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# The Tongass National Forest, Southeast Alaska, USA: A Natural Climate Solution of Global Significance

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**Abstract:** The 6.7 M ha Tongass National Forest in southeast Alaska, USA, supports a world-class salmon fishery, is one of the world's most intact temperate rainforests, and is recognized for exceptional levels of carbon stored in woody biomass. We quantified biomass and soil organic carbon (C) by land use designation, Inventoried Roadless Areas (IRAs), young and productive old-growth forests (POGs), and 77 priority watersheds. We used published timber harvest volumes (roundwood) to estimate C stock change across five time periods from early historical (1909–1951) through future (2022–2100). Total soil organic and woody biomass C in the Tongass was 2.7 Pg, representing ~20% of the total forest C stock in the entire national forest system, the equivalent of 1.5 times the 2019 US greenhouse gas emissions. IRAs account for just over half the C, with 48% stored in POGs. Nearly 15% of all C is within T77 watersheds, >80% of which overlaps with IRAs, with half of that overlapping with POGs. Young growth accounted for only ~5% of the total C stock. Nearly two centuries of historical and projected logging would release an estimated 69.5 Mt $CO_2$e, equivalent to the cumulative emissions of ~15 million vehicles. Previously logged forests within IRAs should be allowed to recover carbon stock via proforestation. Tongass old growth, IRAs, and priority watersheds deserve stepped-up protection as natural climate solutions.

**Keywords:** carbon emissions; carbon stores; inventoried roadless areas; old-growth forest; southeast Alaska; temperate rainforest; Tongass National Forest; natural climate solutions



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## 1. Introduction

The 6.7 M ha Tongass National Forest (TNF) in southeast Alaska, USA, is the largest national forest managed by the USDA Forest Service in the 77.2 M ha national forest system. The region's productive old-growth forests (POGs; wood standing volume >46.6 $m^3$/ha; forests ≥150 years old) [1,2] contain far more old growth than any other national forest, providing opportune settings for large-landscape conservation in one of the world's most relatively intact temperate rainforests [2,3]. The TNF also has been the focus of logging debates for decades with pro-conservation presidential administrations enacting forest protections and pro-development ones allowing increased timber removals. Under President Bill Clinton, the National Roadless Conservation Rule of 2001 [4] protected from development 23.4 M ha of federally Inventoried Roadless Areas (IRAs ≥ 2000 ha) across the entire national forest system, 3.7 M ha of which was in the TNF, the largest such expanse. Roadless areas tend to have higher levels of biodiversity and intact ecosystem services than logged and roaded areas [5–7].

To date, there have been 14 legal attempts to overturn roadless protections as they apply to the Tongass; none have invalidated the conservation rule in appellate courts (e.g., https://earthjustice.org/features/timeline-of-the-roadless-rule; accessed on 15 April 2022). However, both the George W. Bush and Donald Trump administrations used executive powers to roll back roadless protections on the Tongass in favor of old growth logging and development. The Joe Biden administration is set to "repeal or replace" the Trump reversal [8], and thus it is imperative that roadless values are well documented, particularly as conservation outcomes are ostensibly tied to political parties changing hands.

Industrial-scale POG logging began ramping up on the Tongass with passage of the Tongass Timber Act of 1947 that authorized two federally subsidized fifty-year pulp contracts [9]. The contracts expired in 2000 and, in 2016, the Barack Obama administration amended the Tongass Land Management Plan (TLMP) of 2008 with the intent to transition logging out of POGs and into suitable young-growth forests (previously logged, naturally reforested, and now commercially viable) [10]. Professional fish and wildlife societies and many scientists have repeatedly called for stepped-up protections for all POGs and IRAs on the TNF (e.g., https://conbio.org/policy/scb-and-other-science-societies-call-on-president-obama-to-save-tongass-rai; accessed on 12 February 2022). Conservation groups also have proposed 77 priority watersheds for salmon and wildlife known as the "Salmon Forest Proposal" or the "Tongass 77" (herein T77) [11]. Notably, POG logging was prohibited within the T77 under the 2016 TLMP transition amendment; however, that too was reversed by the Trump administration shortly thereafter. On 15 July 2021, the Biden administration announced plans to end all "large-scale old-growth logging" on the TNF, thereby providing de facto protections once again for most POGs, IRAs, and T77 priority areas while restarting the transition to timber harvests focused on young growth (https://www.whitehouse.gov/briefing-room/presidential-actions/2021/01/27/executive-order-on-tackling-the-climate-crisis-at-home-and-abroad/; accessed on 12 April 2022). Some small-scale POG logging would be permitted in transition.

Carbon (C) stocks have been quantified previously on the TNF [12] and recognized as nationally significant by USDA Forest Service researchers [13–15] and in congressional policy reviews [16]. However, the USDA Forest Service has undervalued the C stock importance of the TNF by routinely dismissing stock change from logging as inconsequential to total US greenhouse gases (GHGs) [10,17]. Further, the agency believes that logging emissions are simply offset by the storage of C in harvested wood product (HWP) pools and natural reforestation [10,17,18]. The significance of the region to the development of US forest policy around natural climate solutions demands that spatially explicit data on Tongass carbon stocks be updated and an assessment of stock change be attributable to historical, contemporary, and anticipated logging levels.

It follows that our objectives are to: (1) quantify current biomass and soil carbon stocks within land cover (POG, young growth) and land use categories (IRAs, T77 watersheds); and (2) estimate C emissions spanning ~2 centuries of logging on the TNF. Our analysis is key to shedding light on the importance of IRA protections and policy options for both old growth and young-growth forests. Given the national significance of C stocks on the TNF [12], managing forests to maximize C stock potential would demonstrate the US has made a forest-based nationally determined contribution (NDC) to the Paris Climate Agreement. Article 5.1 of the agreement recognizes the need for countries to take specific actions that conserve and enhance nature-based solutions as C sinks and reservoirs [19].

## 2. Methods

### *2.1. Study Area*

The TNF in southeast Alaska is within the North Pacific Coastal Forest bioregion, which includes several WWF Global 200 ecoregions. At a finer scale, the Tongass also spans the perhumid temperate rainforest climate subzone [20], recognized as globally unique [2,3] (Figure 1). Temperate rainforests are distributed on the Alaskan mainland juxtaposed against the windward edge of the Coast Mountains, separating Alaska from British Columbia. Rainforests are scattered across an archipelago of thousands of islands from the Dixon Entrance (54° N) northward to Yakutat Bay (just north of Glacier Bay, 59° N), a distance of 835 km that includes 30,000 km of shoreline [3]. Interspersed are tree-stunted muskegs, tidewater glaciers, and deeply dissected fjords. Approximately 20% of the TNF is non-forested [10]. Importantly, about 90% of temperate rainforest on the TNF was considered POG in the early 1990s [21], among the largest such concentrations of temperate rainforests [3]. However, only 3% of forested areas include the largest old-growth trees (highest timber volumes) due to high-grade logging prior to the 1990s [1]. "Unproductive" old growth also occurs mostly in muskegs having no commercial timber value [10].


**Figure 1.** Study area (dark gray), defined as land managed by the United States Department of Agriculture Forest Service within the administrative boundary of the Tongass National Forest, southeast Alaska, and the spatial distribution of young-growth forest (light green) and productive old-growth forest (dark green).

The Koppen Climate Classification subtype for the southeast Alaska region of our study area is "Dfc" (Continental Subarctic Climate). Mean precipitation during the winter is 642 mm (125 mm to 1473 mm range) and mean temperature in the summer is 12.5 °C (9.9° to 17.9 °C range), which is on the wetter, cooler side of temperate rainforests globally [3].

Due to the northern latitude and short growing seasons, treeline on the TNF is generally 300 m, declining northward. Old-growth forests are characterized by multi-layered forest canopies mainly of western hemlock (*Tsuga heterophylla*), yellow-cedar (*Calliptropsis nootkatensis*), mountain hemlock (*T. mertensiana*), Sitka spruce (*Picea sitchensis*), western red cedar (*Thuja plicata*), and low growing shore pine (*Pinus contorta*) on wetter sites such as muskegs. Rainforest understories are rich in forbs and shrubs [20,21] with dense mats of oceanic lichens and bryophytes that carpet the ground and extend into the overstory canopy.

Prolific salmonid runs include chum (*O. keta*), coho (*O. kisutch*), king (*O. tshawytscha*), pink (*O. gorbuscha*), sockeye (*O. nerka*), and steelhead trout (*O. mykiss*) that support some of the largest concentrations of brown bears (*Ursus arctos*) and bald eagles (*Haliaeetus *leucocephalus*) in the world [2,3]. Notably, old-growth forests and IRAs provide important refugia for salmonids and Sitka-black tailed deer (*Odocolieus hemionus sitkensis*), considered staple food sources for Alaskan tribes [2,3]

The T77 portion of the study area was based on a spatially explicit ranked-analysis performed by Trout Unlimited, the Nature Conservancy, and Audubon Alaska [11] (https://databasin.org/datasets/72977f90d25a4fcf9f455b9017f2a5e2/; accessed on 5 May 2022).

