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Assessing the Cumulative Impacts of Forest Management on Forest Age Structure Development and Woodland Caribou Habitat in Boreal Landscapes: A Case Study from Two Canadian Provinces

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Abstract: The Canadian boreal forest biome has been subjected to a long history of management for wood production. Here, we examined the cumulative impacts of logging on older forests in terms of area, distribution and patch configuration in the managed forest zones of the Eastern Canadian provinces of Ontario and Quebec. We also examined the consequences of these cumulative impacts on a once widely distributed and now threatened species, the woodland caribou (*Rangifer tarandus caribou*). The cumulative area of recently logged forest (since ~1976) was 14,024,619 ha, with 8,210,617 ha in Quebec and 5,814,002 ha in Ontario. The total area of older forest was 22,672,369 ha, with 12,390,740 ha in Quebec and 10,281,628 ha in Ontario. Patch statistics revealed that there were 1,085,822 older forests with core patches < 0.25 ha and an additional 603,052 < 1.0 ha. There were 52 > 10,00–50,000 ha and 8 < 50,000 ha. Older forest patches (critical caribou habitat) in the 21 local population ranges totalled 6,103,534 ha, distributed among ~387,102 patches with 362,933 < 10 ha and 14 > 50,000 ha. The median percentage of local population ranges that was disturbed was 53.5%, with Charlevoix having the maximum (90.3%) and Basse Côte-Nord the least (34.9%). Woodland caribou local population ranges with disturbed suitable habitats >35% are considered unable to support self-sustaining populations. We found that for the 21 caribou local population ranges examined, 3 were at very high risk (>75% area disturbed), 16 at high risk (>45 ≤ 75% area disturbed), and 2 at low risk (≤35% area disturbed). Major changes are needed in boreal forest management in Ontario and Quebec for it to be ecologically sustainable, including a greater emphasis on protection and restoration for older forests, and to lower the risks for caribou populations.

Keywords: boreal forest; cumulative impacts; forest age structure; older forest; primary forest; woodland caribou; suitable habitat; forest management; logging; clearcuts

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1. Introduction

A major challenge in reaching sustainability in natural resource management is understanding the long-term, cumulative impacts of land use on ecosystem integrity and responding with evidence-based adaptive management. Ecosystem integrity refers to the ability of ecosystems to maintain key ecological processes, recover from disturbances and adapt to new conditions, given the prevailing environmental drivers and perturbations, and continue the natural processes of regeneration [1]. The circumpolar boreal forest biome has now been subject to a long history of management for wood production, and an important focus of research has been the cumulative environmental impacts of logging on water [2], biodiversity [3–5], understory vegetation and coarse woody debris [6], and forest landscapes' age structure [7].

While tropical forests have been the focus of extensive research on biodiversity losses from deforestation and degradation [8], the boreal forest biome also contains globally significant environmental values that are at risk [9]. The boreal forest diversity is characterized by the high landscape-level diversity of stands varying in age, structure, and composition, which generates a wide spectrum of habitats for native species [10]. A major challenge in the boreal forest is accessing accurate information on and assessing the cumulative impacts of land use activities over vast extents of boreal forest landscapes. A further complicating factor is that the ecosystems of the boreal forest are subject to natural disturbance regimes, such as forest fires and insect outbreaks [11]. Hence, the distribution of younger, mature, and older seral stages across the landscape maybe the result of natural disturbance regimes, logging, or both. It follows that data on the disturbance history are required to attribute the origin of forest stand age.

The Canadian boreal zone is dominated by coniferous trees such as *Picea glauca*, *Picea mariana*, *Larix laricina*, *Abies balsamea*, and *Pinus banksiana*, but large areas are also covered by shade-intolerant deciduous trees such as *Populus tremuloides*, *Populus balsamifera*, and *Betula papyrifera*, either in pure stands or, more commonly, intermixed with conifers [12]. The primary drivers of boreal ecosystem dynamics are wildfires, alongside the secondary drivers of insects, diseases, and their interactions [13]. Natural boreal forests, therefore, are not only composed of young postfire stands but also include significant proportions of old-growth stands characterized by different structures and dynamics [14].

Clearcutting is the dominant silvicultural system in use in the managed forest estate of Ontario and Quebec, where most of the overstory trees in the management unit are removed over a short period of time to create a fully exposed microenvironment for the establishment of a new even-aged stand [15]. Regeneration treatments include natural regeneration using self-sown seed or vegetative reproduction, assisted natural regeneration such as scarification, and artificial regeneration by seeding and planting. Associated site treatments can include site preparation through prescribed burning and thinning [15].

The main research question investigated here is whether the cumulative impacts of logging, together with natural disturbances, have, at a landscape scale in the boreal forests of two Canadian provinces (Ontario and Quebec) [10,16–19], resulted in forest degradation. These provinces have a long history of logging, and specifically timber harvesting with short rotations, with ecological impacts that have been shown to differ from natural disturbance regimes and that translate into a shift from natural landscapes dominated by older forests to managed landscapes dominated by early seral and young pole stands [10,17,20,21].

In the last few decades, this shift has had important consequences for organisms that require older forest habitat conditions, such as the woodland caribou (*Rangifer tarandus caribou*) (hereafter, boreal caribou), a once widely distributed but now listed threatened species [22], which is also considered an "umbrella species" [23]. There is a strong scientific consensus, based on a large set of empirical studies, that human-induced disturbances are linked with the global decline of boreal caribou in Canada, e.g., [24–26]. Numerous studies have described the effects of human disturbances in the boreal forest and the mechanisms on boreal caribou ecology and demography. Across Canada, these human disturbances include oil and gas development, mining, hydroelectric development, wind farms, and timber harvesting [27–31], as well as seismic lines (e.g., [32–34]). In Eastern Canada, boreal caribou populations have been mainly affected by industrial forestry [35–38] and by the associated development of logging roads, e.g., [39–44]. Accordingly, we also examined the consequences of the cumulative impacts of timber harvesting across the two provinces in Eastern Canada on the suitable habitat of the boreal caribou in local population ranges within this large region of the boreal biome.

2. Materials and Methods

Our study area, totalling 67.2 M ha, is defined by those forests within the boreal zone that are public (crown) forests managed for wood production and other uses. In Ontario, the managed forest region is called the Area of Undertaking (consisting of Forest Management Units (FMU)), 28.6M ha of which occurs within the boreal zone. In Quebec, the managed forest area (MFA) is 38.6 M ha, consisting of public lands south of the northern forest limit that was defined by a biophysical approach [45]. We overlaid the ranges of 21 boreal caribou local populations that fell within or overlapped the study area, and we retrieved GIS shapefiles for them from provincial sources [46,47]. Each local population range corresponds to the 99% minimum convex polygon that was estimated from all GPS radio-collared female individuals of a given population followed throughout a year and over several years for each population (Figure 1).

