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Estimating carbon stocks and stock changes in Interior Wetbelt forests of British Columbia, Canada

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Abstract

The Interior Wetbelt (IWB) of British Columbia includes the globally rare Inland Temperate Rainforest (ITR) that if managed for its substantial carbon (C) stocks can contribute to Canada's Nationally Determined Commitment under the Paris Climate Agreement. We provide spatially explicit estimates of above- and belowground live and dead biomass and soil C stocks derived from three sources: (1) government online Vegetation Resources Inventory (VRI); (2) the GlobBiomass spatial dataset; and (3) field plots ($n = 27$) within old-growth forests of the ITR. For live aboveground C, we summarize C stocks by elevation classes and decadal forest age. The upper bound on total C densities (above- and belowground live and dead biomass and soil C) based on VRI was a maximum of 806 megagrams (Mg) C ha^{-1}. The mean total biomass C density measured in field plots was 583 Mg C ha^{-1} with a maximum of 1275 Mg C ha^{-1}, which is on par with some of the world's most C-dense temperate forests. About half the C is in live biomass pools with the rest in dead biomass and soil organic C pools. The mean C density from the VRI over all elevations was 182 Mg C ha^{-1}, with soil organic C ~40% and live tree stems ~27%. Vegetation Resources Inventory estimates were 75% lower than field-based measurements with the greatest mismatch in areas with the highest C density. Approximately 22% of the IWB has been logged, the majority since 1970s, resulting in live above ground C declining by at least 18%, although this is likely an underestimate. Logging was heavily concentrated in low (<1000 m; 28.3% of elevation zone) to mid-elevations (1000–2000 m; 20.9%) compared with upper elevations (>2000 m; 1.2%). The region contains underappreciated C stocks that can help Canada meet its climate and conservation targets, but only if there are major forestry reforms that protect C-dense old-growth forests, allow degraded forests time to recover the logging-related C debt, and improve monitoring of C stocks and stock changes.

KEYWORDS

British Columbia, carbon stocks, Inland Temperate Rainforests, Interior Wetbelt, logging, old-growth forests

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INTRODUCTION

Primary forests (unlogged forests of all seral stages) are a global C stock and sink (Keith et al., 2009; Keith et al., 2019; Luyssaert et al., 2008; Mackey et al., 2013) that can play a vital role in climate mitigation policies, including the United Nations' Reduce Emissions from Deforestation and Forest Degradation—REDD+ Programme, Biennial Sessions of the FAO Committee on Forests—COFO24, and Conference of the Parties United Nations Framework on Climate Change—COP24. Article 5 of the Paris Climate Agreement encourages nations to conserve and enhance C sinks and reservoirs (stocks) of greenhouse gases, including forests (UNFCCC, 2016). As interests in nature-based climate solutions gain traction (Griscom et al., 2017; Mackey et al., 2015), it is imperative that countries identify where and how best to manage their forest C reservoirs, particularly old-growth forests (a subset of primary forests) where C is highly concentrated (DellaSala et al., 2020; Mackey et al., 2015; Moomaw et al., 2019), and for C inventory assessments and land-use decision making.

Old-growth forests store up to 50% more C than logged ones (Bois et al., 2009; Fredeen et al., 2005; Keith et al., 2014) and therefore provide a vital ecosystem and climate service (Keith et al., 2009; Luyssaert et al., 2008; Mackey et al., 2015). Hudiburg et al. (2019) found that a century of logging in west coast forests of the United States returned 65% of the C originally stored in the forest to the atmosphere. Offsetting emissions by forest regrowth involves a long lag time for an equivalent stock of C from older forests (in this case hundreds of years) to be resequestered, an unwise proposition during this time of elevated atmospheric carbon dioxide concentration. Additionally, storage in wood products accounts for only 19% of the original stock with some 16% in landfill; the majority (65%–70%) of wood products (e.g., paper and fiberboard) are short-lived (with variable percentages in different systems) (Hudiburg et al., 2019). Thus, in general, logging of old-growth forests creates a net C debt, the size and duration of which depends on amount of C present before logging, intensity of logging at the site and landscape scales, proportion and fate of biomass remaining, proportion of removed biomass transferred to short or long-term wood product pools and their longevity, and sequestration rate of regenerating forests (Harmon, 2019; Hudiburg et al., 2019; Keith et al., 2015). The C debt is exacerbated if forests fail to fully regain tree cover from roads, log landings, and logging slash piles that impede regrowth (Wildlands League, 2020).

From the perspective of assessing climate change mitigation benefits from different forest management systems, wood products have been considered as potential substitution for other sources of products or energy. Such benefits can be quantified in the form of displacement factors as the reduction in emissions achieved per unit of wood used, potentially representing the efficiency of biomass in decreasing emissions (Howard et al., 2021). However, assessing substitution benefits relies on many assumptions related to future supply and demand, markets, technologies, recycling, and energy sources that are all difficult to predict and have been grossly overstated (Harmon, 2019).

Notably, the Interior Wetbelt (IWB) of British Columbia (BC), along the western flanks of the Canadian Rockies and northern Columbia Mountains, is an important northern latitude C reservoir (Matsuzaki et al., 2013), which if protected and properly stewarded can help Canada meet its pledge to protect 30% of lands and waters by 2030 (Nature Canada, 2019). Along the windward slopes and within the wettest biogeoclimatic subzones of the IWB is the Inland Temperate Rainforest (ITR, Coxson et al., 2019; DellaSala et al., 2021; Stevenson et al., 2011), which is one of only three ITRs globally (Russian Far East and Southern Siberia are the other two; DellaSala et al., 2011). The ITR is perhaps the most species-rich lichen temperate rainforest in the world with many lichen species dependent on old-growth forests (Coxson et al., 2019; DellaSala et al., 2021). However, the ITR and the larger IWB forested bioregion have received scant attention in Canada's climate and conservation commitments as cumulative anthropogenic impacts have placed them in endangered and critical ecosystem status, respectively, based on application of the Red-listed Ecosystem Criteria (DellaSala et al., 2021).

A recent analysis of BC government data demonstrated that the oldest forests with the largest trees were logged extensively throughout the province (Price et al., 2021). While 23% of forests in BC remain in old-growth condition, only ~3% is on the highest site index containing the largest trees. Thus, wherever old-growth forests remain they should be a provincial conservation priority (DellaSala et al., 2021; Price et al., 2021). Overall, little is known about the size of the C reservoir in the IWB where substantial amounts of old-growth forest have been logged mostly in the past 50 years (DellaSala et al., 2021; Fredeen et al., 2005; Matsuzaki et al., 2013). This lack of adequate on-the-ground C monitoring raises serious questions about the reliability of C emissions reporting and claims about BC's forests being sustainably managed. Forest C accounting is limited by a lack of comprehensive monitoring, verification of methods, and sufficient data, leading to potential under reporting of the C impacts of industrial logging.

In this study of the IWB, we investigate the C stocks and stock changes within the forest ecosystem, recognizing

that this represents an important part of the whole C system that contributes to potential climate change mitigation. Assessment of the accuracy of even this baseline information about C stocks is lacking for this critical ecosystem type. Thus, our objectives were to: (1) estimate ecosystem C stocks of the IWB forests, with an emphasis on the globally unique ITR, using BC's Vegetation Resources Inventory (VRI, 2018); (2) compare the VRI results with (a) remotely sensed datasets (i.e., GlobBiomass of forest aboveground biomass derived from Earth Observation data, Santoro et al., 2018) and (b) field-based C estimates calculated from plot biomass surveys within old-growth forests in the ITR to assess the reliability of C estimates employing the widely used government dataset; and (3) assess the impacts of historical logging on the area of forest and estimated C stock loss.

METHODS

Study area

Approximately 10.8 million ha (66%) of the 16.46 million ha study area is forested with most (9.43 million ha) of the forest classified as IWB (DellaSala et al., 2021). Within the IWB is the ITR, which totaled ~1.33 million ha (8.1% of the total study area, 14.1% of the IWB forest area) and is mainly distributed above latitude 50°N in disjunct valleys west of the continental divide (Figure 1, DellaSala et al., 2021). Additional areas of ITR occur as isolated valleys in the northern contiguous United States and near 58°N (not in our study area, Coxson et al., 2019; DellaSala et al., 2011). While our C modeling is for the entire IWB bioregion, we emphasized the ITR because of the high C stocks in the old-growth forests (Matsuzaki et al., 2013) and its critical ecosystem status ranking based on the Red-listed Ecosystem Criteria (DellaSala et al., 2021).