This dataset includes the highest ranked watersheds in 14 biogeograpical provinces on the TNF based on a suite of attributes, including: top-ranked habitat for the six salmonid species; habitat of the marbled murrelet (*Brachyramphus marmoratus*), a federally threatened seabird species that nests in old-growth forests from California to Washington; black bear (*Ursus americanus*) and brown bear summer habitat; Sitka black-tailed deer wintering habitat; and estuaries and riparian areas that have large-tree, old-growth forests [11]. Excluded were watersheds already protected, in non-federal ownership, managed for other values (such as urban recreation, experimental forest, or timber), and lacking public support [11]. T77 watersheds total 764,855 ha (~11% of the TNF land base); however, they have never been analyzed for C stocks.

### 2.2. Timber Sale Datasets

We accessed USDA Forest Service datasets on timber volume sold on the TNF and allocated them into five time periods (bins): (1) early historical (ca 1909–1951) [9]; (2) pulp (1952–2000) [22,23]; (3) post pulp (2001–2015) [9]; (4) transition (2016–2021) [10,24]; and (5) future (2022 projected to the end of century) [10].

Tongass management priorities are based on a zoning process known as Land Use Designations (LUDs). In general, there are 18 LUDs nested within three major groupings (summarized herein). LUD 1 includes strictly protected Wilderness and National Monuments; LUD 2 includes Natural Settings managed for non-motorized recreation, old-growth and watershed protections, and Research Natural Areas; and LUD 3 (Development) is managed mainly for timber and mineral extraction. This is in addition to IRAs that are a separate administrative category that precludes most development.

### 2.3. Carbon Datasets

Our spatially explicit gridded estimates of C density (ca. 2019) in woody plant biomass are derived from a combination of published datasets spanning the study area (Table S1). Researchers [25] combined FIA ground measurements ($n$ > 1000 plots) with environmental covariates (e.g., topography, climate, and disturbance) to calibrate a machine learning algorithm producing lower and upper bound 30 m gridded estimates of C density (metric tons of carbon per hectare, t C ha$^{-1}$). These were grouped by woody biomass pools including live trees, roots, woody debris, seedlings/saplings, snags, and understory vegetation. C density estimates represent potential C storage, which should closely approximate current storage in old-growth ecosystems, but do not account for active or historical removals of C from logging. Thus, we applied pixel-level adjustments to estimate current (ca. 2019) C density in woody plant biomass. This was accomplished using tree cover data [26] to establish a baseline of ca. 2000 forest cover (>25% tree canopy within a 30 m grid cell), which we then used to remove (i.e., set to zero) all non-forested pixels from the ca. 2000 C density layers. Grid cells were also set to zero if they were identified in the tree cover data [26] as having lost forest cover during the 2001–2019 period. The remaining grid cells reflect the lower and upper bound estimates of current C density in all woody biomass pools. As a result of logging activities prior to 2000, these data are expected to overestimate C stock in young-growth forest.

For a small portion of the study region not included in prior work [25], we estimated C density using a multi-step approach. First, we combined the forest cover loss information for the 2001–2019 period [26] with the 30 m map of aboveground live dry woody biomass (AGB) density (ca. 2000) [27] to estimate current (ca. 2019) AGB density. Next, for grid cells in which we had estimates (ca. 2019) of both AGB ([27], modified data) and all woody biomass pools combined [25] (modified data), we computed the ratio of C in AGB to all biomass pools by forest group (using USFS data). Finally, we applied these ratios as a scaling factor—again by forest group—to the grid cells in which we had only estimates of AGB density, thus producing lower and upper bound estimates, as well as pixel-level mean estimates, of C density in all woody biomass pools Tongass-wide.

Soil C stocks were included using recently published data for the region. We used a 90 m gridded estimate of soil organic C for the top 1 m of mineral soil, including surface organic horizons [28]. We extracted the study region, resampled the grid cells to 30 m using a nearest neighbor approach and re-projected the data to the same coordinate reference system as the biomass density layers.

C stock herein refers to the total amount of C within a defined area and is generally displayed in units of millions (M) of metric tons (t) or petagrams (1 Pg = 1 billion t). Additional information on the errors and uncertainties associated with the biomass and soil C data sets incorporated here can be found in [25,26,28].

### *2.4. GIS Overlays*

Several geospatial datasets were used to further characterize C stocks within the study area. First, the administrative boundary of the study area, land ownership information, and IRAs designated by the 2001 Roadless Area Conservation Rule were retrieved from the USFS Geodata Clearinghouse (https://data.fs.usda.gov/geodata/; accessed on 12 April 2022). Forest growth information, including spatially explicit delineations of young growth and POG—also produced by the USFS—were obtained via databasin.org. All GIS layers were acquired as Esri (polygon) shapefiles. Additional geospatial data used to identify scenarios of IRAs at risk from potential forest management plan changes were acquired from The Nature Conservancy and Audubon Alaska (18 September 2019, personal communication, D. Albert). We rasterized, re-projected, and resampled all layers to match the spatial resolution (30 m) and coordinate reference system of the C density estimates. Next, across all layers, areas outside of the study region were masked as No-Data grid cells. Areas of overlap between the young growth and POG layers were allocated to the young growth category. We then used raster-based zonal statistics to quantify the magnitude of C stored in woody biomass and soil organic matter (to a depth of 1 m) inside and outside of the areas defined by the various GIS overlays described above. All geoprocessing, analysis, and visualization were performed using R statistical software (version 3.4, https://www.r-project.org; accessed on 5 May 2020), Python (version 3.6, https://www.python.org; accessed on 5 May 2020), GDAL (version 3.2, https://gdal.org; accessed on 5 May 2020), and Esri ArcGIS Pro (version 2.9, https://www.esri.com; accessed on 5 May 2020).

### *2.5. Evaluating At-Risk IRA and POG Scenarios*

Administrative policy changes on the TNF have mainly centered on IRAs. Therefore, using the GIS methods and spatial data sets described above, we analyzed existing C stocks and thus, the potential loss of these C stocks, as part of three policy scenarios: (1) all IRAs within the 2016 TLMP Development LUDs are vulnerable; (2) only IRAs with POGs within 2016 TLMP Development LUDs are vulnerable; and (3) all IRA POGs within the 2016 TLMP Development LUDs considered suitable for logging are vulnerable based on reversion to the 2008 TLMP plan (which could happen under a pro-development future administration).

### *2.6. Estimating Emissions from Harvested Wood Products*

We estimated $CO_2$ emissions associated with past (1909–2021) and projected (2022–2100) logging for wood product pools (HWP) on the TNF following published methods [29]. Logging for wood products removes C from the forest, transferring it to a series of production phases and end uses. Some fraction of the extracted C (i.e., roundwood) is temporarily stored in wood products (e.g., lumber, plywood, paper, etc.) while they remain in use, followed by eventual disposal and emission to the atmosphere [30]. Determining the climate impacts of HWP typically involves estimating C that is temporarily stored in wood products and in solid waste disposal (SWD) sites. The difference between the amount of C in roundwood removed from the forest and that stored in products and SWD sites at any given time constitutes realized emissions [29,30].

The most common method used to estimate $CO_2$ emissions from HWP is the Production Approach, which tracks C in wood that was harvested in a specified area regardless of where the wood is ultimately consumed. There are several accounting options that guide this calculation [29]. Here, we estimated the amount of C from a given year's logging (annually 1909–2100) that remains stored in end uses and landfills over a subsequent 100-year period [30]. This approach approximates the annual climate impact of withholding C from the atmosphere (i.e., C temporarily stored in HWPs) by a certain amount each year for 100 years as described by a series of decay curves [29]. The 100-year disposition approach facilitates tracking the full temporal impact of harvesting and attribution from the year in which the logging occurs to the year when emissions are ultimately realized (i.e., "seen" by the atmosphere).

Figure S1 illustrates the basic set of calculations used to track C in HWP from forest removal to timber products to primary wood products to end uses and finally to disposal, applying regional estimates for product ratios and half-lives at each stage. Harvest records are used to distribute annual cut volumes among specific timber product classes (e.g., softwood, sawtimber). Timber products are further distributed to specific primary wood products (e.g., softwood lumber, softwood plywood, softwood mill residue used for non-structural panels, etc.) using default average primary product ratios from national level accounting that describe primary products output according to regional forest industry structure [31,32].

We implemented the following multi-step procedure [29] in the R software package: (1) enter roundwood harvest data for the reporting period; (2) allocate harvest to product classes (e.g., sawtimber softwood, pulpwood softwood); (3) estimate the weight of harvested wood using average specific gravities by species group; (4) calculate the weight of harvested C for each harvest year; (5) estimate the 100-year annual disposition of C as fractions of roundwood by product class; (6) calculate C stock changes in the HWP pool and emissions for the inventory period; and (7) calculate annual additions to the HWP pool and associated emissions for the inventory period.

As inputs to this procedure, we used TNF timber harvest records for the period 1909–2021 obtained from USDA Forest Service cut history reports [9]. Harvest projections (2022–2100) were based on the Tongass Forest Plan [10]. We applied the average annual proportions of Alaska region harvests distributed to timber product classes ([33]: Table 3). We established decay rates following disposition patterns contained in the literature ([29]: Table 6-A-5) for the Pacific Northwest-West (PNW-W) region. Other researchers [29] did not include comprehensive (i.e., 100-year) decay functions, but rather included disposition patterns based on a subset of points along the trajectory of each function (i.e., years 1–10 and five-year intervals thereafter beginning in year 15). We estimated decay functions for PNW-W softwood sawlog and pulpwood emissions by fitting asymptotic regression functions to these data (SSasymp) in R.