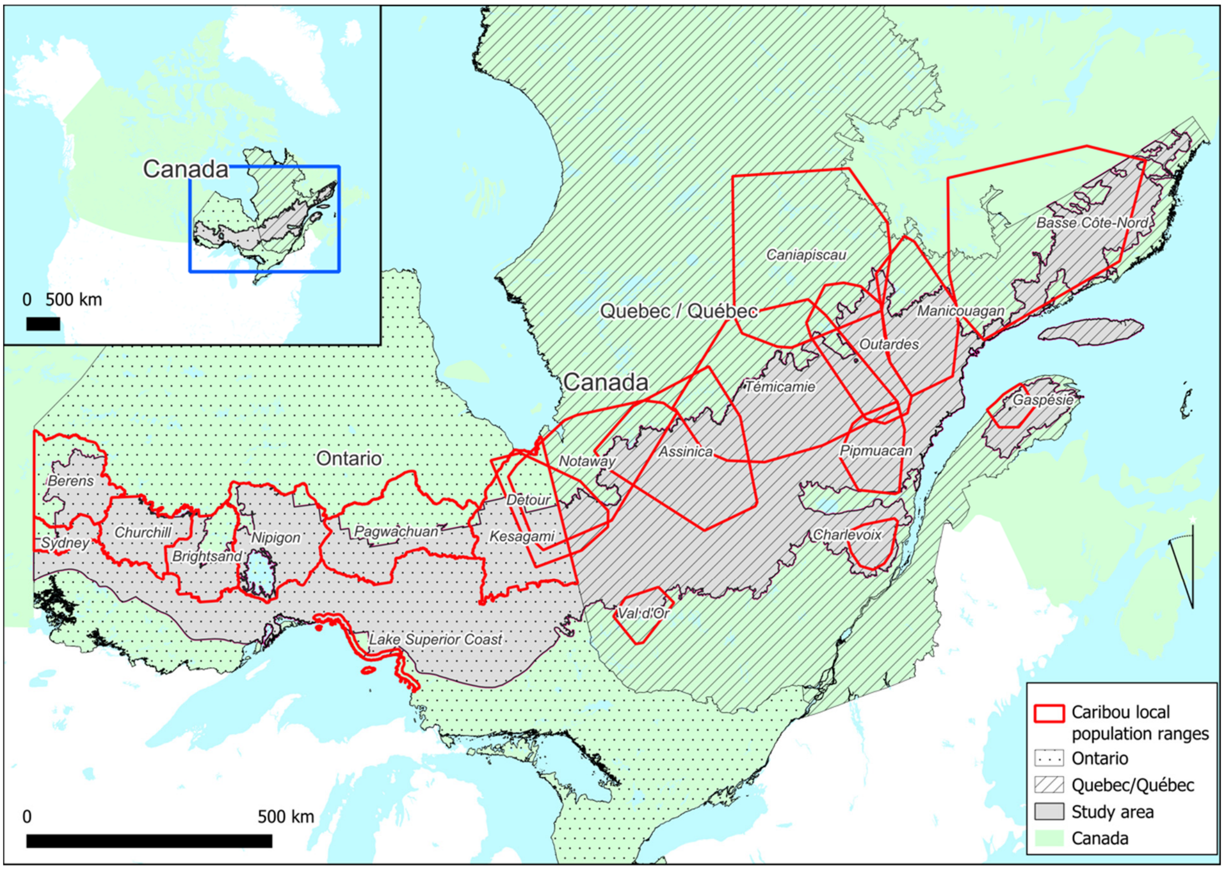

Figure 1. Location of the study area in the Canadian provinces of Ontario and Quebec, and the boreal caribou local population ranges.

The analytical workflow used in this study is illustrated in Figure 2. First, we delineated the forest area using a modelled land cover characterization spatial data layer for Canada at a 30-m pixel resolution [48,49]. The land cover layer for 2019 was used, selecting only forested pixels (mixed wood, broadleaf, and coniferous). We masked the forest cover layer to the study region and calculated the managed public forest area values. We then compiled data on the forest management history, including the year of logging and forest age, from (i) the two provincial forest management inventory databases where the data are georeferenced to polygons within local forest management units (FMU) and (ii) the national modelled datasets on logging history and forest age (Figure 2). These data were processed using the *terra* package [50] in R [51] and QGIS [52].

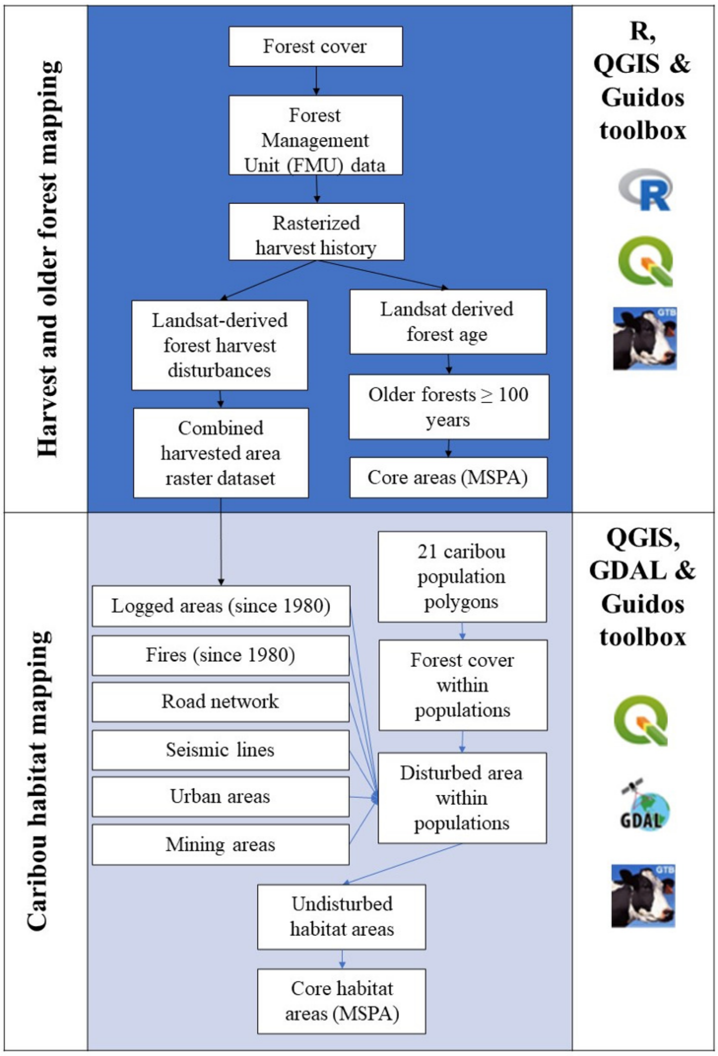

Figure 2. The analytical workflow used in the study. The two main analysis stages are shown on the left-hand side of the figure, a description of each step in the workflow is given in the centre, and the computer program or programming language used is given on the right.

In Ontario, forest management data for each FMU are provided in the Ontario Forest Resource Inventory (FRI). A total of 31 Ontario FMUs overlapped with the study area. All publicly accessible Forest Management Units' data packages were retrieved from the FRI Inventory Packaged Products Version 2 [53]. The years for which data were available varied by FMU, and three FMUs had no data publicly available (Table S1). We identified and extracted productive forest polygons and harvested forest polygons from each FMU, with harvest polygons identified by the "harvest" depletion type ("DEPTYPE") and productive forest identified by "forest" polygon type. We calculated the area of managed productive forest from the extracted forest polygon data. For FMUs with missing data, values were pulled from published reports (Table S1). The harvest polygons were reprojected to Canada Atlas Lambert (EPSG:3978) and rasterized at a 30-m pixel resolution to complement the other rasterized layers used. Raster pixels were assigned a value representing the year of harvest via the "YRDEP" attribute.

For Quebec, we calculated the total managed forest area using "Unité d'aménagement" polygons [54]. We extracted harvested areas from the Quebec southern ecoforest inventory data [55], which are also publicly available in the form of polygonized forest units, spanning from the beginning of the 20th century to 2020. The "origine" attribute was used to extract harvested polygons where the code indicated that harvesting (i.e., logging) had occurred, with partial harvests excluded from the analysis (Table S2). As per Ontario, these polygons were reprojected and then rasterized.

To fill gaps in the harvest records, we added a national Landsat-derived forest harvest layer [56]. This modelled dataset is publicly accessible at a 30-m spatial resolution for all of Canada, showing harvests between 1985 and 2020. We masked these data by the study area and then merged them with the Ontario and Quebec harvest layers. In areas of overlapping pixels, the modelled dataset year was applied as it provided the most recent logging data.