The regional climate is seasonally influenced by maritime weather patterns in spring and winter, shifting to continental air masses in summer (Coxson et al., 2019; Stevenson et al., 2011). Mean temperature in the warmest quarter is 13.5°C and annual precipitation averages ~1000 mm, with the highest amounts in the northern IWB (DellaSala et al., 2011).

Interior Wetbelt forests are dominated by western red cedar (*Thuja plicata*) and western hemlock (*Tsuga heterophylla*) at low- to mid-elevations (up to 1000 m north and 1800 m south) grading to Engelmann spruce (*Picea englemanni*) and subalpine fir (*Abies lasiocarpa*) at upper elevations (≥2000 m). Drought-tolerant Rocky Mountain Douglas-fir (*Pseudotsuga menziesii*, var. *glauca*), western larch (*Larix occidentalis*), and ponderosa pine (*Pinus ponderosa*) occupy drier sites to the south and west (Coxson et al., 2019). The ITR is dominated by western red cedar and western hemlock (Meidinger & Pojar, 1991) with the wettest areas (seeps) along toe-slopes that support exceptionally long-lived (>1600 years) red cedars (Stevenson et al., 2011). Radio C-dating in the ITR indicates the mean fire return interval was 800–1200 years with a median of 467 years (Sanborn et al., 2006). Therefore, we assume that the vast majority of ITR forests were old growth prior to logging. Periodic epizootic outbreaks (e.g., hemlock looper) and wind/ice storms (Burton & Boulanger, 2018; Coxson et al., 2019; Stevenson et al., 2011) are natural disturbance processes within the ITR that may invalidate this assumption in places; however, these disturbances are generally of lower severity and extent than wildfires (Sanborn et al., 2006).

Carbon estimates using VRI data

We structured our estimate of C by pool based on the BC's VRI Data Standards (2018) and C pools commonly used in C accounting. Vegetation Resources Inventory is a photo-based, two-phased vegetation inventory design consisting of photo interpretation plots (2 km^2) followed by ground sampling at provincial scales for crown land, private, forest woodlots, tree farms, and community watersheds. Stand volumes are estimated using basal area and trees per hectare supplied by photo interpreters using species and biogeoclimatic zone-specific equations (Kozak, 1994). Stands of like age and composition are delineated into spatially explicit polygons using multispectral photo interpretations. Species composition, tree height and age, basal area, and trees per hectare are used in conjunction with growth and yield coefficients (Lambert et al., 2005; Ung et al., 2008) to estimate volume and aboveground biomass (Kivari et al., 2011). In general, VRI employs forest C calculation techniques consistent with the Canadian Forest Service Carbon Budget Model (CBM-CFS3; Natural Resources Canada, 2020). All data sources and calculations for C pools are described in Appendix S1: Table S1 and are available online (Ministry of Forests, Lands, Natural Resource Operations and Rural Development Forest Analysis and Inventory Branch, 2020).

Vegetation Resources Inventory reporting units are polygons attributed with stand structural information in similar forest types ranging from 0.5 to 500 ha. For our analysis, we used a regular 250- by 250-m grid. The grid was overlaid onto the VRI reporting units, and for each grid cell, the value assigned to the polygon under the cell center was assigned to the grid cell. Cells for which there are no VRI data were excluded from analyses and are not depicted in C maps. Situations where VRI data are missing include some private lands, exclusive tree farm

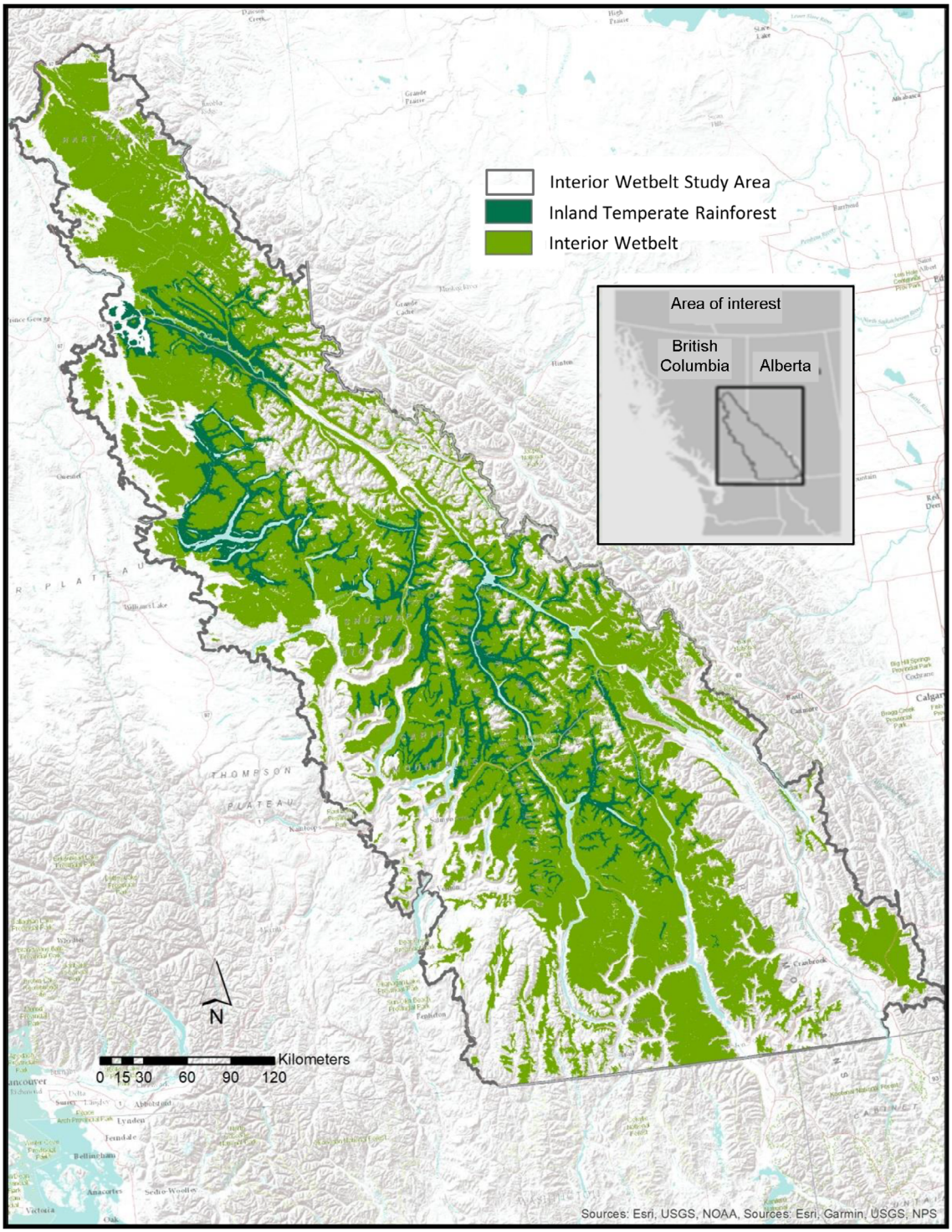

FIGURE 1 Interior Wetbelt (IWB) study area of British Columbia, Canada, showing general landform features and the notable Inland Temperate Rainforest (ITR). Figure archived on https://databasin.org/datasets/5ed2062988e741f38922fd924ed07a54/

licenses, and some steep topography. Soil C values for this study were obtained from a global soil organic C database (Global Soil Partnership, 2017) to provide an estimate of the contribution of the soil pool to the total ecosystem C stock.

Carbon stock by elevation

We partitioned live aboveground C into three elevation zones: low (0 to <1000 m, 23% of study area), mid (1000–2000 m, 62%), and high (>2000 m, 15%) (Figure 2).

Notably, the C stock refers to the total amount of C within a defined area, such as an elevation zone, and generally displayed with units of teragrams (Tg; 1 million megagrams [Mg]). We distinguish the stock from the C density that refers to the quantity of C per unit area, with units of Mg of C ha^{-1}. This distinction is useful when considering the spatial distribution of C that is then aggregated over a defined area.

We calculated the differences between logged and unlogged aboveground live C stocks in each elevation zone for the entire region by subtracting the mean C density (in megagrams of carbon ha^{-1}) for unlogged cells from the C density for cells logged in each decade and then multiplied the difference by the area of cells logged in that decade.