We note that our results do not reflect total gross emissions from logging; rather, they are limited to the fate of harvested roundwood removed from the forest. Other logging-related emissions, including decay of logging residue, decomposition of litter, and loss of soil organic C were not included. Similarly, the results do not reflect net emissions as they do not consider, for example, C sequestration associated with forest regrowth nor do they account for emissions reductions that might be realized through material substitution, i.e., when wood is substituted for other building materials such as concrete or steel, although wood substitution benefits have been grossly overstated [34].

## 3. Results

### 3.1. Young vs. Productive Old Growth Forests

POGs represent about 30% of the Tongass land base and 92% of the productive forests overall. The balance includes unproductive old growth mainly on muskegs as well as non-forest types (see Figure 1). About 8% of the productive forest on the TNF or 3% of the total land base is in young growth condition, almost exclusively the result of old-growth clearcut logging. POG logging and associated road building has resulted in high levels of localized fragmentation, particularly on Prince of Wales Island (*Taan* in Tlingit), the largest and most productive island in terms of POG in the archipelago (Figure 1).

### 3.2. Timber Volume Sold by Time Period

Annual logging levels throughout the first half of the 20th century (i.e., early historical era) were 243,000 $m^3$ $yr^{-1}$, with the lowest levels recorded in 1909 at 37,000 $m^3$ (Table 1, Table S2). Logging ramped up substantially in the second half of the 20th century (pulp era), averaging ~2 million $m^3$ $yr^{-1}$ and peaking in 1973 at nearly 3.6 million $m^3$, followed by a sharp decline in the late 1990s to <900,000 $m^3$ $yr^{-1}$ (Table 1, Table S2). Between 2001 and 2015 (post pulp era), average logging volume was 230,000 $m^3$ $yr^{-1}$. From 2016 to 2021 (transition), average logging fell to 132,000 $m^3$ $yr^{-1}$, with the lowest level recorded at 71,000 $m^3$ in 2019 (Table 1, Table S2). Projecting forward, annual logging levels are expected to rise to 279,000 $m^3$ $yr^{-1}$ from 2022 to 2031, and then to 595,000 $m^3$ $yr^{-1}$ from 2032 to the end of the century (Table 1, Table S2). Nearly all of the projected harvest volume would come from young-growth forests should the transition to young-growth logging hold.

**Table 1.** Past (1909–2021) and projected (2022–2100) timber harvest levels on the Tongass National Forest by era, including average (thousand cubic meters per year) and total (thousand cubic meters) harvest levels. Projections are based on [10]. See Table S2 for annual harvest data.

| Years | Era | Average Harvest ($1 \times 10^3$ $m^3$ $yr^{-1}$) | Total Harvest ($1 \times 10^3$ $m^3$) |
|---|---|---|---|
| 1909–1951 | Early Historical | 243 | 10,450 |
| 1952–2000 | Pulp | 2041 | 100,018 |
| 2001–2015 | Post Pulp | 230 | 3452 |
| 2016–2021 | Transition | 132 | 789 |
| 2022–2031 | Projections | 279 | 2793 |
| 2032–2100 | Projections | 595 | 41,059 |

### 3.3. Carbon Stocks

Total C stocks on the TNF are approximately 2679 Mt C (or ~2.7 Pg C, Table 2) with C density varying spatially across the region (Figure 2). Nearly half (48%; 1283.3 Mt) of the C is stored in POGs, split nearly evenly between soil (52.7%; 676.5 Mt C) and woody biomass (47.3%; 607.3 Mt C) (Table 2, Figures 3 and S2). Young growth accounts for just 4.8% (128.8 Mt C) of the total C, with nearly all of it (96%; 124.0 Mt C) outside IRAs (Table 2, Figure 3). IRAs account for just over half (51.3%; 1373.7 Mt) of the C, with soil and woody biomass accounting for 61.5% (845.4 Mt C) and 38.5% (528.3 Mt C) of that C, respectively (Table 2, Figures 3 and S3). Nearly 15% (392.9 Mt C) of all C in the study area is within T77 watersheds, with >80% (328.1 Mt C) of that C overlapping with IRAs and half of that (163.7 Mt C) overlapping with POG (Table 2, Figure 3). As anticipated, the C density of woody biomass in POG (293.5 (259–327) t C $ha^{-1}$) is greater than the C density of woody biomass in young-growth forest (281.6 (249–314) t C $ha^{-1}$) (Table 2); however, given the source data used in our analysis [25], C density in young-growth forest is likely overestimated.

**Table 2.** Carbon stocks (million metric tons) in woody plant biomass and soil organic matter by forest age class (productive old growth vs. young growth) inside and outside of Inventoried Roadless Areas (IRAs) and within the T77 watersheds in the Tongass National Forest, southeast Alaska. POG = Productive Old Growth; YG = Young Growth. Values in parentheses indicate ranges (lower and upper bounds). Biomass was scaled [25] to determine lower and upper bounds using the range of ratios between the live trees measured by Forest Inventory Analysis (FIA) plot data and the other C pools (excluding soils) [12]. Soil was not scaled (see [28]), hence the lack of ranges.

| | Area (ha) | Soil (Mt C) | Woody Biomass (Mt C) | Total (Mt C) |
|---|---|---|---|---|
| ***Inside T77 Watersheds*** | | | | |
| **Inside IRAs** | | | | |
| POG | 256,897 | 92.2 | 71.6 (63.2–79.8) | 163.7 (155.4–171.9) |
| YG | 1112 | 0.4 | 0.2 (0.2–0.3) | 0.6 (0.6–0.7) |
| Other | 429,312 | 117.6 | 46.1 (40.7–51.3) | 163.7 (158.3–168.9) |
| Subtotal | 687,321 | 210.2 | 117.9 (104.1–131.3) | 328.1 (314.4–341.5) |
| **Outside IRAs** | | | | |
| POG | 52,143 | 18.8 | 16.1 (14.3–18.0) | 35.0 (33.1–36.8) |
| YG | 20,904 | 8.4 | 6.1 (5.4–6.8) | 14.5 (13.8–15.2) |
| Other | 35,251 | 10.6 | 4.7 (4.2–5.3) | 15.4 (14.8–15.9) |
| Subtotal | 108,298 | 37.8 | 27.0 (23.8–30.1) | 64.8 (61.7–67.9) |
| **Total** | | | | |
| POG | 309,040 | 111.0 | 87.7 (77.5–97.8) | 198.7 (188.5–208.8) |
| YG | 22,015 | 8.8 | 6.3 (5.6–7.0) | 15.1 (14.4–15.9) |
| Other | 464,563 | 128.2 | 50.8 (44.9–56.6) | 179.0 (173.1–184.8) |
| Total | 795,619 | 248.1 | 144.8 (128.0–161.4) | 392.9 (376.0–409.4) |
| ***All Tongass*** | | | | |
| **Inside IRAs** | | | | |
| POG | 1,060,035 | 349.5 | 311.7 (275.5–347.4) | 661.2 (625.0–696.9) |
| YG | 7978 | 2.9 | 1.8 (1.6–2.0) | 4.7 (4.5–5.0) |
| Other | 2,657,417 | 493.0 | 214.8 (189.8–239.3) | 707.8 (682.7–732.3) |
| Subtotal | 3,725,431 | 845.4 | 528.3 (466.9–588.7) | 1373.7 (1312.3–1434.1) |
| **Outside IRAs** | | | | |
| POG | 1,009,308 | 327.0 | 295.6 (261.3–329.5) | 622.6 (588.3–656.5) |
| YG | 178,473 | 73.3 | 50.7 (44.8–56.5) | 124.0 (118.1–129.8) |
| Other | 1,860,951 | 376.8 | 181.6 (160.5–202.3) | 558.4 (537.3–579.2) |
| Subtotal | 3,048,732 | 777.1 | 527.9 (466.6–588.3) | 1305.1 (1243.7–1365.4) |
| **Total** | | | | |
| POG | 2,069,344 | 676.5 | 607.3 (536.8–676.9) | 1283.8 (1213.3–1353.3) |
| YG | 186,451 | 76.3 | 52.5 (46.4–58.5) | 128.8 (122.7–134.8) |
| Other | 4,518,369 | 869.8 | 396.5 (350.2–441.6) | 1266.3 (1220.0–1311.4) |
| Total | 6774,163 | 1622.6 | 1056.3 (933.4–1177.0) | 2678.8 (2556.0–2799.5) |