We extracted data on plantations—which are artificially regenerated stands that have been converted from naturally regenerating forests—and forests undergoing assisted regeneration (via seeding and planting) within the study area from the forest inventory datasets and provincial landcover databases. In the Ontario FRI, any forest polygons with development stage ("DEVSTAGE") codes indicating that the forest was planted or seeded were extracted ("newplant", "newseed", "ftgplant", "ftgseed"). This was complemented by plantation pixels extracted from the Ontario Land Cover Compilation (OLCC) dataset [57], at a 15-m resolution, resampled to 30-m to complement the national forest cover data. From the Quebec forest inventory, we used the "origine" attribute, with specific plantation-related codes identified and extracted (Table S2). The polygonal forest resource datasets were reprojected to EPSG:3978 and rasterized at a 30-m pixel resolution, and all identified plantation and assisted regeneration areas were merged into a single layer. We calculated the total area of plantations and forests undergoing assisted regeneration from this layer for each province. Planted pixels were also considered to be harvest pixels for the calculation of the total harvest area.

We also extracted disturbance information to produce a more comprehensive disturbance layer for analysis. For Ontario, we used information from the OLCC and from the FRI. Pixels categorized as disturbed from the OLCC included impacts from mining, infrastructure, agriculture, and undifferentiated rural. Mining in the boreal forest is open-pit mining, where the habitat is destroyed and linear infrastructures are created for the transportation of minerals. Although these land disturbances are spatially limited when compared with industrial logging, which covers entire regional areas, they may locally be stressful for caribou and are human disturbances that result in the reduction of habitat quality when they occur within local population ranges.

We also extracted and rasterized from the FRI any polygons with a polygon type of unclassified as per previous layers. For Quebec, we extracted disturbance pixels from the Utilisation du territoire dataset, which classifies land cover in Quebec at a 10-m pixel resolution [58]. Any areas classified as "Agricole, Anthropique, Coupes et régénérations" or "Non classifié" were extracted and resampled to 30 m.

We quantified older forests (≥100 years old) from the provincial forest inventory datasets and supplemented them with modelled data. For Ontario, we extracted and rasterized forest polygons with an origin year ("OYRORG") of 1920 or earlier (after being updated to account for recent depletion events). For Quebec, we identified forests ≥100 years through the "cl_age" variable in the Carte écoforestière à jour database [59], with polygons categorized as "VIN", "VIR" and all categories with forest age classes ≥100 years. To address spatial and temporal gaps in the FRI, we also included modelled forest age data at a 30-m pixel resolution from Maltman et al. [60]. We selected and added to the old forest layer forest pixels with an estimated age of ≥100 years. We further cleaned the layer through the removal of known logged and disturbed areas from the provincial dataset from the older forest layer.

We conducted a Morphological Spatial Pattern Analysis (MSPA) [61] (hereafter, "patch analysis") on the primary forest layer using the GuidosToolbox [62] to delineate the core forest from edges and other non-core pixels. The edge width was set to 30 m (one pixel) as a conservative estimate of the edge effect on forest habitat. From the subset of pixels identified as "core" forest, contiguous pixels were grouped into patches (including diagonally contiguous), and the number and area of these patches were calculated.

We mapped boreal caribou suitable habitat within the 21 ranges of local populations in three steps. First, we extracted treed wetland and coniferous forest from the national land cover map for 2019 and masked the population ranges that overlapped with the study area. We selected treed wetland and coniferous forest as they most closely aligned to the selected boreal caribou biophysical habitat attributes listed in the National Scientific Assessment of Critical Habitat for Boreal Caribou [22], which states that they generally select upland and lowland mature and old undisturbed coniferous forests or peatlands, while avoiding shrub-rich habitats, deciduous forests, and anthropogenically disturbed areas. The spatial habitat requirements of boreal caribou are large tracts of mature and old undisturbed coniferous forest that facilitate their antipredator spacing-out strategy [63].

When timber harvesting operations increase in boreal caribou populations' range, areas of clearcuts lead to the fragmentation of the caribou's suitable habitat, while the proliferation of early seral habitats increases the abundance of other cervids, particularly moose (*Alces americanus*), given the accessible and palatable vegetation in clearcuts [64]. This higher abundance of ungulates triggers a numerical response of wolves (*Canis lupus*) that increases the predation pressure on caribou [65,66]. In addition, black bears (*Ursus americanus*), which also benefit from the palatable vegetation in clearcuts, become incidental predators of caribou calves [67]. The predation risk on boreal caribou is exacerbated by the expansion of logging roads that facilitate predator movement [44,68], predator–prey encounters [69] that directly impact caribou calves [39], and adult caribou survival [41]. Hence, caribou mortality increases in proximity to cutblocks and logging roads, both for calves and adults [70].

Second, we assembled a disturbance layer for land within the boreal caribou local population ranges that intersected the study area, sourced from national and provincial datasets [22,71]. The disturbances included contemporary harvest (since 1980) buffered by 500 m; the combined provincial disturbance layer (powerlines, railways, seismic lines, pipelines dams, airstrips, mines, reservoirs, settlements, well sites, agriculture, and oil and gas) buffered by 500 m [57,58]; roads buffered by 500 m, sourced from [59,72,73]; and fires since 1980, sourced from [74]. All disturbances and buffer distances used in our analysis were previously determined by the Scientific Report on Critical Habitat Assessment of the Boreal Caribou [22]. We rasterized vector datasets as per earlier layers, and all caribou disturbances were merged into a single raster layer. Insect infestations were not included as a disturbance factor in our analysis.

Third, within each of the 21 boreal caribou local population ranges, we calculated the percentage of the area with critical caribou habitat and the percentage of the area that was disturbed. Using Environment Canada methods [22], we assessed the level of risk that each local population of boreal caribou is exposed to in each critical habitat region based on proportional disturbance thresholds for the level of risk to stable or positive population growth: $\leq$10% disturbance is very low risk; >10 $\leq$ 35% is low risk; >35 $\leq$ 45% is moderate risk; >45 $\leq$ 75% is high risk; and >75% is very high risk, with >35% disturbance being unsuitable for supporting stable caribou populations. We also conducted a patch analysis on the critical caribou habitat to generate patch statistics.

3. Results

The cumulative area of recently logged forest (from ~1976 to 2020) was 14,024,619 ha, with 8,210,617 ha in Quebec and 5,814,002 ha in Ontario (Table 1, Figures 3 and 4). The annual area logged peaked in the year 2000 at 462,097 ha, with a sharp decline in 2008 coincidental with the global financial crisis (Figure 4). While there was a reduction in the rate of cumulative area logged from 2008, the cumulative area continued to increase monotonically.

The total area of older forests ($\geq$100 years old) was 2,124,934 ha, with 11,840,474 ha in Quebec and 9,408,867 ha in Ontario (Table 1; Figure 5). Of this, the patch analysis assigned 8,359,381 ha as core area (Table 2). The patch count statistics (Table 3) revealed that there were 1,085,822 core older forest patches <0.25 ha and an additional 603,052 < 1.0 ha. There were 52 > 1000–50,000 ha and 8 > 50,000 ha (Figure 5).

Table 1. Aggregate forest statistics for study area. Category percentages show the fraction of natural forest land cover.

	Category	Forest Area ha		
		Quebec	Ontario	Total
a.	Natural forest land cover	27,587,508	22,479,508	50,067,016
b.	Recently logged (since ~1976)	8,210,617 (30%)	5,814,002 (26%)	14,024,619 (28%)
c.	Older forests (≥100 years old)	11,840,474 (43%)	9,408,867 (42%)	21,249,341 (42%)

Table 2. Total area in each patch statistics category for older forests (≥100 years old) and for boreal caribou habitat in the caribou critical habitat ranges. Class definitions are derived from the Morphological Spatial Pattern Analysis (MSPA) (patch analysis). Core areas are defined as interior forests, edge areas represent forest edges, perforations are interior forest edges, branches are edge forests connected to a forest patch at one end, bridges are forest corridors connected to the core at both ends, islets are patches too small to contain a core, and loops are edges connected to the same core habitat.