Carbon density by decade of logging

For each elevation zone, we calculated mean C density by decade of logging (i.e., stand age) (Figure 3) for each of three BC government cutblock data sources: Consolidated Cutblocks (2020); Results Openings (2020); and Forest Tenure Cutblock Polygons FTA 4.0 (2020). This dataset shows the product of a union among the CONS_CLIP, Results, and FTA cutblock layers. The union operation was performed using a 50-m XY tolerance to equate near-identical polygons. Due to discrepancies in areas of overlap among the three inputs, the layers were prioritized in the following order for the union and for attributing harvest decade: CONS_CLIP, Results, and FTA. Attributes among the three layers were not combined in the final product to show discrepancies in values. Metadata for the three inputs can also be found as follows: CONS_CLIP (Consolidated cutblocks; https://catalogue.data.gov.bc.ca/dataset/harvested-areas-of-bc-consolidated-cutblocks-); Results (Results openings; https://catalogue.data.gov.bc.ca/dataset/results-openings-svw); and FTA (FTA 4.0; https://catalogue.data.gov.bc.ca/dataset/forest-tenure-cutblock-polygons-fta-4-0) (https://www.for.gov.bc.ca/HFD/library/Documents/bib95354a.pdf).

Because the rigor of inventory standards and reporting obligations has improved over time, cutblock data prior to 1970s must be interpreted with caution. Some anomalies occurred in the trend of mean C density with age for these older time periods, as well as the most recent decade (raw data presented in Appendix S1: Table S2). Additionally, for VRI values that were severely off the expected trend in plots of carbon accumulation, we used linear interpolation methods. These values were calculated assuming linear

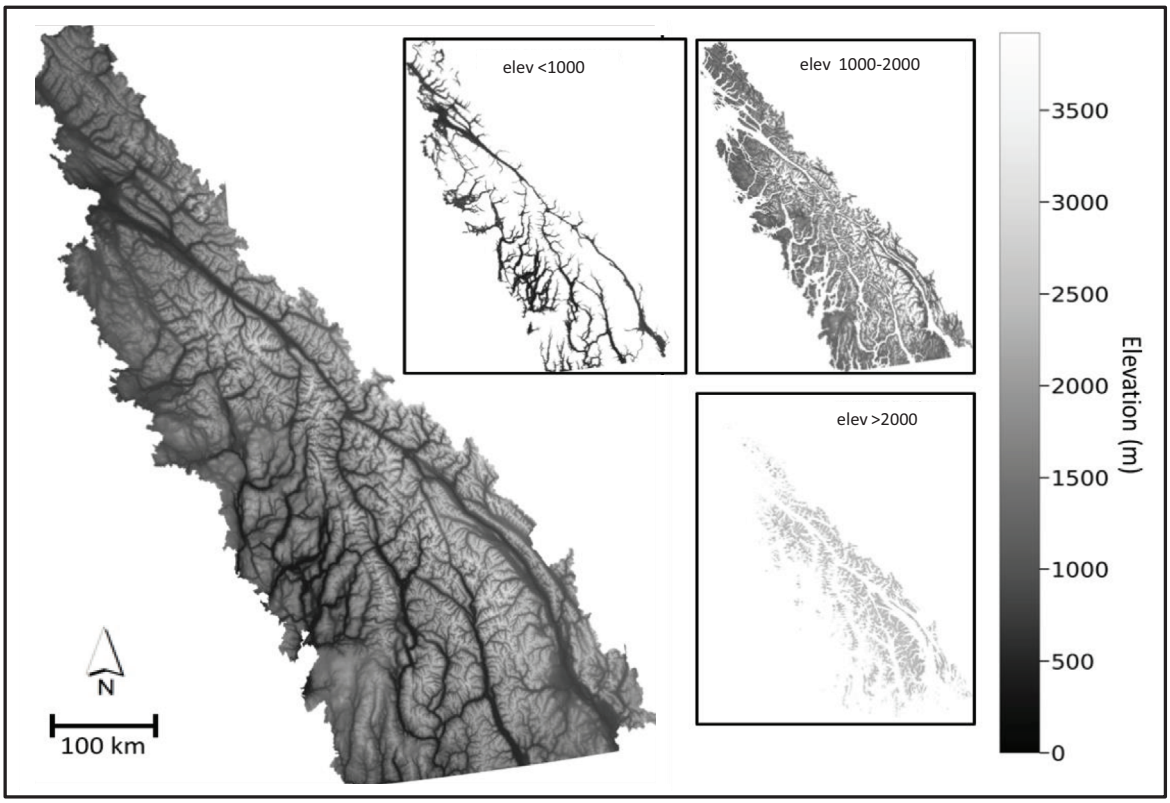

FIGURE 2 Elevation zones (in meters) used for analyzing aboveground live C data for the Interior Wetbelt forest study area, British Columbia, Canada. Canadian Digital Elevation and Surface Models: https://maps.geogratis.gc.ca/wms/elevation_en

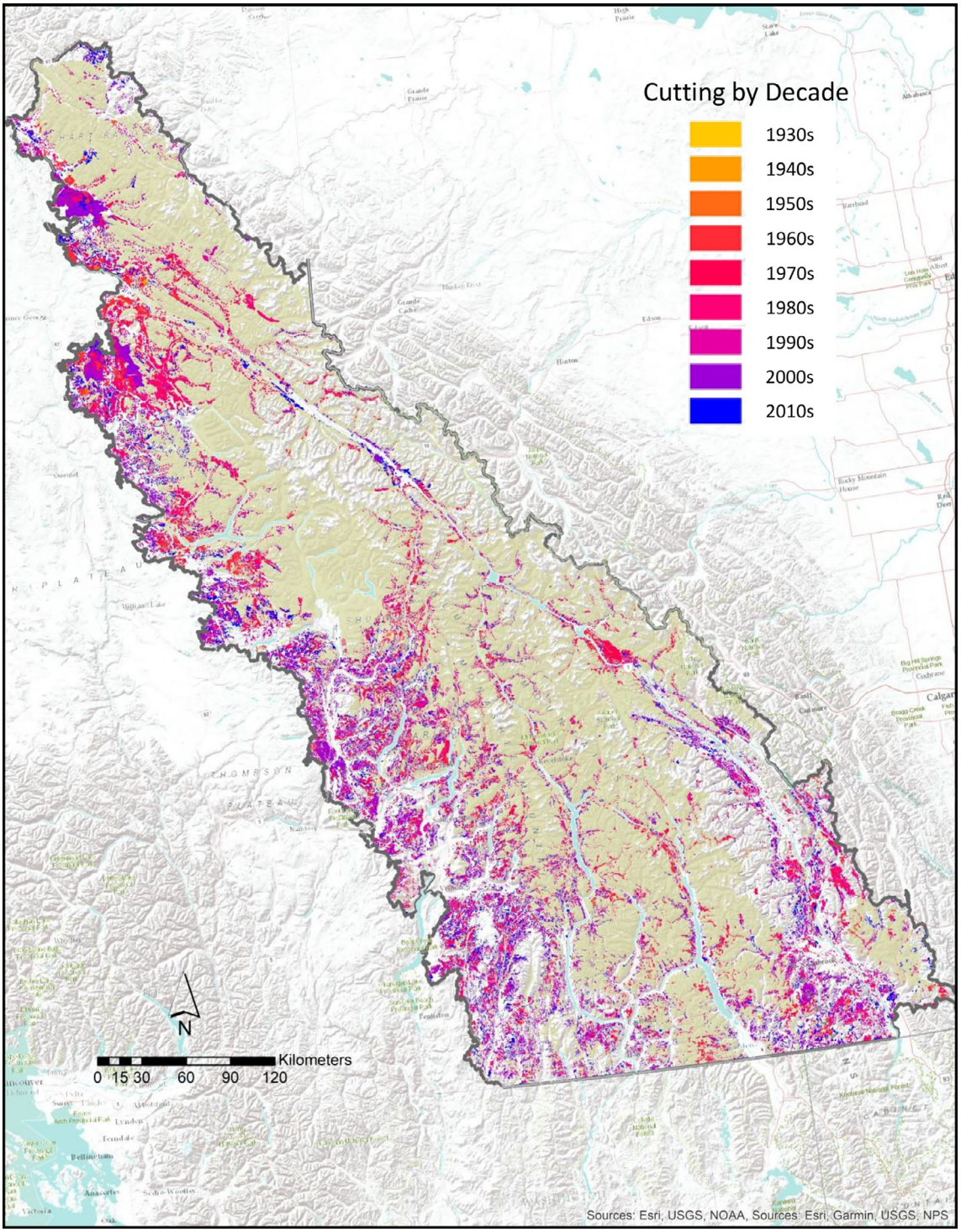

FIGURE 3 Logged area by decade for the Interior Wetbelt forest study area, British Columbia, Canada, from the 1930s to the 2010s using Consolidated Cutblocks (2020); Results Openings (2020); Forest Tenure Cutblock Polygons FTA 4.0 (2020). Archived at https://databasin.org/search/#query=inland%20BC

accumulation rates between points whose values seemed reasonable. Carbon values for year 0 were assumed to be 0. Missing values for the 0- to 9-year interval were assigned the interpolated value for 5 years. Using species growth curves was beyond the scope of our study and not readily available for the dominant conifer species in the region.