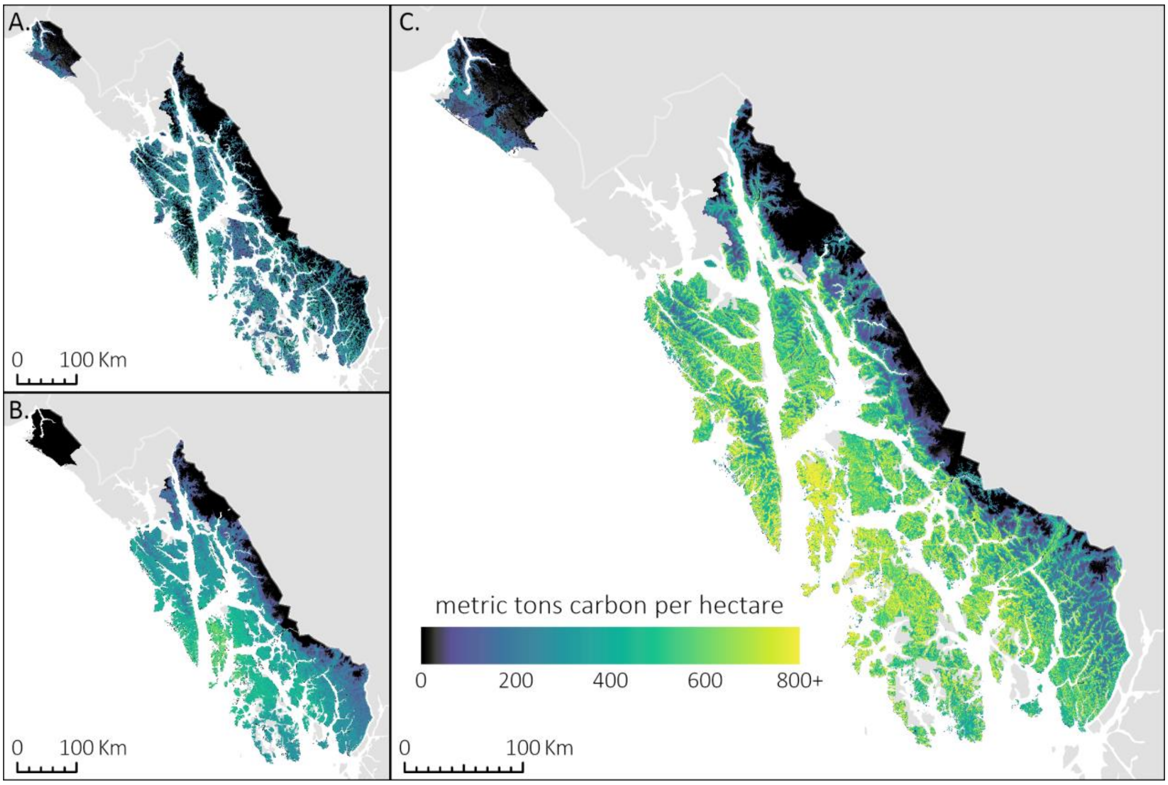


**Figure 2.** Spatial distribution of carbon (metric tons $ha^{-1}$) stored in (**A**) woody plant biomass (carbon pools include trees, roots, woody debris, seedlings/saplings, dead snags, and understory vegetation), (**B**) soil organic matter (top 1 m of mineral soil plus surface organic horizons), and (**C**) the sum of biomass and soil in the Tongass National Forest.

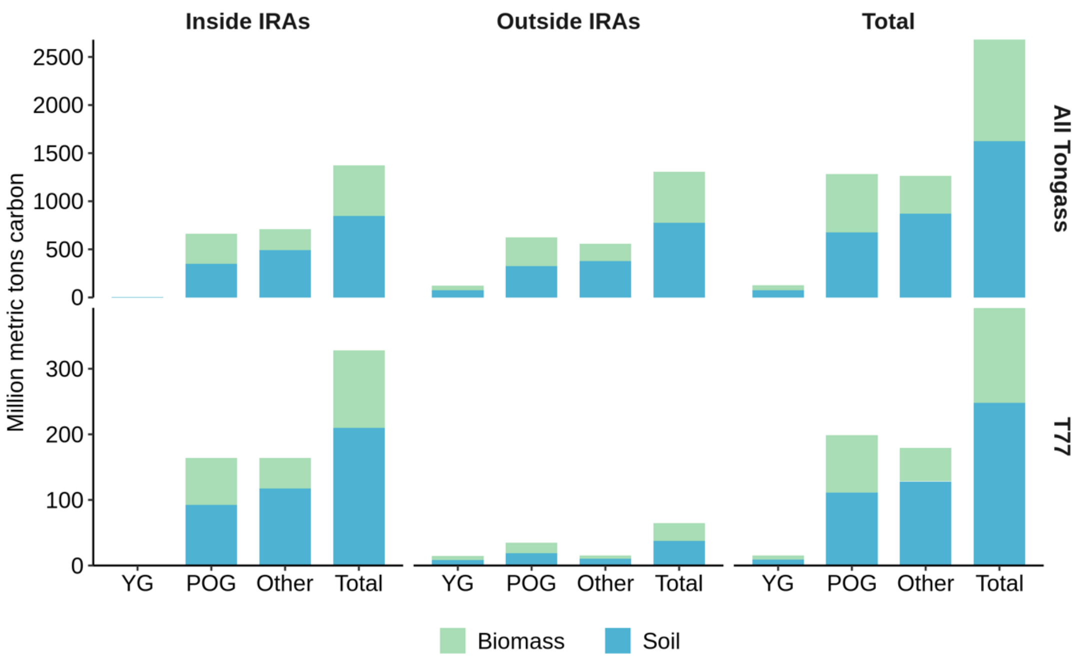


**Figure 3.** Carbon (million metric tons) stored in woody plant biomass and soil by forest age class (YG = young growth; POG = productive old growth) both inside and outside of Inventoried Roadless Areas (IRAs) and inside Tongass 77 watersheds (T77; bottom row) on the Tongass National Forest (top).

### 3.4. At-Risk Scenarios

About 11% of the total IRAs on the TNF are within LUDs that could be developed (Scenario 1, Table 3). Some 40% of the vulnerable IRAs and their C stock contain POG (Scenario 2, Table 3). About half those in at-risk IRAs would be exposed to development under the Trump administration's rollback of roadless protections (Scenario 3, Table 3). Notably, West Chichagof-Yakobi and Prince of Wales Island, along with several smaller islands close to the mainland, show the highest concentration of IRA vulnerabilities to development (Figure 4). Overall, our analysis illustrates the importance of retaining the protective measures of IRAs on the TNF.

**Table 3.** Area (hectares, ha) and carbon stocks (million metric tons) affected by three policy scenarios centered on at-risk inventoried roadless areas. See Section 2.5. for description of scenarios. Note, the areas of these regions are not mutually exclusive and are depicted visually in Figure 4. Values within parentheses are ranges (lower and upper bound). Biomass was scaled [25] to determine lower and upper bounds using the range of ratios between the live trees measured by Forest Inventory Analysis (FIA) plot data and the other C pools (excluding soils) [12]. Soil was not scaled (see [28]), hence the lack of ranges.

| Scenario | Area (ha) | Soil (Mt C) | Woody Biomass (Mt C) | Total (Mt C) |
|---|---|---|---|---|
| 1. | 1,015,701 | 342.6 | 196.8 (173.9–219.3) | 539.4 (516.5–561.9) |
| 2. | 408,808 | 148.1 | 117.5 (103.9–131.0) | 265.6 (252.0–279.1) |
| 3. | 201,483 | 75.3 | 60.6 (53.6–67.6) | 135.9 (128.8–142.8) |

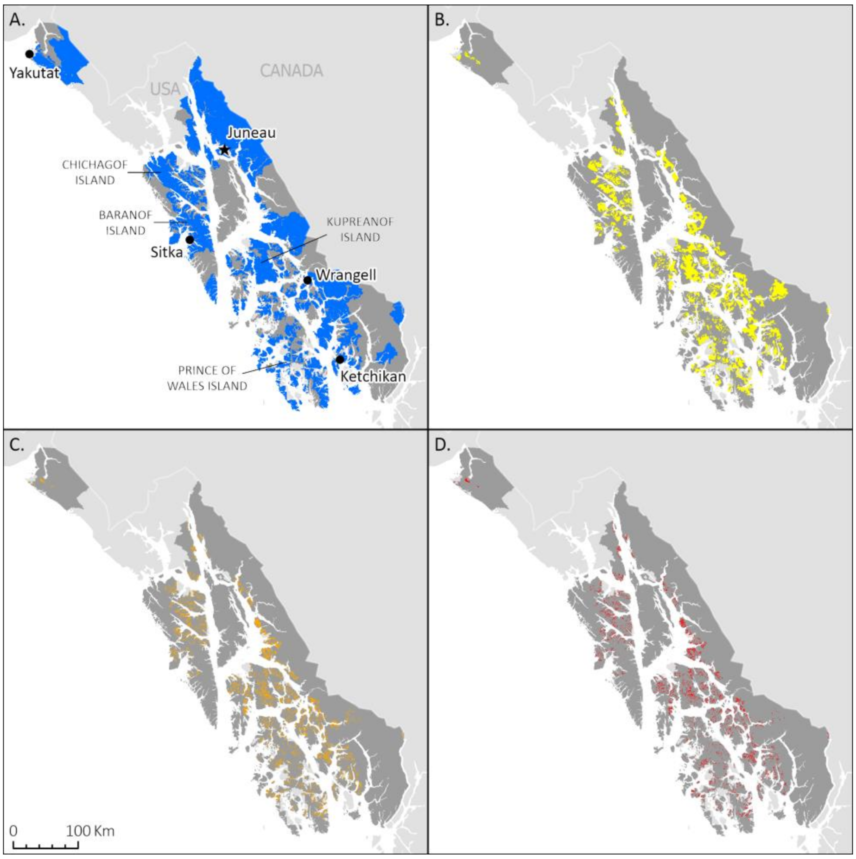


**Figure 4.** Spatial distribution of inventoried roadless areas based on: (**A**) all roadless areas (blue), (**B**) scenario 1 (yellow), (**C**) scenario 2 (orange), and (**D**) scenario 3 (red). Study area shown in gray. See Section 2.5. for description of scenarios.