Class	Older Forests (≥100 Years) (ha)	Critical Caribou Habitat in Local Population Ranges (ha)
Core	8,359,381	6,103,534
Edge	3,423,706	1,190,911
Perforation	424,040	532,055
Branch	2,348,692	395,647
Bridge	3,477,735	369,369
Islet	2,538,021	182,047
Loop	680,345	249,439

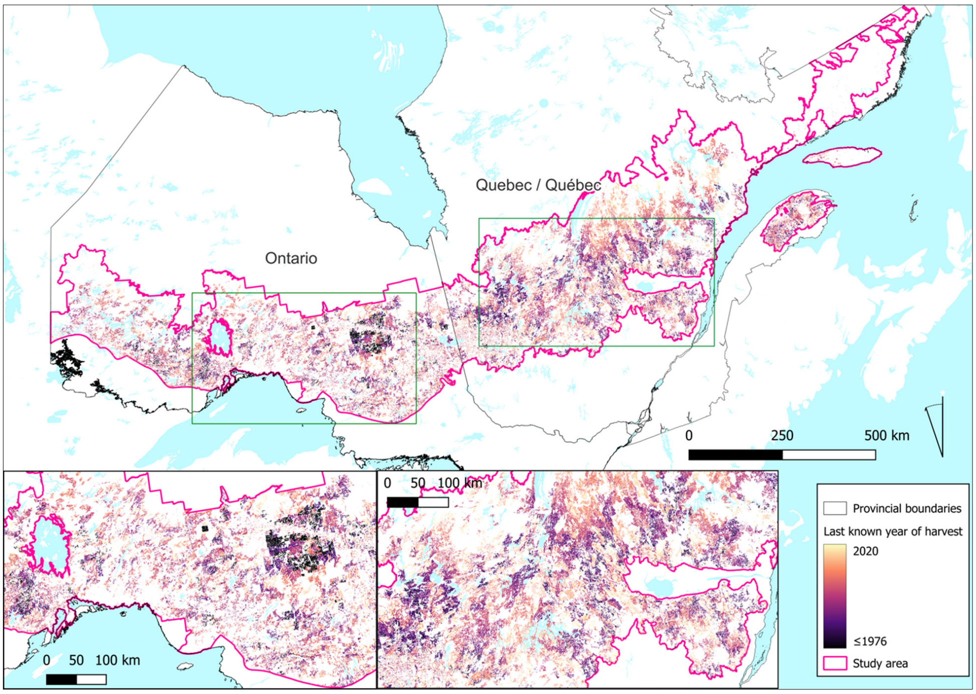

Figure 3. Overview of logged forest within the study area from provincial FRI data for the period ∼1976 to 2020.

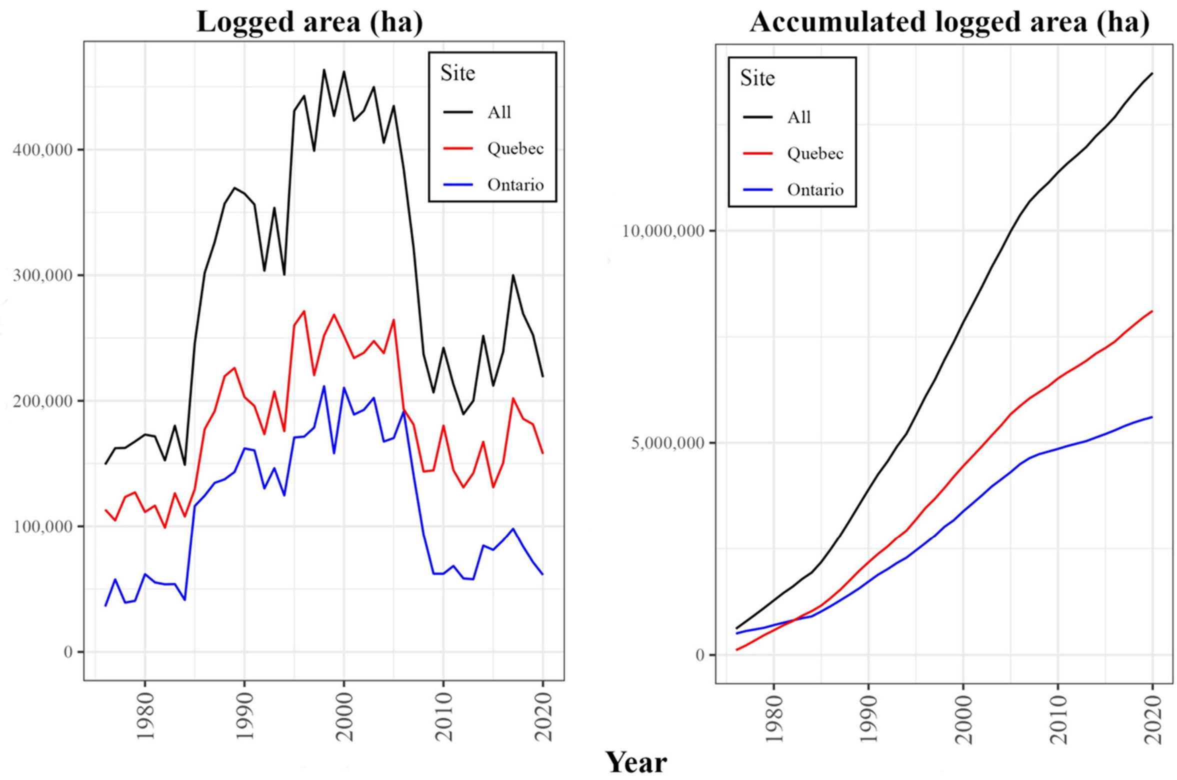

Figure 4. Area of recently logged forest ~1976 to 2020. The national modelled data were used to fill gaps in the provincial forest resource inventory data commenced in 1985.

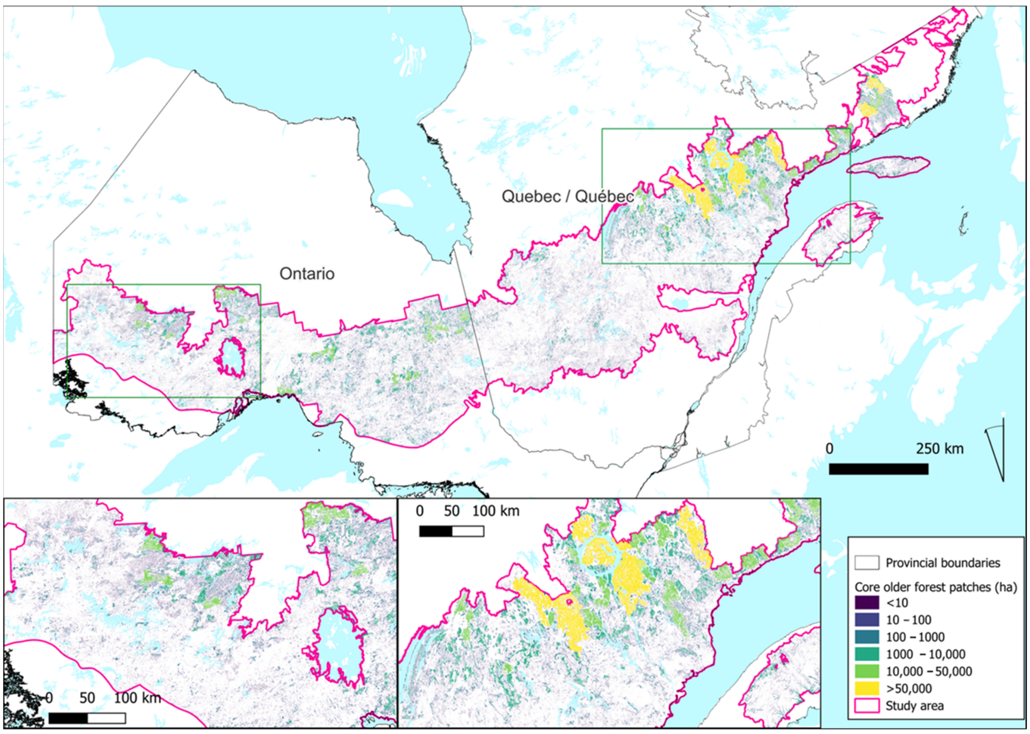

Figure 5. The distribution of older forests (≥100 years old) within the study area, coloured by patch size category.