Validation using other datasets

We validated the values of aboveground live tree C derived from the VRI data using two independent methods. First, we compared the spatial distribution of C densities reported in the GlobBiomass dataset with values from the

VRI dataset by subtracting GlobBiomass C density from VRI values to characterize differences. The second validation focused on the ITR due to its high C stocks (Matsuzaki et al., 2013). We utilized data collected from 27 field plots in old-growth forests distributed across the northern, middle, and southern sections of the ITR based on randomly selected VRI polygons with reasonable roadside access (i.e., <3 km from a road). Plots were located at least 200 m from the nearest road. We used a nested design of fixed radius circular plots to measure trees of different sizes (Appendix S1: Table S3). In large plots (56.43 m radius, 1 ha), we measured dbh and height of all live and dead trees ≥100 cm dbh and only dead trees with a ≤45-degree angle of lean. In medium plots (11.28 m radius, 0.04 ha), we measured dbh and height of all live and dead trees ≥10 cm dbh and ≥1.3 m in height and only dead trees with a ≤45-degree angle of lean. In small plots (5.64 m radius, 0.01 ha), we measured live and dead saplings and seedlings <10 cm dbh and ≥1.3 m in height. Two 24-m transects (fixed at plot center) were also oriented randomly to measure diameter, length, and decay class of coarse woody debris, which was dead wood ≥7.5 cm in diameter at the point of intersection and a >45-degree angle of lean (Appendix S1: Table S4). Coarse woody debris was sampled and reported in the total C stock. However, because this metric is not consistently reported in the VRI dataset, it could not be used for validation of VRI estimates.

Calculations of aboveground biomass applied the allometric equations for Canadian tree species from Ung et al. (2008) within the tree size range from which the equations were derived from secondary forests. We also applied the general allometric equations for North American species groups from Chojnacky et al. (2014) for larger tree sizes that were included in the derivation of these equations from a large dataset (details in Appendix S1). Biomass of living and dead trees were calculated on a unit area basis by summing the individual trees in each sample plot, calculating C density on a per hectare basis, and scaling the estimate to the VRI polygon. We then compared live aboveground C density from VRI cells matching the ITR plots.

RESULTS

Carbon estimates using VRI

In our VRI analyses, uncut forests, as anticipated, have much higher aboveground live C density than younger forests (Table 1). Low- to mid-elevation forests also have >2× aboveground live C density than high-elevation forests. For the full study area across the three elevation zones, total C stocks are 831.6 ± 3.8 Tg (95% CI used throughout study).

Notably, ~22% of the total study area was logged primarily since the 1970s (Figure 3, DellaSala et al., 2021). Loss in C stock due to logging was 177 Tg (Table 1), which represents about 18% of the C stock from the original uncut forest. Low-elevation forests have the highest uncut mean live tree C density (109 ± 0.2 Mg C ha^{-1}), but mid-elevation forests, with 62% of the total area and an uncut mean C density of 82.35 ± 0.10 Mg C ha^{-1}, account for 64% of live tree C loss due to logging (114 ± 0.9 Tg).

C density for all C pools (above- and belowground live and dead biomass and soil) over the entire study area derived from the VRI ranges from 0 to 806 Mg C ha^{-1} with a mean of 182 Mg C ha^{-1} based on spatial mapping (Figure 4; maps of C densities for all pools are in Appendix S1: Figures S1–S3). The proportions in each pool are from the average across the whole study area (Table 2). About half the C is in live C pools with the rest in dead pools and soils. The soil pool has the highest C density (73 ± 0.2 Mg C ha^{-1} or 40%) followed by live stem C (49 ± 0.1 Mg C ha^{-1} or 27%).

Validation versus GlobBiomass

Over all elevations and stand ages, GlobBiomass aboveground live biomass C densities (including all vegetation) are generally higher than those for VRI, based on either raw or adjusted values. Overall comparison of C stocks in the whole study area of the IWB is based on the raw data (Appendix S1: Table S2), with 1034 ± 1.3 Tg estimated from GlobBiomass, which is 168 Tg (19%) more than estimated from the VRI with 865.96 ± 2.42 Tg C stock loss due to logging calculated from the adjusted data in Table 1, and a loss of 79 Tg based on the GlobBiomass compared with 177 Tg based on VRI. A major difference in estimates was that the spatial data from the GlobBiomass map for areas logged in recent decades were not as sensitive in detecting areas of low biomass resulting from younger stand ages (Table 1), although some areas of low biomass were detected (Figure 6). Spatially, GlobBiomass densities are generally greater across most of the study area except for riparian areas where VRI values are generally higher (Figure 5).

Considering the entire study area without regard to elevation or logging decade, the VRI data produce a mean C density of 73.54 ± 0.11 Mg C ha^{-1} (n = 1884) versus a mean C density of 87.83 ± 0.13 Mg C ha^{-1} (n = 1884) for GlobBiomass. The two datasets have a similar shape with C densities decreasing sharply at approximately 250 and 200 Mg C ha^{-1}, respectively, and with the VRI having a flatter distribution (Figure 6).

TABLE 1 Adjusted C densities, and resulting C stocks, and C stock change attributed to logging for the VRI dataset (https://www2.gov.bc.ca/gov/content/industry/forestry/managing-our-forest-resources/forest-inventory) and GlobBiomass (GB) https://globbiomass.org/products/global-mapping/

Year	Stand age (years)	VRI mean C density (Mg C ha^{-1})	VRI C stock (Tg)	VRI C stock change (Tg)	GB mean C density (Mg C ha^{-1})	GB C stock (Tg)	GB C stock change (Tg)
Low elevation: 0 to <1000 m							
Uncut[a]	90+	108.72	210.07	0.000	93.19	179.86	
1930	80–89	93.50[b]	0.01	−0.001	80.89	0.005	−0.0007
1940	70–79	78.28	0.12	−0.046	80.5[b]	0.12	−0.02
1950	60–69	62.58	0.32	−0.234	80.17	0.41	−0.07
1960	50–59	60.06	4.78	−3.874	88.61	7.05	−0.367
1970	40–49	33.86	4.56	−10.078	82.72	11.14	−1.41
1980	30–39	26.59	4.33	−13.368	76.13	12.39	−2.78
1990	20–29	28.02	3.53	−10.164	66.31	8.35	−3.388
2000	10–19	16.81[b]	2.72	−14.863	59.72	9.66	−5.418
2010	0–9	5.60[b]	0.52	−9.623	30.0[b]	2.80	−5.90
Total			230.95	−62.250		231.78	−19.33
Medium elevation: 1000–2000 m							
Uncut	90+	82.35	549.78	0.00	95.31	636.67	
1930	80–89	65.24[b]	0.02	−0.005	91.70[b]	0.03	−0.001
1940	70–79	48.20	0.05	−0.03	88.22	0.09	−0.007
1950	60–69	42.87	0.28	−0.26	93.06	0.62	−0.01
1960	50–59	47.81	4.65	−3.36	89.30[b]	8.69	−0.58
1970	40–49	28.80	8.65	−16.08	85.54	25.67	−2.93
1980	30–39	17.29	6.84	−25.72	73.34	28.99	−8.68
1990	20–29	17.81	5.57	−20.17	59.89	18.72	−11.07
2000	10–19	10.69[b]	4.34	−29.12	48.70	19.79	−18.94
2010	0–9	3.56[b]	0.88	−19.46	24.30[b]	6.00	−17.54
Total			581.06	−114.22		745.29	−59.78
Upper elevation: >2000 m							
Uncut	90+	35.35	22.23	0.00	54	33.96	
1930	80–89	...	...	...	...		
1940	70–79	28.00[b]	0.00	0.00	51.70[b]	0.003	−0.0001
1950	60–69	24.33	0.00	−0.002	49.48	0.01	−0.0009
1960	50–59	20.65[b]	0.00	−0.001	48.50[b]	0.005	−0.0005
1970	40–49	16.98	0.05	−0.05	48.00[b]	0.13	−0.02
1980	30–39	9.92	0.02	−0.05	47.39	0.09	−0.01
1990	20–29	6.30	0.01	−0.02	30.97	0.03	−0.02
2000	10–19	3.74[b]	0.00	−0.04	26.37	0.03	−0.03
2010	0–9	1.25[b]	0.00	−0.02	13.20[b]	0.006	−0.02
Total			22.32	−0.18		34.27	−0.10
Full study area total							
			834.32	−176.66		1011.34	−79.21

Note: See Appendix S1: Table S2 for raw numbers.