### 3.5. Estimated Carbon Emissions

Our estimates of committed 100-year carbon dioxide emissions attributable to HWP (1910–2013) exhibit strong agreement with previous estimates [33] for the USFS Alaska Region (Tongass and Chugach National Forests combined; Figure S4). On the TNF, over the period 1909–2100, committed 100-year emissions track annual logging levels, rising sharply from the 1950s and peaking in the 1970s, followed by a decreasing trend into the 21st century (Figure 5). During this period (pulp era, 1952–2000), committed 100-year emissions average >900,000 t $CO_2$ $yr^{-1}$, the most of any period (Table 4). By the transition era (2016–2021), average committed emissions dropped more than 90% to 60,449 t $CO_2$ $yr^{-1}$ (Table 4). With logging levels projected to rise into the future, committed emissions are anticipated to more than double to approximately 128,374 t $CO_2$ $yr^{-1}$ between 2022 and 2031 and then more than double again to 273,492 t $CO_2$ $yr^{-1}$ from 2032 onward (Table 4). Despite the expected increases, projected emissions should remain far below the peak emissions of the 1970s (Figure 5B, Table 4). Following a similar trend, annual realized emissions peaked during the pulp era (1952–2000), averaging >750,000 t $CO_2$ $yr^{-1}$ followed by a drop to <250,000 t $CO_2$ $yr^{-1}$ by the present day (Figure 5B, Table 4). Cumulative realized emissions show the fastest increase during the second half of the 20th century (Figure 5B), and over the full period of the analysis (1909–2100), we estimated 69.5 Mt $CO_2$ of cumulative emissions from HWP (Table S2).

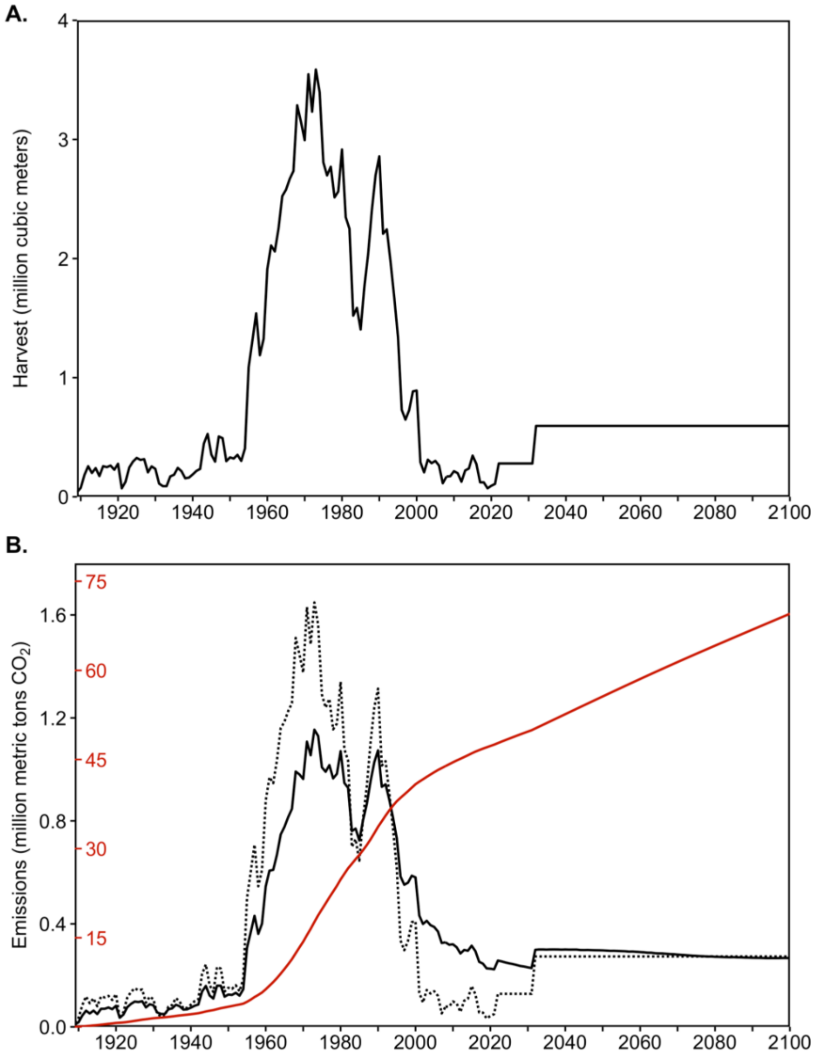


**Figure 5.** (**A**) Historic (1909–2021) and projected (2022–2100) annual harvest volumes (million cubic meters) for the Tongass National Forest. (**B**) Estimated 100-yr emissions from harvested wood products

(i.e., based on (**A**)), including annual committed (black dotted line), annual realized (black solid line), and cumulative realized (red line) emissions (million metric tons $CO_2$). Committed emissions reflect the $CO_2$ emissions that are annually committed to reach the atmosphere given the total harvested volume in a given year. Realized emissions model a more temporally realistic disposition of $CO_2$ emissions to the atmosphere following published wood product decay curves (see methods). Cumulative realized emissions track the cumulative sum of annual realized emissions through time.

**Table 4.** Historic (1909–2021) and projected (2022–2100) carbon dioxide emissions from harvested wood products (HWP) on the Tongass National Forest by era. Average (metric tons $CO_2$ per year) and total (million metric tons $CO_2$) annual committed and realized emissions are based on a 100-year HWP disposition period. See Table S2 for all annual-level estimates as well as cumulative realized emissions for the 1909–2100 timeframe.

| Years | Era | Committed 100-Year Emissions | | Realized 100-Year Emissions | |
|---|---|---|---|---|---|
| | | Average ($t\ CO_2\ yr^{-1}$) | Total ($Mt\ CO_2$) | Average ($t\ CO_2\ yr^{-1}$) | Total ($Mt\ CO_2$) |
| 1909–1951 | Early Historical | 111,692 | 4.8 | 81,673 | 3.5 |
| 1952–2000 | Pulp | 938,147 | 46.0 | 761,687 | 37.3 |
| 2001–2015 | Post Pulp | 105,763 | 1.6 | 346,387 | 5.2 |
| 2016–2021 | Transition | 60,449 | 0.4 | 244,912 | 1.5 |
| 2022–2031 | Projections | 128,374 | 1.3 | 242,374 | 2.4 |
| 2032–2100 | Projections | 273,492 | 18.9 | 284,168 | 19.6 |

## 4. Discussion

### *4.1. Timber Volume and Associated Impacts*

Logging on the TNF can be traced back to at least 1909 with timber volume at 37,000 $m^3$; logging remained at relatively low levels of $\leq$243,000 $m^3\ yr^{-1}$ for decades prior to World War II. The relatively low early historical levels were mainly because Alaska was the last old growth timber frontier in the USA and the high cost of access (roads) and shipping logs overseas. However, the onset of the pulp era, and signing of two 50-year contracts in the 1950s, ushered in nearly a 15-fold increase over the early historical period, with a peak in logging volume in 1973 followed by a precipitous decline when the pulp contracts expired in 2000. During peak years, the largest tree POG forests were disproportionately targeted due to high levels of timber volume at the stand level [1]. Timber volumes hit their lowest contemporary levels in 2019, a 50-fold decrease from the 1973 peak. Logging levels are projected to increase ~8-fold from the 2019 low through the end of the century, with most of the volume anticipated from young forests (if the transition to young-growth logging holds). In general, future fluctuations in timber volumes are anticipated under the TLMP transition plan due to a range of factors, including timber demand (e.g., exports vs. domestic), political pressure (presidential administrations), forest plan amendments, and institutional factors related to the time required by the agency to fully transition.

Historical logging on the TNF has come at the expense of primary, old-growth rainforest and intact forest landscapes (roadless areas), which have been replaced by >186,451 ha of production, high road density (>2.6 km/km$^2$), and naturally regenerated monocultures lacking the structural complexity, C storage capacity, and biodiversity of old growth [2,3]. Much of the logging has been concentrated on Prince of Wales Island, the largest island with the most POG in the Alexander Archipelago [35]. Notably, over 8000 km of roads crisscross the TNF, 2400 km (30%) of which are on Prince of Wales Island alone (https://dot.alaska.gov/stwdplng/scenic/byways-pow.shtml, accessed on 11 February 2022). The impacts of road building can extend 1 km on either side of the road, potentially affecting sensitive taxa, water quality, C storage and sequestration among other impacts [6]. Additionally, since 1980, the timber volume sold from the TNF has generated a deficit, with administrative expenses exceeding revenues and sales proceeding regardless due to congressionally subsidized below-cost timber sales at a cost of approximately $1.7 billion (https:

//www.taxpayer.net/energy-natural-resources/cutting-our-losses-tongass-timber-2/, accessed on 11 February 2022). The TNF represents the most expensive timber program in the national forest system mainly because of road construction and maintenance costs in a remote, island-dominated region.

Despite peak logging periods and high-grade logging practices [1], 92% of productive forests on the TNF remain in old growth condition, compared to 8% in young growth (following previous clearcut logging). Earlier studies reported 90% of productive forests were POG based on USDA reports in 1991 [21]. Others [1,35] reported 88% of the entire region of southeast Alaska (state and native Alaskan corporation lands included) was POG at the time. Slight differences in POG estimates are likely due to differences in spatial extent and methods among studies. Nevertheless, the TNF is unique in that most of its forests remain POG, unlike those in the conterminous USA where nearly all old growth was logged long ago and replaced by intensively managed timber lands.