Table 3. Counts of core patch sizes by size class for older forests and for critical caribou habitat in the 21 local population ranges.

Patch Size (ha)	Patch Count	
	Older Forests (≥100 yrs)	Critical Caribou Habitat in Local Population Ranges
0–0.25	1,085,822	176,818
0.25–0.5	360,189	63,465
0.5–1	242,863	43,315
1–2	156,393	33,776
2–3	69,139	15,377
3–4	40,443	9176
4–5	26,705	6188
5–10	62,695	14,818
10–25	44,435	11,888
25–50	16,892	5113
50–100	8548	3095
100–250	4701	2125
250–500	1452	869
500–1000	664	505
1000–10,000	542	505
10,000–50,000	52	55
50,000–250,000	7	12
250,000–500,000	1	2

The core critical caribou habitat in the 21 local population ranges totalled 6,103,534 ha (Table 2; Figure 6), distributed among ~387,102 patches with 362,933 < 10 ha and 14 > 50,000 ha (Table 3). The median percentage of local population ranges that was disturbed was 53.5%, with Charlevoix having the maximum (90.3%) and Basse Côte-Nord the least (34.9%) (Table 4, Figure 6). Ranges with ≤35% of the area disturbed are recognized as at the maximum level of disturbance that will support range self-sustaining populations [22]. For the 21 boreal caribou ranges examined, 4 were at very high risk, 15 at high risk, and 2 at low risk (Table 4).

Table 4. Area of critical caribou habitat within the 21 local population ranges, the proportion of each range that is disturbed, and the assessed level of risk.

Population	Local Population Range Area (ha)	Critical Boreal Caribou Habitat Area (ha)	% Local Population Range Disturbed	Level of Risk	Previous Boreal Caribou Assessment (Source: Environment Canada (2011))
Assinica	5,109,938	850,283	72.6	High	NA
Basse Côte-Nord	3,490,665	1,663,848	34.9	Low	NA
Berens	1,612,106	369,895	46.4	High	RNSS/RSS, as likely as not
Brightsand	1,525,297	241,067	65.6	High	RNSS/RSS, as likely as not
Caniapiscau	540,674	262,596	34.9	Low	NA
Charlevoix	777,738	60,548	90.3	Very High	RNSS, very unlikely
Churchill	2,035,815	427,948	49.0	High	RSS, likely
Coastal	162,874	7531	45.3	High	RSS, likely
Detour	1,977,443	676,313	50.9	High	NA
Gaspésie	425,460	42,938	87.5	Very High	NA
Kesagami	3,373,204	1,042,716	53.5	High	RNSS, very unlikely
Manicougan	2,742,141	1,062,412	47.2	High	RSS, likely
Manouane	2,716,465	812,296	58.1	High	RNSS/RSS, as likely as not
Nipigon	2,928,933	243,926	74.4	High	RSS, likely

Table 4. *Cont.*

Population	Local Population Range Area (ha)	Critical Boreal Caribou Habitat Area (ha)	% Local Population Range Disturbed	Level of Risk	Previous Boreal Caribou Assessment (Source: Environment Canada (2011))
Notaway	2,371,806	877,779	46.3	High	NA
Outardes	2,775,318	983,492	50.7	High	NA
Pagwachuan	2,165,773	408060	67.8	High	RSS, likely
Pipmuacan	1,911,249	279,546	75.2	Very High	RNSS, unlikely
Sydney	578,902	69,528	50.0	High	RNSS, unlikely
Témicamie	6,465,416	1,336,048	67.8	High	NA
Val d'Or	385,381	54,876	75.8	Very High	RNSS, unlikely

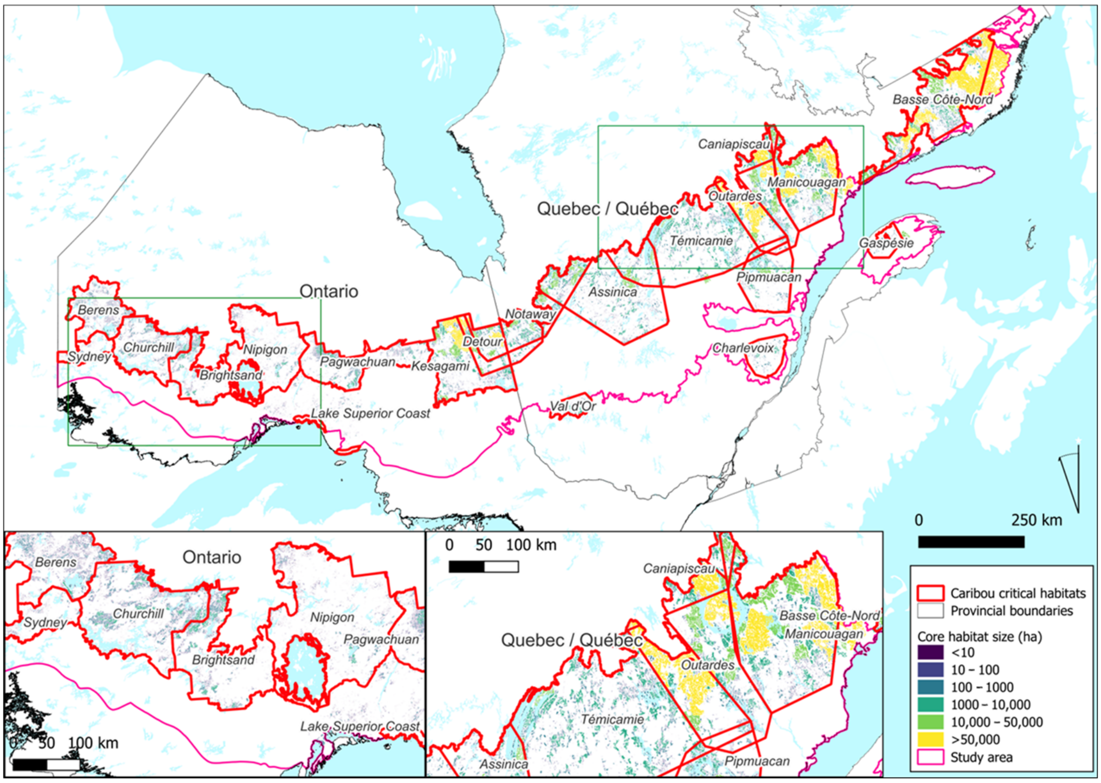

Figure 6. The distribution of core caribou habitat patches within the 21 critical habitat population ranges, coloured by patch size category.

4. Discussion

Our main findings (Table 1, Figure 3) reveal a total recently logged area of ~14 M ha that constitutes around 28% of the study area. We use the term "recently logged since ~1976" as the results are limited by the available data sources, and this is an estimate of when reliable provincial forest management information systems and FMU record keeping were implemented. However, it is well established that Eastern Canada has a long history of logging, throughout much of the 19th century [75]. Eastern Quebec, for example, experienced selective logging during the 19th century, with intensification of logging during the first half of the 20th century as clearcutting, plantations, and salvage logging following wildlife or insect outbreaks [76] ramped up only after 1975 [18]. Consequently, it cannot be assumed that forests with no record of recent logging after approximately the early 1900s have never been logged and therefore would meet the formal definition of primary forest [77]. Further analysis revealed that the forests for which there is no record of recent logging (since ~1976) contain a range of age classes, including ~21.2 M ha of older forests. Most of the remaining older forests are found at the northern boundary of the study area, with smaller areas in the south reflecting the long legacy of logging combined with natural disturbances (Figure 7).