Abbreviations: C, carbon; ha, hectare; Mg, megagrams; Tg, teragrams (1 million Mg); VRI, Vegetation Resources Inventory.

[a]For modeling purposes, we show carbon losses backdated to 1930s; however, large-scale cutblocks were not implemented in this region until around the 1950s.

[b]Values changed from original by interpolation.

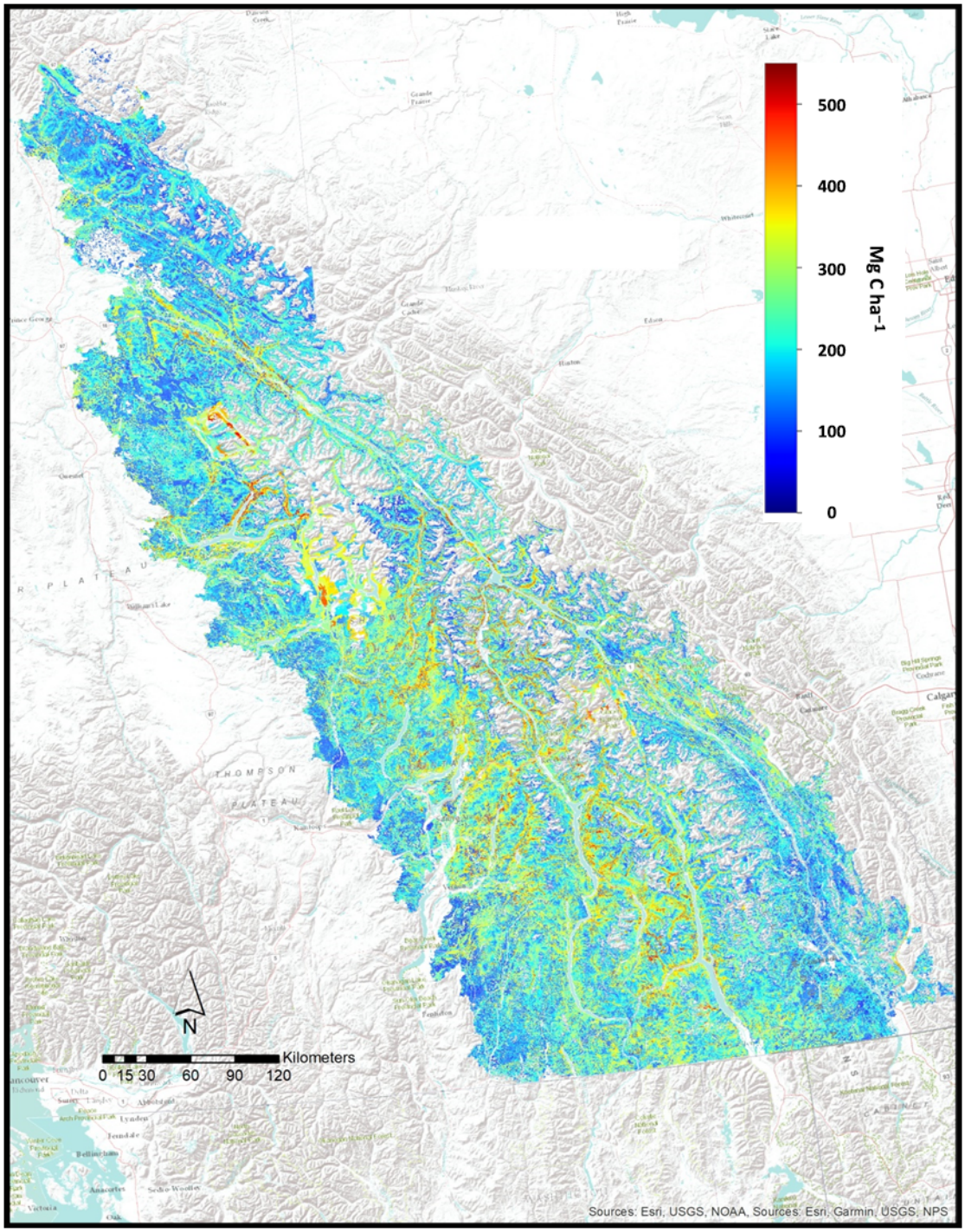

FIGURE 4 Total C (above- and belowground live and dead biomass and soil) as calculated from Vegetation Resources Inventory dataset (https://www2.gov.bc.ca/gov/content/industry/forestry/managing-our-forest-resources/forest-inventory) and global soil C map (http://www.fao.org/global-soil-partnership/pillars-action/4-information-and-data-new/global-soil-organic-carbon-gsoc-map/en/) for the Interior Wetbelt, British Columbia, Canada

Validation versus field plot data

Aboveground live C densities were higher when calculated from field plot data than from the corresponding polygon in the VRI dataset (Figure 7). On average, field plot calculations yielded a mean C density for aboveground live biomass of 353.1 ± 41.9 Mg C ha^{-1} (n = 27) versus 201.5 ± 43.5 Mg C ha^{-1} (n = 27) for the VRI dataset, with field plots exceeding the VRI C density by 75%. The C density in live above- and belowground

TABLE 2 Average carbon density and percentage of total carbon by pool over the British Columbia Interior Wetbelt study area calculated from the VRI biomass data (https://www2.gov.bc.ca/gov/content/industry/forestry/managing-our-forest-resources/forest-inventory) and the global soil map (http://www.fao.org/global-soil-partnership/pillars-action/4-information-and-data-new/global-soil-organic-carbon-gsoc-map/en/) (n = 1884 for all pools; 95% CI)

Pool	Carbon density (Mg C ha^{-1})	Percent of total
Live stem	48.52 ± 0.06	27
Live bark	7.26 ± 0.001	4
Live branch	11.30 ± 0.01	6
Live foliage	6.46 ± 0.01	4
Live above ground	73.54 ± 0.08	40
Live below ground	24.27 ± 0.03	13
Total live	97.80 ± 0.11	54
Dead above ground	8.42 ± 0.01	5
Dead below ground	2.78 ± 0.003	2
Total dead	11.20 ± 0.01	6
Soil	72.99 ± 0.02	40
Total	182.00 ± 0.15	100

Note: Coarse woody debris not reported due to uncertainties in the VRI data.
Abbreviation: VRI, Vegetation Resources Inventory.

biomass in the field plots was an average of 433.8 Mg C ha^{-1} (range 115.1–1172.2 Mg C ha^{-1}), dead standing tree biomass was 82.2 Mg C ha^{-1} (range 21.0–284.2 Mg C ha^{-1}), and coarse woody debris (CWD) was 67.3 Mg C ha^{-1} (range 20.8–247.1 Mg C ha^{-1}). Dead biomass is an important component of the C stock, as well as providing wildlife habitat, but is highly variable ranging from 3% to 51% of the total biomass in plots (Appendix S1: Table S5).

DISCUSSION

Impacts of logging on forest carbon stocks

Our three estimates for total C were compared with other BC province studies, including those in the vicinity of our study area with the highest value (583 Mg C ha^{-1}) of forest biomass reported in our ITR field plots (Table 3).

Live above ground C in the IWB study area declined by an estimated 18% due to total forested area logged over several decades based on the VRI with its inherent uncertainties in derived C densities and their spatial distribution. Our results suggest that the C stock loss predicted from the VRI data is likely an underestimate because the high C densities in primary forests are not accounted for adequately (as shown in Figure 7) and problems noted in cutblock datasets prior to the 1970s (discussed below). Further, the impact on biomass carbon is likely even greater given the highest carbon densities are in the lowest elevation areas that were disproportionately logged (also see DellaSala et al., 2021).