### *4.2. Carbon Stock (Carbon Reservoir)*

Our findings underscore the significance of the C stock on the TNF. Using FIA plot data, researchers [12] reported the total Tongass C stock of 2.8 $\pm$ 0.5 Pg as compared to 2.7 Pg (upper bound 2.8) in our study. The earlier study [12] also noted that the TNF represented 8% of the total C stock in all forests in the conterminous USA. Our figure of 20% compares the Tongass C stock to that of the national forest system [36] rather than all conterminous USA forests [12], showcasing the significance of the TNF among federally managed national forests. The high C stock value of the TNF is particularly noteworthy given that the TNF represents just under 9% of the total area of the national forest system but has a relatively large share (20%) of the national forest C stock. This relative comparison speaks not only to the significance of the TNF as a C reservoir, but also as a region of conservation focus, allowing decision makers to prioritize strategically important natural climate solutions [37,38]. Notably, the 2.7 Pg C stock estimate for the TNF represents a $CO_2e$ of 1.5 times US aggregate GHG emissions in 2019 (https://www.epa.gov/sites/default/files/2021-04/documents/us-ghg-inventory-2021-main-text.pdf?VersionId=uuA7i8WoMDBOc0M4ln8WVXMgn1GkujvD; accessed on 15 April 2022.

In this study and a prior one [12], a substantial amount of the stored C was in the soils. We reported ~53% and 47% of C in soils and woody biomass, respectively, compared to the earlier [12] estimate of 66% and 36% of C in the soil and woody biomass pools. Our findings for IRAs are closer to earlier figures [12], with 62% and 39% of C in soils and biomass, respectively. Differences in C stock estimates likely reflect the datasets used (FIA plots vs. pooled datasets in our study) and perhaps differences in site productivity among sampled areas. Importantly, our study provides a spatially explicit and updated dataset that can be publicly accessed (databasin.org).

It should be noted that we assessed only the C stock value of the TNF. Prior researchers [12] provided an estimate of the annual C sequestration rate of unlogged forests at 0.04–0.33 Tg C $yr^{-1}$, which would build on the C sink potential of the TNF as logging transitions out of the most C rich and biodiverse areas.

### *4.3. Importance of IRAs and Tongass 77 Watersheds*

Inventoried roadless areas have a long history of conservation in the USA, beginning in the 1970s with the RARE I and RARE II (Roadless Area Review and Evaluation) mapping processes used for making wilderness nominations to Congress [39]. Subsequently, a lot of attention has focused on IRAs, with some areas being designated wilderness, and most others protected administratively (National Roadless Conservation Rule) because of their superior biodiversity values compared to logged areas [5–7].

The TNF is a "hot spot" of IRA values and challenges, representing 16% of the nation's total IRAs and the subject of numerous court cases. While IRA fish and wildlife habitat values have been documented on the TNF [40], our study is the first to quantify the C stock value of IRAs, which contain over half the entire C stock on the TNF. Importantly, the C stock within IRA POGs (and POGs generally) are likely to remain relatively stable compared to the interior of Alaska and the southern extent of the North Pacific coastal temperate rainforest biome subject to more extreme climate change [41–43].

The protection of IRAs also has enjoyed broad public support (>95% of thousands of comments received by the USDA Forest Service have been supportive; https://www.usda.gov/media/press-releases/2021/11/19/usda-announces-steps-restore-roadless-protections-tongass-national; accessed on 14 February 2022) from Alaskan tribes, scientists, conservation groups, and fishing and recreational interests that may benefit economically and culturally (traditional tribal values) from these intact ecosystems if they are fully protected.

The T77 watersheds also contain important POG habitat, but the T77 conservation strategy alone represents far less C savings than IRAs, with only about 15% of the total C stock in T77s, mostly within the T77 POGs. The lower C stock value is likely an artifact of the selection process for the T77, which was weighted toward salmon conservation regardless of the presence of POGs, so long as watersheds were intact (no roads) and productive in terms of salmon. Nevertheless, the T77 watersheds have biodiversity and other values that extend well beyond the C-centric focus of our study [11].

### 4.4. Stock Change Due to Logging

The USDA Forest Service has repeatedly stated that emissions from logging on the TNF are insignificant compared to total US GHGs and thus logging emissions can be summarily dismissed since they are offset by both natural forest regeneration and storage in HWP pools [10,24]. However, offsetting emissions by forest regrowth involves a time lag of at least a century for an equivalent stock of C to be re-sequestered [30]. While forest regeneration on productive Tongass sites proceeds quickly (within a decade), and is from natural seed sources (nearby standing trees), young forests are expected to remain on short logging rotations with harvests planned every 55–70 years on productive sites under the TLMP transition plan. On average, after 100 years, storage in wood products from the PNW, for example, accounts for ~13% of the original C stock with an additional ~29% in landfills [29]. Thus, wood products represent little more than delayed emissions [30]. Additionally, the extensive road network, including log-landings and haul-out sites, mean an unknown amount of the C stock may never be replaced so long as those areas remain treeless.

Our estimates of logging emissions from the TNF are conservative given that they involve the conversion of roundwood in cubic meters to $CO_2$ emissions. Accounting for out-of- boundary emissions in wood processing and log transport is beyond the scope of our study; however, these additional emissions can be substantial given that up to 50% of roundwood logs can be exported over large distances (e.g., to China and Japan) [10].

## 5. Conclusions

As one of the world's last relatively intact temperate rainforests, the TNF provides ecosystem services that are of global significance and warrant expanded conservation. The TNF represents ~12% of the entire Pacific Northwest Coastal Forest bioregion, an expansive rainforest region spanning several globally distinctive ecoregions and climatic subzones from the Coast Redwoods to the northern Kodiak Island archipelago in Alaska, which collectively make up 34% of all the world's temperate rainforests, the largest such concentration [3]. Some 2.1 M ha of the TNF remains as POG, also among the largest such amounts for temperate rainforests [2,3]. The TNF, contains 16% of the nation's IRAs, which, along with the Chugach National Forest to the north, represent the most relatively intact national forest in the national forest system. Its abundant salmon runs (all six *Oncorhynchus* species) and wildlife populations, some of which are imperiled in the lower 48 states, achieve their highest densities in intact watersheds such as the Tongass 77 [11].

Our study builds on the knowledge base of the Tongass' disproportionate values by documenting that some 20% of the entire national forest C stock is remarkably held by this single national forest alone, providing if nothing else a C reservoir of national significant.

Most of the C stock is in POGs, roughly distributed between roaded areas and IRAs. By contrast, only ~5% of the C stock is within young growth and mostly roaded areas.

The maritime climate and intact forests of the TNF have climate refugia properties compared to more extreme climatic zones in the interior of Alaska and temperate rainforests further south [41–43], thereby offering a relatively stable C reservoir. However, due to declining late-season snow cover that prevents late-winter root freezing, yellow-cedar is experiencing a range contraction, and is a climate-sensitive focal species [44]. Importantly, many fish and wildlife species that benefit from IRAs and POGs are the staple foods of Native Alaskans, representing an important bio-cultural connection made possible by the relative intactness of the Tongass rainforest system.

Despite its global recognition, including its near incomparable position among old-growth temperate rainforests, the TNF is a dynamic system where island biogeographic effects have contributed to isolation factors with potentially high species turnover rates [45]. Notably, the cumulative addition of novel anthropogenic fragmentation from expansive roads and clearcuts may result in more consequential isolation of vulnerable species over time, especially on Prince of Wales Island where logging and roads are greatest. For instance, the Alexander Archipelago wolf (*Canis lupus ligoni*) has been repeatedly proposed for listing under the USA Endangered Species Act with the US Fish and Wildlife Service recently determining that listing may be warranted (https://www.fws.gov/alaska/stories/service-completes-initial-review-petition-list-alexander-archipelago-wolf-species-status#:~:text=The%20U.S.%20Fish%20and%20Wildlife,you%20can%20access%20the%20document; accessed on 14 February 2022). Concerns over the status of wolf populations on Prince of Wales Island are mainly due to declining deer populations and hunting pressures [46]. However, the relative intactness of IRAs, POGs, and the T77 offer the best prospects for maintaining viable wildlife populations that are otherwise under combined pressures of climate change and anthropogenic habitat fragmentation.

Our results, coupled with broad scientific and public interest in the TNF as "America's rainforest," provide a foundation for a multi-pronged conservation strategy that includes: (1) protecting all remaining old growth, IRAs, and T77 priority areas from logging as strategic carbon reserves [38]; (2) supporting the transition to logging young-growth forests that by some accounts can already accommodate a full transition without further POG logging [47]; and (3) increasing ecological-based restoration of high road density areas (e.g., road decommissioning). A small portion (7978 ha) of young-growth forest is within IRAs where logging was likely conducted by helicopter. Those areas should be candidates for proforestation [37] to restore carbon stocks over time. Thus, a climate-smart strategy centered on sequestration and accumulation of C is generally essential to addressing the climate crisis [37] and would offer co-benefits, including a host of ecosystem services derived from C dense forests [48] as well as potential climate refugia [41–43].

The TNF is uniquely positioned for large-landscape conservation that protects remaining primary rainforest given that the transition out of old growth logging is taking place before most, if not all, of the primary forests are gone, unlike most nations that only transition when primary forests are liquidated and replaced by industrial forest lands [49]. As the national champion of forest C stocks, federally mandated protection of TNF POGs, IRAs, and T77 areas would offer global leadership on the establishment of land-based targets under the Paris Climate Agreement, while following through on the Glasgow leaders' declaration to end global forest losses by 2030 (which included President Biden) [50].