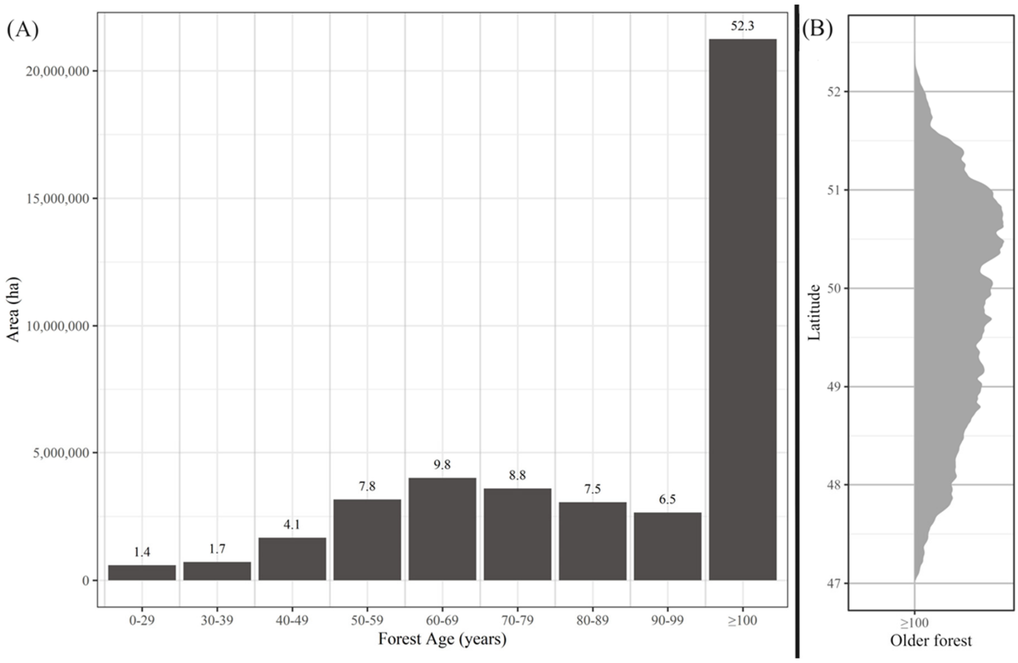

Figure 7. Distribution of stand age in forests within the study area for which there was no record of logging since ~1976 (**A**) and the latitudinal distribution of older forest (≥100 years old) in the study area (**B**). Numbers above each bar represent the percentage area of forest within each age category outside areas for which there is a record of logging.

The annual amount of recently logged forests increased dramatically from 1972 until 2008 (Figure 4) and then dropped, coinciding with the global financial crisis, which heralded a steep decline in demand for wood resources [78]. While annual logging rates remain well below the pre-2008 peak, what is critical from an environmental and biodiversity perspective is the impacts from the ongoing and growing cumulative harvested area [79–81] (Figure 6).

The cumulative impact from the ~14 M ha of recently logged forest differs from the complexities of the natural disturbance regimes and resulting forest succession pathways observed in Canadian boreal forests [13]. Previous studies in Quebec have found that the landscape-level extent of older forests has decreased in boreal forests managed for industrial wood production, resulting in a loss of stand age diversity, particularly older forests, to the expanse of early-successional and young forest stands, which become more abundant than they were under historical natural disturbance regimes [16,82–84]. Indeed, [82] and [85] have shown that logging has significantly increased the rate of disturbances in this region. This decrease in older forests when compared with historical natural conditions is accompanied by the resulting decline in structural attributes—such as large live and dead standing trees and coarse woody debris associated with older forests—which negatively affects biodiversity [19,20,86]. Recently logged stands are more vulnerable than older stands to eastern spruce budworm (*Choristoneura fumiferana* Clem.) and windthrow [87].

While the total area of older forests (~21.2 M ha) is substantial (Table 1), it occurs as a vast scatter of patches embedded within a highly anthropically disturbed forest landscape structure in terms of both species composition and spatial configuration (Tables 2 and 3, Figure 6) [88–90]. There are thus only eight remaining patches ≥50,000 ha, which is the area threshold for defining Intact Forest Landscapes (IFL) [89]. IFL are important in Canadian boreal forest for the conservation of biodiversity, ecological processes, and other ecosystem services [88]. The largest of these IFL are found at the northern border of the managed forest estate and are contiguous with the extensive unmanaged forest landscapes that lay beyond to the north.

4.1. Caribou Habitat

We identified core suitable caribou habitat in the 21 local population ranges found within the managed forest estate of our study area. Only two ranges had disturbance levels ≤35%, the recognized maximum level of disturbance that will likely support, with a 60% probability, range self-sustaining populations (Table 4). The remaining 19 ranges were assessed at high to very high risk and therefore require a "restoration" rather than "conservation" management response [22].

The predominance of the cumulative impact of logging on the loss and degradation of suitable caribou habitat is now well established [90–92]. In an inter-population chronosequence model, Environment Canada [22] has shown that nearly 70% of the variation in caribou recruitment across twenty-four study areas spanning the full range of boreal caribou distribution and range condition in Canada was explained by a single composite measure of the total disturbance comprising buffered anthropogenic and fire disturbances. Most of the variation in caribou recruitment could be attributed to the negative effects of anthropogenic disturbance, which includes logging as well as logging roads and other linear infrastructures such as seismic lines, which are mostly prevalent in the Prairie provinces of Western Canada [22]. This disturbance–recruitment relationship was also detected for single population responses as a function of cumulative range disturbances over time [42]. Both direct and indirect impacts arise, including on caribou behaviour, an increased predator–prey encounter risk [69], the higher efficiency of predator movement in timber harvested landscapes due to the considerable development of logging road networks [44], and the resulting effects on caribou vital rates and demographic trends. Moreover, the landscape configuration resulting from intensive logging forces caribou to use small remnants of suitable habitat (i.e., undisturbed mature and older forest) that are intermingled with more risky habitats (including cutblocks and logging roads) [79].

4.2. Forest Degradation

The definition of forest and deforestation is well established in international agreements [77], albeit not without controversy [93]. However, the definition of forest degradation remains the focus of ongoing discussion and more attention is now being paid to it in policy (e.g., European Union regulation prohibiting the import of certain commodities and products associated with deforestation and forest degradation [94]). The conversion of naturally regenerating forest to plantations or planted forest constitutes habitat conversion and therefore results in a loss of biodiversity and a reduction in key ecosystem services [95]. Forest regeneration in harvested stands in the FMU data for Quebec reported a substantial area (20%) of harvested forest with assisted regeneration through tree plantations, totalling ~8.2 M ha. The Ontario province's forest management practices include artificial regeneration (direct seeding, planting), with planting considered suitable for a wide range of sites, and it is often the regeneration option chosen for productive and competitive sites [96].

In analyzing national contributions to the 2020 Global Forest Resources Assessment, the FAO found that countries defined degraded forest based on a range of factors, including the presence of forest disturbances (logging, wildfire); changes in forest structure (including decreases in forest canopy); the loss of productivity; the loss of biodiversity; soil damage/erosion; reductions in the provision of ecosystem goods and services; negative effects on other land uses (e.g., by causing a loss of downstream water quality); and the loss of carbon, biomass, and growing stock [97]. Our results therefore reveal two major categories of forest degradation in the managed forest estate of Ontario and Quebec, which have accrued due to the cumulative ecological impacts of logging: (1) there has been a loss of stand age diversity, particularly older forests, to the expanse of early-successional and young forest stands; and (2) the loss and degradation of critical caribou habitat and an increase in the risks to self-sustaining boreal caribou populations.