British Columbia's Forest Planning and Practices Regulation (BC Government, 2004) permits 7% of harvested cutblocks to be permanently converted (deforested) to roads, landings, and other access structures made unsuitable for the establishment of "crop trees." The cumulative effects of industrializing the forested land-base will therefore substantially reduce sequestration and storage capacity as more old-growth forests are impacted by logging and roads (DellaSala et al., 2021). While we did not account for additional C losses due to the expansive road network and log landings, road densities range from 0.36 to 1.37 km^2 in the study area (Coxson et al., 2019). Importantly, logging was mostly concentrated in the most C-dense old-growth forests at low to mid-elevations resulting in their imperiled conservation status, with more recent entries into upper elevations as accessible and profitable timber supply is exhausted (DellaSala et al., 2021).

Many studies demonstrate that logging forests with high C density reduces ecosystem C storage substantially. Smiley et al. (2016) reported a 27% to 43% reduction in prelogging 1910 C stocks during two logging periods (1920s–1940s and 1954–1998) within coastal Douglas-fir forests on Vancouver Island, Victoria, BC, with total ecosystem C remaining at a deficit through 2074 given ongoing logging. Matsuzaki et al. (2013) reported a logging-related decline of 64%–78% in all nonsoil C stocks within the ITR on sites subjected to moderate retention (30% of trees retained—although this level of retention is rare in BC) and clear-cut logging, respectively. Trofymow et al. (2007) reported that diminished stocks from logging coastal BC temperate rainforests would not return to prelogging levels this century (21st) due to short-rotation logging and conversion of old-growth forests to commodity production, a situation not unlike IWB forestry practices. Fredeen et al. (2007) reported clear-cut sites in wetter subboreal forests in our study area had net C emissions for 8–10 years postlogging before returning to net C uptake by the regrowing forest, but the C stocks are small in these clear-cut stands for decades. Across a chronosequence at the same site, highest total C stocks were generally in the oldest forest stands >250 years old, with very low C stocks in clear-cuts in the first few decades following replanting (Bois et al., 2009; Fredeen et al., 2005).

Depletion of live C stocks due to logging has many consequential effects by reducing inputs into the dead biomass and soil C pools. Young forests maintained under a logging rotation system do not produce the large amounts of coarse woody debris that accumulate over

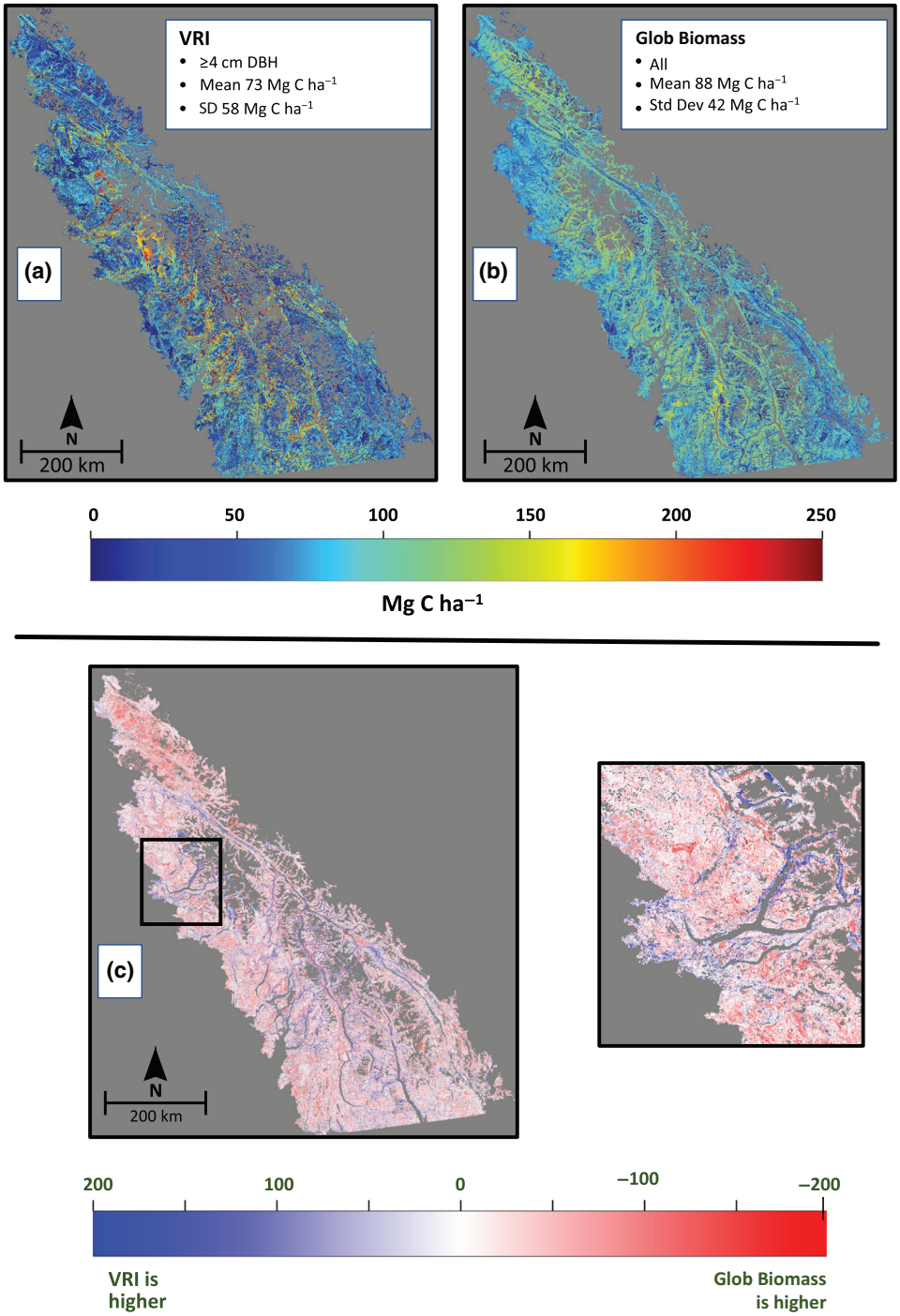

FIGURE 5 Spatial distribution of aboveground live tree C densities for the Interior Wetbelt study area, British Columbia, Canada, based on: (a) Vegetation Resources Inventory (VRI) data; (b) GlobBiomass data; and (c) VRI minus GlobBiomass estimates. (c) Insert VRI C density minus GlobBiomass C density

centuries in old-growth forests (Wells & Trofymow, 1997). They also produce reduced inputs of litter, fine root turnover, and rhizosymbionts. The effects of logging on clearing ground vegetation and disturbing the soil result in soil C loss due to erosion. Physical disturbance of the soil and changed microclimatic conditions enhance decomposition and heterotrophic respiration rates, thus reducing the soil C stock. These processes deplete C stocks in dead biomass and soil organic matter and may also affect postlogging forest regrowth and

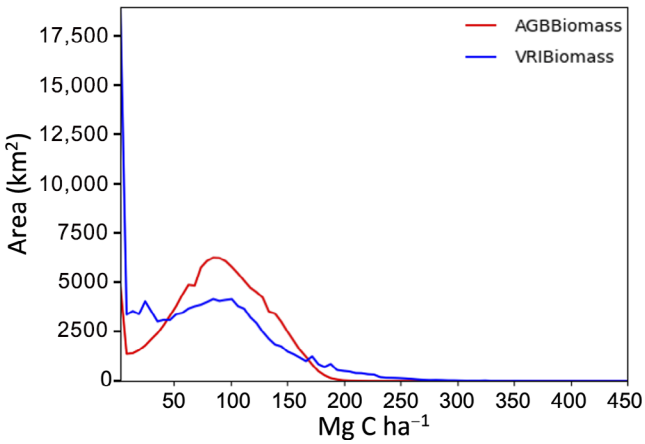

FIGURE 6 Distribution of C densities over the Interior Wetbelt study area, British Columbia, Canada, for Vegetation Resources Inventory (VRI, blue line) and GlobBiomass (red line) datasets

