Executive Order 14008 is a call to action to work together with stakeholders to conserve, connect and restore 30% of U.S. lands and waters by 2030 (White House, 2021). The Tongass is the ancestral homeland of the Tlingit and Haida Peoples, who developed a climate adaptation plan with stakeholders that identifies potential impacts on tree and vertebrate species and actions to increase resilience. Collaboration and consistency with national and international climate and conservation goals will be essential.

Area-based preservation must contribute more effectively to meeting international goals that aim to protect elements of biodiversity, including preventing the accelerating extinctions and protecting the remaining intact forests as well as mature and old forests from extractions.

An integrated climate-biodiversity agenda is gaining momentum at multiple levels. We propose Strategic Forest Reserves for permanent protection of forest carbon and biodiversity at the highest levels (GAP 1 and 2, IUCN categories I–VI) to support targets that protect 30% of the area by 2030 and 50% by 2050. We found that southern Alaska's forests have high landscape integrity, carbon stocks and habitat availability for key species, and should be protected on federal lands before irreversible losses of these forests continue (Goldstein et al., 2020). The Tongass and Chugach have 30% of the forest area protected at GAP 1 or 2. Although the Chugach has no area protected at the GAP 1 level, this could be improved by transitioning current areas with less protection to GAP 1. It is possible to elevate the preservation status of GAP 3 areas on federal lands by phasing out grazing, mining, and logging and strengthening protection by administrative rule. Inventoried Roadless Areas are key GAP 3 areas that have already been identified and are available for permanent protection. Making good on our national and international pledges will determine whether resilience and climate stability can provide life support for future generations on Earth.

Conflict of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Data Availability Statement

All custom scripts written for the analysis are publicly available through GitHub (https://github.com/ecospatial-services/seak_preservation). Furthermore, all datasets used in this study are publicly available through online repositories. The National Forest Systems Land Unit dataset is available from https://data.fs.usda.gov/geodata/edw/datasets.php. The tree canopy cover dataset is available from https://glad.umd.edu/dataset/global-2010-tree-cover-30-m. The forest landscape integrity dataset is available from https://www.forestintegrity.com/. The forest carbon stock dataset is available from https://daac.ornl.gov/VEGETATION/guides/Global_Maps_C_Density_2010.html. The MODIS burned area data are available through Google Earth Engine https://code.earthengine.google.com/. The Protected Area Database of the US (version 3.0) is available from https://www.usgs.gov/programs/gap-analysis-project/science/pad-us-data-download. The species habitat datasets are available for the Continental US from https://gapanalysis.usgs.gov/apps/species-data-download and for Alaska http://akgap.uaa.alaska.edu/species-data. The CHELSA-BIOCLIM + climate dataset is available from https://www.envidat.ch/#/metadata/bioclim_plus.

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