The Canadian Government claims that its forests have been managed according to the principles of sustainable forest management for many years [98], yet this notion of sustainability is tied mainly to maximizing wood production and ensuring the regeneration of commercially desirable tree species following logging [99]. From this perspective, the commercial logging of natural forests does not constitute either deforestation or degradation, so long as the forest remains dominated by naturally regenerating, commercially valued tree species and the wood supply is sustained (e.g., the sustained yield forestry concept). The managed boreal forests of the Canadian provinces of Ontario and Quebec have, on this basis, largely avoided deforestation. However, substantial areas of managed boreal forests are now dominated by early-successional and regenerating stands with less extant older forests and are now out of range of their historical natural proportions [21,82].

A greater emphasis is now needed on the protection and restoration of older forests [5,20]. As noted by [79], the remaining large older forest tracks need to be set aside conjointly as caribou habitat must be restored within the ranges of local populations. In FMUs where logging continues, alternatives to short-rotation clearcutting are needed [10,17,19,83,100,101] in order to increase the prevalence of larger, older forest patches.

5. Conclusions

The cumulative impact of logging in the managed forest estate of Ontario and Quebec has resulted in the truncation of the landscape-level diversity of stand ages, particularly with regard to older forests, by solely using even-aged management harvesting with clearcuts. This has degraded the boreal forest environment and increased the prevalence of at-risk boreal caribou populations. Major changes are needed to boreal forest management in Ontario and Quebec for it to be ecologically sustainable for caribou populations but also for other elements of biodiversity associated with older forests and their attributes.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/land13010006/s1. Table S1: Availability of Ontario FRI data for all FMUs in the study region; Table S2: Quebec southern ecoforest inventory data codes for the ORIGINE attribute, with designations assigned for this study.

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References

1. Rogers, B.M.; Mackey, B.; Shestakova, T.A.; Keith, H.; Young, V.; Kormos, C.F.; DellaSala, D.A.; Dean, J.; Birdsey, R.; Bush, G.; et al. Using ecosystem integrity to maximize climate mitigation and minimize risk in international forest policy. *Front. For. Glob. Chang.* **2022**, *5*, 929281. [CrossRef]
2. Wei, X.; Giles-Hansen, K.; Spencer, S.A.; Ge, X.; Onuchin, A.; Li, Q.; Burenina, T.; Ilintsev, A.; Hou, Y. Forest harvesting and hydrology in boreal Forests: Under an increased and cumulative disturbance context. *For. Ecol. Manag.* **2022**, *522*, 120468. [CrossRef]

3. Lorås, J.; Eidissen, S.E. What the "seven-flitch log" may tell us. Changes in the boreal forest ecology over the past 500 years. *Blyttia* **2019**, *77*, 81–94.
4. Bouderbala, I.; Labadie, G.; Béland, J.-M.; Tremblay, J.A.; Boulanger, Y.; Hébert, C.; Desrosiers, P.; Allard, A.; Fortin, D. Long-term effect of forest harvesting on boreal species assemblages under climate change. *PLoS Clim.* **2023**, *2*, e0000179. [CrossRef]
5. Drapeau, P.; Villard, M.-A.; Leduc, A.; Hannon, S.J. Natural disturbance regimes as templates for the response of bird species assemblages to contemporary forest management. *Divers. Distrib.* **2016**, *22*, 385–399. [CrossRef]
6. Muurinen, L.; Oksanen, J.; Vanha-Majamaa, I.; Virtanen, R. Legacy effects of logging on boreal forest understorey vegetation communities in decadal time scales in northern Finland. *For. Ecol. Manag.* **2019**, *436*, 11–20. [CrossRef]
7. Boucher, Y.; Auger, I.; Arseneault, D.; Elzein, T.; Sirois, L. Long-term (1925–2015) forest structure reorganization in an actively managed temperate-boreal forest region of eastern North America. *For. Ecol. Manag.* **2021**, *481*, 118744. [CrossRef]
8. Longo, M.; Saatchi, S.; Keller, M.; Bowman, K.; Ferraz, A.; Moorcroft, P.R.; Morton, D.C.; Bonal, D.; Brando, P.; Burban, B.; et al. Impacts of Degradation on Water, Energy, and Carbon Cycling of the Amazon Tropical Forests. *J. Geophys. Res. Biogeosci.* **2020**, *125*, e2020JG005677. [CrossRef]
9. Bradshaw, C.J.A.; Warkentin, I.G.; Sodhi, N.S. Urgent preservation of boreal carbon stocks and biodiversity. *Trends Ecol. Evol.* **2009**, *24*, 541–548. [CrossRef]
10. Gauthier, S.; Vaillancourt, M.-A.; Leduc, A.; De Grandpré, L.; Kneeshaw, D.D.; Morin, H.; Drapeau, P.; Bergeron, Y. (Eds.) *Ecosystem Management in the Boreal Forest*; Presses de l'Université du Québec: Québec, QC, Canada, 2009.
11. Anyomi, K.A.; Neary, B.; Chen, J.; Mayor, S.J. A critical review of successional dynamics in boreal forests of North America. *Environ. Rev.* **2022**, *30*, 563–594. [CrossRef]
12. Brandt, J.P.; Flannigan, M.D.; Maynard, D.G.; Thompson, I.D.; Volney, W.J.A. An introduction to Canada's boreal zone: Ecosystem processes, health, sustainability, and environmental issues. *Environ. Rev.* **2013**, *21*, 207–226. [CrossRef]
13. Bergeron, Y.; Fenton, N.J. Boreal forests of eastern Canada revisited: Old growth, nonfire disturbances, forest succession, and biodiversity. *Botany* **2012**, *90*, 509–523. [CrossRef]
14. Harper, K.A.; Bergeron, Y.; Drapeau, P.; Gauthier, S.; De Grandpré, L. Structural development following fire in black spruce boreal forest. *For. Ecol. Manag.* **2005**, *206*, 293–306. [CrossRef]
15. OMNR. *Emulating Natural Disturbances: Cleacut silviculture in Ontario*; Ministry of Natural Resources: Ontario, ON, Canada, 2013.
16. Bergeron, Y.; Drapeau, P.; Gauthier, S.; Lecomte, N. Using knowledge of natural disturbances to support sustainable forest management in the northern Clay Belt. *For. Chron.* **2007**, *83*, 326–337. [CrossRef]
17. Bergeron, Y.; Leduc, A.; Harvey, B.D.; Gauthier, S. Natural fire regime: A guide for sustainable management of the Canadian boreal forest. *Silva Fenn.* **2002**, *36*, 81–95. [CrossRef]
18. Boucher, Y.; Arseneault, D.; Sirois, L.; Blais, L. Logging pattern and landscape changes over the last century at the boreal and deciduous forest transition in Eastern Canada. *Landsc. Ecol.* **2009**, *24*, 171–184. [CrossRef]
19. Gauthier, S.; Bernier, P.; Kuuluvainen, T.; Shvidenko, A.Z.; Schepaschenko, D.G. Boreal forest health and global change. *Science* **2015**, *349*, 819–822. [CrossRef]
20. Drapeau, P.; Nappi, A.; Imbeau, L.; Saint-Germain, M. Standing deadwood for keystone bird species in the eastern boreal forest: Managing for snag dynamics. *For. Chron.* **2009**, *85*, 227–234. [CrossRef]
21. Drapeau, P.; Leduc, A.; Bergeron, Y. Bridging Ecosystem and Multiple Species Approaches for Setting Conservation Targets in Managed Boreal Landscapes. In *Setting Conservation Targets for Managed Forest landscapes*; Villard, M., Jonsson, B.G., Eds.; Cambridge University Press: Cambridge, UK, 2009; pp. 129–160.
22. Environment Canada. *Scientific Assessment to Inform the Identification of Critical Habitat for Woodland Caribou, Boreal Population, in Canada—2011 Update: Introduction*; Environment Canada: Ontario, ON, Canada, 2011; Available online: https://www.canada.ca/en/environment-climate-change/services/species-risk-public-registry/related-information/scientific-assessment-critical-habitat-woodland-caribou-boreal-2011-sec1.html (accessed on 23 April 2023).
23. Hill, D.; Simpson-Marran, M.; Gould, L.; Nason, S. *Status of Boreal Woodland Caribou Conservation in Canada: A Summary of Range Planning, Restoration, and Opportunities to Win on Caribou and Climate*; The Pembina Institute: Calgary, AB, Canada, 2021.
24. COSEWIC. *OSEWIC Assessment and Status Report on the Caribou Rangifer tarandus, Newfoundland Population, Atlantic-Gaspésie Population, Boreal Population in Canada—2014*; Government of Canada: Ottawa, ON, Canada, 2014.
25. Festa-Bianchet, M.; Ray, J.C.; Boutin, S.; Côté, S.D.; Gunn, A. Conservation of caribou (*Rangifer tarandus*) in Canada: An uncertain future1This review is part of the virtual symposium "Flagship Species – Flagship Problems" that deals with ecology, biodiversity and management issues, and climate impacts on species at risk and of Canadian importance, including the polar bear (*Ursus maritimus*), Atlantic cod (*Gadus morhua*), Piping Plover (*Charadrius melodus*), and caribou (*Rangifer tarandus*). *Can. J. Zool.* **2011**, *89*, 419–434. [CrossRef]
26. Schaefer, J.A. Long-Term Range Recession and the Persistence of Caribou in the Taiga. *Conserv. Biol.* **2003**, *17*, 1435–1439. [CrossRef]
27. Dyer, S.J.; O'Neill, J.P.; Wasel, S.M.; Boutin, S. Avoidance of Industrial Development by Woodland Caribou. *J. Wildl. Manag.* **2001**, *65*, 531–542. [CrossRef]
28. Muhly, T.; Serrouya, R.; Neilson, E.; Li, H.; Boutin, S. Influence of In-Situ Oil Sands Development on Caribou (*Rangifer tarandus*) Movement. *PLoS ONE* **2015**, *10*, e0136933. [CrossRef] [PubMed]