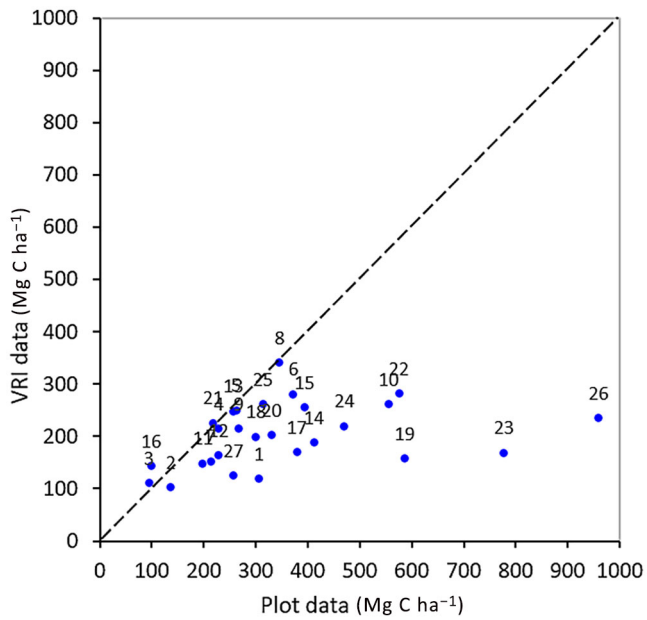

FIGURE 7 Vegetation Resources Inventory (VRI) aboveground live C density versus C densities based on field plot data (https://databasin.org/datasets/1d79c395b32d49d5b3f7f7aee52ccd8c/). Points below 1:1 line indicate values calculated from field plots that are higher than those from VRI. Points above the 1:1 line indicate VRI value is higher than that calculated from field plot

hence future C sequestration (Borrelli et al., 2017; Mayer et al., 2020).

Logging is the main human-induced impact on C stocks in these forests (DellaSala et al., 2021), but stock changes also result from natural disturbance events that are increasingly affected by climate change. In general, the carbon deficit from logging as assessed in our study would ideally be compared against insect and wildfire fluxes that are believed to minor in the ITR, but possibly larger in the IWB, particularly in the upper elevation spruce-fir forests (Kopra & Feller, 2007). This information is currently lacking in our study area. Canada's forests are indeed impacted by wildfires and insect outbreaks with emissions from such natural disturbances approximately half that of logging (Stinson et al., 2011). C stock loss by combustion in fires is mostly from fine fuels that are relatively rapidly regenerated.

The C debt in the IWB from logging will take a least a century to recover, thereby contributing to Canada's greenhouse gas emissions during a global climate emergency and increasing the challenge of meeting Canada's contribution to the Paris Climate Agreement. Alternatively, Canada's Federal and British Columbia's Provincial governments could effectively assist their climate and conservation commitments through two nature-based strategies. First, by prohibiting further old-growth forest logging and thereby avoiding additional C emissions from depletion of forest ecosystem C stocks (see Matsuzaki et al., 2013), and second, by taking advantage of the C sequestration potential of previously logged forests by allowing them to continue growing (i.e., without future logging) and recover ecosystem C stocks—an approach to forest management called proforestation (Moomaw et al., 2019). Doing so would place IWB forests on par with the world's most biomass C-dense forests (Keith et al., 2009) and with the protection afforded other high C value forests such as the Great Bear rainforest on the BC coast (DellaSala et al., 2021).

Model uncertainties and inconsistencies in carbon stock estimates

Uncertainties occur in all the data sources used in our study. The main sources of uncertainty in estimation of C stocks from field plots include the following: (1) the representativeness of the location and number of field plots in describing the forest type across the landscape; and (2) the allometric equations used to convert tree inventory data to the amount of biomass C. These equations are derived from sampling the biomass of individual trees that may be combined within a local area or scaled up to a national scale. Tree architecture and, hence, the allometric relationships vary with environmental conditions influencing productivity. National-scale equations have the advantages of consistency across species, inclusion of error terms, consistency when comparing results with other studies or regions, and a more robust dataset from a larger sample size with smaller variance (Chojnacky et al., 2014; Ung et al., 2008). In a comparison of locally derived equations or broad generalized equations,

TABLE 3 Total forest biomass by carbon pool and study area in BC forests

Study area	Total forest biomass (Mg C ha^{-1})	Carbon pool	Source
Inland Temperate Rainforest (uncut Interior Cedar-Hemlock)	455	Live trees, snags, CWD, forest floor but not soils	Matsuzaki et al. (2013)
Coastal Temperate Rainforest (old-growth western hemlock), eastern Vancouver Island	417	Aboveground biomass, belowground biomass, dead organic litter, dead wood, soil	Trofymow et al. (2007)
Coastal Temperate Rainforest (old-growth western hemlock), western Vancouver Island	532	Aboveground biomass, belowground biomass, dead organic litter, dead wood, soil	Trofymov and Blackwell (1998)
Interior Spruce, central BC (old-growth)	423; 324	Aboveground biomass, CWD, coarse textured versus fine textured soils	Fredeen et al. (2005)
Interior Spruce, central BC	268; 363	Above ground live only versus total	Bois et al. (2009)
Engelmann Spruce-Subalpine, Interior BC	365	Live/dead trees, understory, forest floor, roots, dead woody material, mineral soil	Feller (1997)
VRI (uncut)[a]	124	Live/dead above- and belowground biomass	This study
GlobBiomass (uncut)[a]	133	Live/dead above- and belowground biomass	This study
Field plots (old growth)[a]	583	Live/dead above- and belowground biomass and CWD	This study

Abbreviations: BC, British Columbia; VRI, Vegetation Resources Inventory.
[a]Represent only the Inland Temperate Rainforest and not the larger Interior Wetbelt.

Feller (1992) concluded that geographical and site-specific variations in tree growth influenced parameters in the equations, but the biomass estimated was similar except for extremely poor productivity sites. We selected generalized allometric equations derived at the national scale and tested various equations over the size range of the trees sampled in the plots (Appendix S1: Figure S5). Nonetheless, we used the plot data for external validation of the VRI demonstrating how VRI artificially truncates the amount of C at 90-year-old stands, which is most problematic given trees in our study area can live for >1600 years.

The satellite-derived land product of predicted aboveground biomass estimates of the GlobBiomass map was compared with independent reference data (Rozendaal et al., 2017). The validation process involves testing the spatial and temporal consistency of the product and quantifying uncertainties. The reference sites for North America were derived from those reported in Luyssaert et al. (2007), and these like other global reference sites consisted of forest stands of a range of ages and disturbance histories. Thus, old-growth characteristics were not well represented. Uncertainties in the validation process include the representativeness of forest types and ages, spatial mismatches due to geolocation errors and differences between map pixel size and plot area, high spatial variability due to small plot sizes, and the format of the remotely sensed data used for biomass retrieval.

Aboveground biomass exceeding 200–300 Mg ha^{-1} was generally underestimated globally, but in North America, the bias was at about 100 Mg ha^{-1} (Rozendaal et al., 2017). In the validation for North America, there were only 12 grid cells in the map that had measured reference site biomass >200 Mg ha^{-1}, whereas all the field plots measured in our study in the ITR had higher biomass. The accuracy of the biomass map for North America was calculated as a relative root mean square error of 21.7% and a bias of −2.7 Mg ha^{-1}. Regional assessment of the global biomass map for Canada using national forest inventory statistics of growing stock volume and forest area showed reasonable agreement for boreal and temperate forests, although some underestimation. The validation process concluded that in the temperate forest biome, biomass was underestimated at ≥150 Mg ha^{-1} (Rozendaal et al., 2017). The global map product represents current C stocks in biomass from forests of a range of ages, and this biomass will be lower than that in the primary forest sites sampled.

Comparison between the VRI and GlobBiomass of their spatial distributions of C stock densities across the study area showed generally higher values from GlobBiomass,

with the notable exception of riparian areas. Characteristics of these specific ecosystems in terms of forest structure and topography could be investigated to help improve the remote sensing algorithms for mapping. Although uncertainties occur in both data sources, detecting such differences highlights the need for greater effort in monitoring and calibrating with high biomass sites. The fact that GlobBiomass has been shown to underestimate areas of high biomass, and yet is generally higher than the VRI, suggests the need for improved testing of the VRI estimates.