Notably, Article 5.1 of the Paris Agreement states [19], "Parties should take action to conserve and enhance, as appropriate, sinks and reservoirs of greenhouse gases." Additionally, the Summary for Policy Makers (SPM) of the Working Group II contribution to the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report [51] noted that "safeguarding biodiversity and ecosystems is fundamental to climate resilient development, in light of the threats climate change poses to them and their roles in adaptation and mitigation (very high confidence)." Our results support the inclusion of the Tongass National Forest in a forest carbon reserve system centered on IRAs, POGs, the T77, and a portion of young growth to conserve and enhance the substantial carbon values and resilience potential of the United States.

**Supplementary Materials:** The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/land11050717/s1, Figure S1: Approach to quantifying harvested wood product pools (HWP) storage and emissions; Figure S2: Spatial distribution of total carbon (metric tons $ha^{-1}$) in woody plant biomass and soil in at-risk scenarios for IRAs (inventoried roadless areas): (A) all IRAs, (B) Scenario 1, (C) Scenario 2, and (D) Scenario 3. Figure S3: Spatial distribution of T77 watersheds and total carbon (metric tons $ha^{-1}$) in woody plant biomass and soil pools combined. Figure S4: Committed 100-year emissions from both Tongass and Chugach National Forest timber harvests (1910–2013). Comparison of our study with prior research. Table S1: Carbon datasets used in this study. Table S2: Historic (1909–2021) and projected (2022–2100) harvest levels (thousand cubic meters per year, $1 \times 10^3$ $m^3$ $yr^{-1}$), committed 100-year emissions (thousand metric tons carbon dioxide equivalents per year, $1 \times 10^3$ $tCO_2$ $yr^{-1}$), annual realized emissions ($1 \times 10^3$ $tCO_2$ $yr^{-1}$), and cumulative realized emissions ($1 \times 10^3$ $tCO_2$ $yr^{-1}$) on the Tongass National Forest. All emissions estimates are based on a 100-year HWP disposition period. Supplemental references provided [52].

**Author Contributions:** All authors were involved in writing and approval of this manuscript. D.A.D. was involved in all aspects of the research including conceptualization, methods, formal analysis, investigation, data curation, and writing; W.S.W. was involved in concept development, methods, and writing; S.R.G. was involved in writing, data analysis and visualization, and methods. All authors have read and agreed to the published version of the manuscript.

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## References

1. Albert, D.M.; Schoen, J.W. Use of Historical Logging Patterns to Identify Disproportionately Logged Ecosystems within Temperate Rainforests of Southeastern Alaska. *Conserv. Biol.* **2013**, *27*, 774–784. [CrossRef] [PubMed]
2. Orians, G.; Schoen, J.W. *North Pacific Temperate Rainforests: Ecology and Conservation*; University of Washington Press: Seattle, WA, USA, 2013.
3. DellaSala, D.A.; Moola, F.; Alaback, P.; Paquet, P.C.; Schoen, J.W.; Noss, R.F. Temperate and boreal rainforests of the Pacific Coast of North America. In *Temperate and Boreal Rainforests of the World: Ecology and Conservation*; DellaSala, D.A., Ed.; Island Press: Washington, DC, USA, 2011; pp. 42–81.
4. USDA Forest Service. National Roadless Conservation Rule. *66 Fed. Reg.* **2001**, *3*, 244–248.
5. Strittholt, J.R.; DellaSala, D.A. Importance of roadless areas in biodiversity conservation in forested ecosystems: A case study —Klamath-Siskiyou ecoregion, U.S.A. *Conserv. Biol.* **2001**, *15*, 1742–1754. [CrossRef]
6. Ibisch, P.L.; Hoffmann, M.T.; Kreft, S.; Pe'er, G.; Kati, V.; Biber-Freudenberger, L.; DellaSala, D.A.; Vale, M.M.; Hobson, P.R.; Selva, N. A global map of roadless areas and their conservation status. *Science* **2017**, *354*, 1423–1427. [CrossRef]
7. Dietz, M.S.; Barnett, K.; Belote, R.T.; Aplet, G.H. The importance of U.S. national forest roadless areas for vulnerable wildlife species. *Glob. Ecol. Conserv.* **2021**, *32*, e01943. [CrossRef]
8. Executive Office of the President. Roadless Rule Revision. 2021. Available online: https://www.reginfo.gov/public/do/eAgendaViewRule?pubId=202104&RIN=0596-AD51 (accessed on 5 April 2022).
9. USDA Forest Service. Forest Management Reports and Accomplishments. Cut History 1908 to Present. 2021. Available online: https://www.fs.usda.gov/wps/portal/fsinternet/cs/detail/!ut/p/z1/04_Sj9CPykssy0xPLMnMz0vMAfIjo8zijQwgwNHCwN_DI8zPyBcqYKAfjlVBmA9cQRQx-g1wAEci9eNREIXfHD9KH0CHtDHb4KfR35uqn5BbmhohEGWCQCHVD_f/dz/d5/L2dBISEvZ0FBIS9nQSEh/?position=Not&ss=1110&navtype=&pnavid=160000000000000&navid=160120000000000&cid=fsbdev2_038785 (accessed on 12 April 2022).

10. USDA Forest Service. Tongass National Forest—Land and Resource Management Plan Amendment. 2016. Available online: https://www.fs.usda.gov/Internet/FSE_DOCUMENTS/fseprd527907.pdf (accessed on 12 April 2022).
11. Smith, M.A. (Ed.) Ecological Atlas of Southeast Alaska. Audubon Alaska. 2016. Available online: https://indd.adobe.com/view/bb243dff-5852-44c5-bdf5-4b1be96bdc53 (accessed on 12 April 2022).
12. Leighty, W.W.; Hamburg, S.P.; Caouette, J. Effects of Management on Carbon Sequestration in Forest Biomass in Southeast Alaska. *Ecosystems* **2006**, *9*, 1051–1065. [CrossRef]
13. Barrett, T.M. *Storage and Flux of Carbon in Live Trees, Snags, and Logs in the Chugach and Tongass National Forests*; Gen. Tech. Rep. PNW-GTR-889; U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station: Portland, OR, USA, 2014; 44p.
14. Birdsey, R.A.; Dugan, A.J.; Healey, S.P.; Dante-Wood, K.; Zhang, F.; Mo, G.; Chen, J.M.; Hernandez, A.J.; Raymond, C.L.; McCarter, J. *Assessment of the Influence of Disturbance, Management Activities, and Environmental Factors on Carbon Stocks of U.S. National Forests*; Gen. Tech. Rep. RMRS-GTR-402; U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: Fort Collins, CO, USA, 2019.
15. D'Amore, D.; McGuire, A.D. Forestry as a Natural Climate Solution: The Positive Outcomes of Negative Carbon Emissions. USDA Forest Service PNW Research Station. 2020. Available online: https://www.fs.fed.us/pnw/sciencef/scifi225.pdf (accessed on 12 April 2022).
16. Congressional Research Center (CRS). U.S. Forest Carbon Data: In Brief. Updated 5 May 2020. Prepared for Members and Committees of Congress. 2020. Available online: https://crsreports.congress.gov (accessed on 12 April 2022).
17. USDA Forest Service. Draft Environmental Impact Statement Rulemaking for Alaska Roadless Areas. 2019. Available online: https://www.fs.usda.gov/nfs/11558/www/nepa/109834_FSPLT3_4876629.pdf (accessed on 12 April 2022).
18. USDA Forest Service. Baseline Estimates of Carbon Stocks in Forests and Harvested Wood Products for National Forest System Units. Alaska Region. Climate Change Advisors Office of the Chief. Alaska Region, 34p. 6 March 2015. Available online: https://www.fs.fed.us/climatechange/documents/AlaskaRegionCarbonAssessment.pdf (accessed on 5 April 2022).
19. United Nations. Paris Agreement. 2015. Available online: https://unfccc.int/sites/default/files/english_paris_agreement.pdf (accessed on 5 April 2022).
20. Alaback, P. Biodiversity patterns in relation to climate: The coastal temperate rainforests of North America. In *High-Latitude Rain Forests and Associated Ecosystems of the West Coast of the Americas: Climate, Hydrology, Ecology and Conservation*; Lawford, R., Alaback, P., Fuentes, E.R., Eds.; Ecological Studies 116; Springer: Berlin/Heidelberg, Germany, 1995; pp. 105–133.
21. DellaSala, D.A.; Hagar, J.C.; Engel, K.A.; McComb, W.C.; Fairbanks, R.L.; Campbell, E.G. Effects of silvicultural modifications of temperate rainforest on breeding and wintering bird communities, Prince of Wales Island, Southeast Alaska. *Condor* **1996**, *98*, 706–721. [CrossRef]
22. USDA Forest Service. Tongass National Forest Land Management Plan Revision. 1997. Available online: https://www.fs.usda.gov/detail/tongass/landmanagement/planning/?cid=stelprdb5445359 (accessed on 5 April 2022).
23. Brackley, A.M.; Rojas, T.D.; Haynes, R.W. Timber Products Output and Timber Harvests in Alaska: Projections for 2005-25. Gen. Tech. Rep. PNW-GTR-677. 2006. Available online: https://www.fs.usda.gov/Internet/FSE_DOCUMENTS/fsbdev2_038293.pdf (accessed on 5 April 2022).
24. USDA Forest Service. Cut and Sold (New)—CUTS203F. 2020. Available online: https://www.fs.fed.us/forestmanagement/documents/sold-harvest/reports/2020/2020_Q1-Q4_CandS_R10.pdf (accessed on 12 April 2022).
25. Buma, B.; Thompson, T. Long-term exposure to more frequent disturbances increases baseline carbon in some ecosystems: Mapping and quantifying the disturbance frequency-ecosystem C relationship. *PLoS ONE* **2019**, *14*, e0212526. [CrossRef]
26. Hansen, M.C.; Potapov, P.V.; Moore, R.; Hancher, M.; Turubanova, S.A.; Tyukavina, A.; Thau, D.; Stehman, S.V.; Goetz, S.J.; Loveland, T.R.; et al. High-Resolution Global Maps of 21st-Century Forest Cover Change. *Science* **2013**, *342*, 850–853. [CrossRef]
27. Harris, N.L.; Gibbs, D.A.; Baccini, A.; Birdsey, R.A.; De Bruin, S.; Farina, M.; Fatoyinbo, L.; Hansen, M.C.; Herold, M.; Houghton, R.A.; et al. Global maps of twenty-first century forest carbon fluxes. *Nat. Clim. Chang.* **2021**, *11*, 234–240. [CrossRef]
28. McNicol, G.; Bulmer, C.; D'Amore, D.; Sanborn, P.; Saunders, S.; Giesbrecht, I.; Arriola, S.G.; Bidlack, A.; Butman, D.; Buma, B. Large, climate-sensitive soil carbon stocks mapped with pedology-informed machine learning in the North Pacific coastal temperate rainforest. *Environ. Res. Lett.* **2019**, *14*, 014004. [CrossRef]
29. Hoover, C.M.; Birdsey, R.; Goines, B.; Lahm, P.; Marland, G.; Nowak, D.; Prisley, S.; Reinhardt, E.; Skog, K.; Skole, D.; et al. Chapter 6: Quantifying Greenhouse Gas Sources and Sinks in Managed Forest Systems. In *Quantifying Greenhouse Gas Fluxes in Agriculture and Forestry: Methods for Entity-Scale Inventory*; Eve, M., Pape, D., Flugge, M., Steele, R., Man, D., Riley-Gilbert, M., Biggar, S., Eds.; Technical Bulletin Number 1939; Office of the Chief Economist, US Department of Agriculture: Washington, DC, USA, 2014; 606p.
30. Hudiburg, T.W.; Law, B.E.; Moomaw, W.R.; Harmon, M.E.; Stenzel, J.E. Meeting GHG reduction targets requires accounting for all forest sector emissions. *Environ. Res. Lett.* **2019**, *14*, 095005. [CrossRef]
31. Skog, K.E. Sequestration of carbon in harvested wood products for the United States. *For. Prod. J.* **2008**, *58*, 56–72.
32. Smith, J.E.; Heath, L.S.; Skog, K.E.; Birdsey, R.A. *Methods for Calculating Forest Ecosystem and Harvested Carbon with Standard Estimates for Forest Types of the United States*; US Department of Agriculture, Forest Service, Northern Research Station: Newtown Square, PA, USA, 2006.