The estimates of soil C are derived from a global map that has associated uncertainties when downscaled to smaller regions (FAO, 2020). The sampling density in Canada of 1–5 profiles per 1000 km^2 is moderate to high compared with other countries, and error rates for concordances are reported from 10% to 30% and some higher. The map of sampling densities shows a moderate level of uncertainty for the temperate region in BC. We use this mapped soil C data to provide estimates of the contribution of the soil pool to the total ecosystem C stock, rather than ignoring this pool. However, the mapped values do not account for the effects of logging on soil C and the consequent spatial variation due to forest disturbance history. Soil C loss due to logging primary temperate forest and conversion to managed secondary forest was reported as an average of 8%–11% from global meta-analyses (Mayer et al., 2020).

Our study examined historical data and C stock changes based on rates of logging only. These historical data and identifying ages of forest stands regrowing post-logging have high uncertainty. The anomalies in the trends of mean C density by decadal age class in both the VRI and GlobBiomass datasets indicate that identifying forest age and the relationship between age and forest biomass may have created errors. Notably, logged sites recorded in the cutblock dataset underrepresent pre-1970s logging rates, especially in the southern portion of the study area where logging began earlier than reported. For instance, BC Forestry Service Annual reports (https://www.for.gov.bc.ca/hfd/pubs/docs/mr/annual/annualrpt.htm, accessed 16 October 2021) indicate that the amount of wood volume scaled from the Nelson and Prince George districts, respectively, in our study area were 1950s (1.91 million m^3 and 2.65 million m^3), 1940s (0.98 million m^3 and 0.83 million m^3), and 1930s (0.69 million m^3 and 0.23 million m^3). Thus, logging in the 1930s was roughly 1/3 (Nelson) to 1/10 (Prince George) compared to what it was in the 1950s—not 1/35th based on the cutblock dataset. Additionally, the decadal carbon strata used in the spatial analysis are not as accurate as trees cored in the field and this too may have missed considerable areas logged in the 1930s–1940s, further underrepresenting the carbon deficit.

Climate change has high potential to affect ecosystem processes including photosynthesis, respiration, and nutrient cycling, as well as altering fire and hydrological regimes (Burton & Boulanger, 2018; Nitschke & Innes, 2013) and insect outbreaks (Burton & Boulanger, 2018; Meddens et al., 2012) that may trigger ecosystem-level shifts in places (Holmes et al., 2015). Notably, ClimateBC projections for our study area showed by midcentury summer temperatures may increase by 3.8°C, precipitation increasing mostly in the fall, with more rain and less snow (Foord, 2016). Reduced snowpack may alter seeps needed to maintain the ITR and drier summers could result in more fires in the IWB; however, relative to the IWB, the ITR, overall, may function as fire refugia (Hamann & Wang, 2005). Additionally, estimates of current and projected forest ecosystem C could be generated using more sophisticated simulation modeling that considers all major environmental impacts on key ecosystem services like C storage and sequestration over time to better assess refugia potential (e.g., Bachelet et al., 2015).

While our study of C dynamics in the ITR was a landscape-scale assessment based on the inventory data across the whole region and representing a mosaic of forest age classes, we are mindful of discrepancies between measured and modeled C. Field plot measurements of aboveground live C provide a direct and external validation of point-based VRI estimates. In this comparison (e.g., Figure 7), VRI estimates were, with minor exceptions, 75% lower on average than field-based measurements. The mismatch between VRI and field measurements was greatest for sites with the highest C density. Furthermore, aboveground live tree C densities for uncut low- and mid-elevation forests (stand age 90+ years) using VRI (108.72 ± 0.21 and 82.35 ± 0.10 Mg C ha^{-1}, respectively) were much lower than those reported previously. Finding the sources of these inconsistencies and correcting them would add confidence to government C accounting systems, particularly in C-dense primary forests.

Our study examined historical data and C stock changes based on rates of logging and assumptions that unlogged sites in the ITR were at least all previously old growth (>90 years ago). Periodic insect outbreaks and wildfires likely reduced the spatial extent of old-growth forests in the IWB particularly during drought stress (Kopra & Feller, 2007). However, prior to logging the ITR was likely mostly old growth due to extremely long fire rotation intervals (Sanborn et al., 2006), whereas mixed-severity wildfire regimes were likely prominent in the drier IWB portions (Burton & Boulanger, 2018).

MANAGEMENT RECOMMENDATIONS AND CONCLUSIONS

The IWB and ITRs of BC are important yet greatly under-appreciated C stocks with the capacity to sequester and store even more C for long periods given the potential for old-growth forests to act as refugia, especially within the ITR. However, the BC government is not managing this region under nature-based climate solution approaches that maximize forest C stocks and increase the sink potential via proforestation (Moomaw et al., 2019). Thus, the contribution of C-dense forests to Canada's National Determined Contribution (NDC) under the Paris Climate Agreement remains unresolved. Failure to adequately acknowledge the loss of forest ecosystem C from forestry practices, incorporate the full scope of forest biomass impacts, and account for forest regeneration problems following logging are serious reporting omissions, especially considering the magnitude and velocity of the climate emergency (Ripple et al., 2021) and the need to keep additional C out of the atmosphere by avoiding land-use practices that create a substantial and ongoing C debt (Harmon, 2019; Hudiburg et al., 2019; IPCC, 2018; Law et al., 2018; Mackey et al., 2013, 2015; Moomaw et al., 2019). Expanding core protected areas in collaboration with First Nations via a climate conservation network focused on C-dense forests (i.e., old-growth forests), prohibiting primary forest logging, and pursuing proforestation would better position BC to meet its climate and conservation commitments while safeguarding biodiversity and other important ecosystem services presently at risk from industrial logging (Brandt et al., 2014; DellaSala et al., 2021).

Accurately quantifying and mapping C stocks is imperative for managing all of BC's forests (coastal and interior) considering rising atmospheric CO_2 concentrations, observed and projected climate change impacts, and the potential contribution of emissions reductions from the land and forestry sectors (IPCC, 2018). The comparison of field plot measurements with inventory or mapped-based estimates of C stocks demonstrates the serious undervaluation of old-growth forests. This has resulted in inadequate recognition of the mitigation potential of protecting these C stocks, as well as the magnitude of losses incurred by logging. Our efforts at quantifying current C stocks and losses indicate that forest management practices can substantially alter the trajectory of C released into the atmosphere if practices are modified to regard the many benefits of C storage (also see Brandt et al., 2014; Keith et al., 2019; Matsuzaki et al., 2013). Our study uncovered inconsistencies and inaccuracies in C accounting methodologies that point to the need for consistent data collection at the provincial level if the contributions of BC forests are to be properly accounted for in climate mitigation. Nonetheless, our approach to C accounting may help the governments of BC and Canada better account for the extent of IWB forest C stocks, as well as the potential C sink value, and inform revised NDC targets under the Paris Agreement.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data used are as follows:

Combined Cut-blocks for Wetbelt Analysis, Inland BC: https://databasin.org/datasets/6556cb6a4a734c8c8b6f12f46b231137/

Consolidated Cutblocks: https://www.for.gov.bc.ca/ftp/HTS/external/!publish/consolidated_cutblocks/About%20Consolidated%20Cut%20Blocks%202020.pdf

Forest Tenure Cutblock Polygons FTA4.0: https://catalogue.data.gov.bc.ca/dataset/forest-tenure-cutblock-polygons-fta-4-0

Results-Openings svw: https://catalogue.data.gov.bc.ca/dataset/results-openings-svw

Global Soil Partnership: http://www.fao.org/global-soil-partnership/pillars-action/4-information-and-data-new/global-soil-organic-carbon-gsoc-map/en/

Change monitoring inventory British Columbia: https://www2.gov.bc.ca/assets/gov/environment/natural-resource-stewardship/nr-laws-policy/risc/cmi_ground_sampling_addendum_2020.pdf

GlobBiomass: http://globbiomass.org/products/global-mapping

Vegetation Resource Inventory: https://www2.gov.bc.ca/gov/content/industry/forestry/managing-our-forest-resources/forest-inventory

Field plot data archived: https://databasin.org/datasets/6288d3cb6cf74997b118d8be38785d00/

Inland Temperate Rainforest and Interior Wetbelt Forest, BC: https://databasin.org/datasets/5ed2062988e741f38922fd924ed07a54/

Canadian Digital Elevation and Surface Models: https://maps.geogratis.gc.ca/wms/elevation_en

Study Area Boundary: https://databasin.org/datasets/b16b310928ad4c9ab21105cdefe03d87/

Additional data sources may be found in Appendix S1.

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