33. Loeffler, D.; Anderson, N.; Stockman, K.; Skog, K.; Healey, S.; Jones, J.G.; Morrison, J.; Young, J. *Estimates of Carbon Stored in Harvested Wood Products from United States Forest Service Alaska Region, 1910–2012*; Unpublished Report; U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Forestry Sciences Laboratory: Missoula, MT, USA, 2014; 27p.
34. Harmon, M.E. Have product substitution carbon benefits been overestimated? A sensitivity analysis of key assumptions. *Environ. Res. Lett.* **2019**, *14*, 065008. [CrossRef]
35. Albert, D.; Schoen, J.W. A conservation assessment for the Coastal Forests and Mountains Ecoregion of Southeastern Alaska and the Tongass National Forest. In *Chapter 2, The Coastal Forests and Mountains Ecoregion of Southeastern Alaska and the Tongass National Forest: A Conservation Assessment and Resource Synthesis*; Schoen, J., Dovichin, E., Eds.; The Nature Conservancy: Anchorage, AK, USA, 2007.
36. Smith, J.E.; Domke, G.M.; Nichols, M.C.; Walters, B.F. Carbon stocks and stock change on federal forest lands of the United States. *Ecosphere* **2019**, *10*, e02637. [CrossRef]
37. Moomaw, W.R.; Masino, S.A.; Faison, E.K. Intact forests in the United States: Proforestion mitigates climate change and serves the greatest good. *Front. For. Glob. Chang.* **2019**, *2*, 27. [CrossRef]
38. Law, B.E.; Berner, L.T.; Buotte, P.C.; Mildrexler, D.J.; Ripple, W.J. Strategic forest reserves can protect biodiversity in the western United States and mitigate climate change. *Commun. Earth Environ.* **2021**, *2*, 254. [CrossRef]
39. Turner, T. *Roadless Rules: The Struggle for the Last Wild Forests*; Island Press: Washington, DC, USA, 2009.
40. Albert, D.M. Conservation Significance of Large Inventoried Roadless Areas on the Tongass National Forest. Audubon Alaska. 2019. Available online: https://ak.audubon.org/sites/default/files/2019_consv_significance_of_roadless_12-14-19.pdf (accessed on 12 April 2022).
41. DellaSala, D.A.; Brandt, P.; Koopman, M.; Leonard, J.; Meisch, C.; Herzog, P.; Alaback, P.; Goldstein, M.I.; Jovan, J.; MacKinnon, A.; et al. Climate Change May Trigger Broad Shifts in North America's Pacific Coastal Rainforests. In *Reference Module in Earth Systems and Environmental Sciences*; DellaSala, D.A., Goldstein, M.I., Eds.; Elsevier: Oxford, UK, 2015. [CrossRef]
42. Vynne, C.; Dovichin, E.; Fresco, N.; Dawson, N.; Joshi, A.; Law, B.E.; Lertzman, K.; Rupp, S.; Schmiegelow, F.; Trammell, E.J. The importance of Alaska for climate stabilization, resilience, and biodiversity conservation. *Front. For. Glob. Chang.* **2021**, *4*, 1–17. [CrossRef]
43. Buma, B.; Batllori, E.; Bisbing, S.; Holz, A.; Saunders, S.C.; Bidlack, A.L.; Creutzburg, M.K.; DellaSala, D.A.; Gregovich, D.; Hennon, P.; et al. Emergent freeze and fire disturbance dynamics in temperate rainforests. *Austral Ecol.* **2019**, *44*, 812–826. [CrossRef]
44. Hennon, P.E.; A'more, D.V.; Schabergy, P.G.; Wittwer, D.T.; Shanley, C.S. Shifting climate, altered niche, and a dynamic conservation strategy for yellow-cedar in the North Pacific coastal rainforest. *BioScience* **2012**, *62*, 147–158. [CrossRef]
45. Dawson, N.; MacDonald, S.O.; Cook, J.A. Endemic Mammals of the Alexander Archipelago. Southeast Alaska Conservation Assessment, Chapter 6.7. 2007. Available online: http://www.unm.edu/~{}msbweb/isles/Dawson_et_al%202007%20endemics%20AA.pdf (accessed on 5 April 2022).
46. Schoen, J.; Person, D. Alexander Archipelago Wolf (Canis lupus ligoni). Chapter 6.4. Southeast Alaska Conservation Assessment. 2016. Available online: https://www.conservationgateway.org/ConservationByGeography/NorthAmerica/UnitedStates/alaska/seak/era/cfm/Documents/6.4_Wolf.pdf (accessed on 5 April 2022).
47. DellaSala, D.A.; Furnish, J. Can young-growth forests save the Tongass Rainforest in Southwest Alaska? In *Encyclopedia of the World's Biomes*; Goldstein, M.I., DellaSala, D.A., Eds.; Elsevier: Oxford, UK, 2019. [CrossRef]
48. Brandt, P.; Abson, S.O.; DellaSala, D.A.; Feller, R.; von Wehrden, H. Multifunctionality and biodiversity: Ecosystem services in temperate rainforests of the Pacific Northwest, USA. *Biol. Conserv.* **2014**, *169*, 362–371. [CrossRef]
49. Keenan, R.J.; Reams, G.A.; Achard, F.; de Freitas, J.V.; Grainger, A.; Lindquist, E. Dynamics of global forest area: Results from the Global Forest Resource Assessment 2015. *For. Ecol. Manag.* **2015**, *352*, 9–20. [CrossRef]
50. United Nations Climate Change. Glasgow Leaders' Declaration on Forests and Land Use. UN 2104 Clim. Change Conf. COP26 SEC—Glasg. 2021. Available online: https://ukcop26.org/glasgow2105leaders-declaration-on-forests-and-land-use/ (accessed on 19 April 2022).
51. Intergovernmental Panel on Climate Change (IPCC). Climate Change Impacts, Adaptation, and Vulnerability. 2022. Available online: https://www.ipcc.ch/report/sixth-assessment-report-working-group-ii/ (accessed on 15 April 2022).
52. Stockmann, K.; Anderson, N.; Stockman, K.; Young, J.; Skog, K.; Healey, S.; Morrison, J.; Young, J. *Loeffler. Estimates of Carbon Stored in Harvested Wood Products from United States Forest Service Intermountain Region, 1911–2012*; Unpublished Report; USDA, Forest Service, Rocky Mountain Research Station: Missoula, MT, USA, 2014.