29. Polfus, J.L.; Hebblewhite, M.; Heinemeyer, K. Identifying indirect habitat loss and avoidance of human infrastructure by northern mountain woodland caribou. *Biol. Conserv.* **2011**, *144*, 2637–2646. [CrossRef]
30. Skarin, A.; Nellemann, C.; Rönnegård, L.; Sandström, P.; Lundqvist, H. Wind farm construction impacts reindeer migration and movement corridors. *Landsc. Ecol.* **2015**, *30*, 1527–1540. [CrossRef]
31. Weir, J.N.; Mahoney, S.P.; McLaren, B.; Ferguson, S.H. Effects of Mine Development on Woodland Caribou *Rangifer tarandus* Distribution. *Wildl. Biol.* **2007**, *13*, 66–74. [CrossRef]
32. Dickie, M.; Serrouya, R.; DeMars, C.; Cranston, J.; Boutin, S. Evaluating functional recovery of habitat for threatened woodland caribou. *Ecosphere* **2017**, *8*, e01936. [CrossRef]
33. Mumma, M.A.; Gillingham, M.P.; Johnson, C.J.; Parker, K.L. Functional responses to anthropogenic linear features in a complex predator-multi-prey system. *Landsc. Ecol.* **2019**, *34*, 2575–2597. [CrossRef]
34. Mumma, M.A.; Gillingham, M.P.; Parker, K.L.; Johnson, C.J.; Watters, M. Predation risk for boreal woodland caribou in human-modified landscapes: Evidence of wolf spatial responses independent of apparent competition. *Biol. Conserv.* **2018**, *228*, 215–223. [CrossRef]
35. Fortin, D.; Buono, P.-L.; Schmitz, O.J.; Courbin, N.; Losier, C.; St-Laurent, M.-H.; Drapeau, P.; Heppell, S.; Dussault, C.; Brodeur, V.; et al. A spatial theory for characterizing predator–multiprey interactions in heterogeneous landscapes. *Proc. R. Soc. B Biol. Sci.* **2015**, *282*, 20150973. [CrossRef]
36. Hins, C.; Ouellet, J.-P.; Dussault, C.; St-Laurent, M.-H. Habitat selection by forest-dwelling caribou in managed boreal forest of eastern Canada: Evidence of a landscape configuration effect. *For. Ecol. Manag.* **2009**, *257*, 636–643. [CrossRef]
37. Leclerc, M.; Dussault, C.; St-Laurent, M.-H. Multiscale assessment of the impacts of roads and cutovers on calving site selection in woodland caribou. *For. Ecol. Manag.* **2012**, *286*, 59–65. [CrossRef]
38. Vors, L.S.; Schaefer, J.A.; Pond, B.A.; Rodgers, A.R.; Patterson, B.R. Woodland Caribou Extirpation and Anthropogenic Landscape Disturbance in Ontario. *J. Wildl. Manag.* **2007**, *71*, 1249–1256. [CrossRef]
39. Dussault, C.; Pinard, V.; Ouellet, J.-P.; Courtois, R.; Fortin, D. Avoidance of roads and selection for recent cutovers by threatened caribou: Fitness-rewarding or maladaptive behaviour? *Proc. R. Soc. B Biol. Sci.* **2012**, *279*, 4481–4488. [CrossRef] [PubMed]
40. Leblond, M.; Dussault, C.; Ouellet, J.-P. Avoidance of roads by large herbivores and its relation to disturbance intensity. *J. Zool.* **2013**, *289*, 32–40. [CrossRef]
41. Leblond, M.; Dussault, C.; Ouellet, J.-P. Impacts of Human Disturbance on Large Prey Species: Do Behavioral Reactions Translate to Fitness Consequences? *PLoS ONE* **2013**, *8*, e73695. [CrossRef] [PubMed]
42. Rudolph, T.D.; Drapeau, P.; Imbeau, L.; Brodeur, V.; Légaré, S.; St-Laurent, M.-H. Demographic responses of boreal caribou to cumulative disturbances highlight elasticity of range-specific tolerance thresholds. *Biodivers. Conserv.* **2017**, *26*, 1179–1198. [CrossRef]
43. Rudolph, T.D.; Drapeau, P.; St-Laurent, M.; Imbeau, L. *Status of Woodland Caribou (Rangifer tarandus Caribou) in the James Bay Region of Northern Quebec. Scientific Report Presented to the Ministère des Ressources Naturelles et de la Faune du Québec and the Grand Council of the Crees (Eeyou Istchee)*; Ministère des Ressources Naturelles et de la Faune du Québec and the Grand Council of the Crees (Eeyou Istchee): Montreal, QC, Canada, 2012.
44. St-Pierre, F.; Drapeau, P.; St-Laurent, M.-H. Stairway to heaven or highway to hell? How characteristics of forest roads shape their use by large mammals in the boreal forest. *For. Ecol. Manag.* **2022**, *510*, 120108. [CrossRef]
45. Jobidon, R.; Bergeron, Y.; Robitaille, A.; Raulier, F.; Gauthier, S.; Imbeau, L.; Saucier, J.-P.; Boudreault, C. A biophysical approach to delineate a northern limit to commercial forestry: The case of Quebec's boreal forest. *Can. J. For. Res.* **2015**, *45*, 515–528. [CrossRef]
46. Forêts, Faune et Parcs Quebec. *MFFP—Espèces Fauniques Menacées ou Vulnérables au Québec—Caribou des Bois, Écotype Forestier*; Forêts, Faune et Parcs Quebec: Quebec, QC, Canada, 2022. Available online: https://www3.mffp.gouv.qc.ca/faune/especes/menacees/fiche.asp?noEsp=53 (accessed on 14 June 2023).
47. Land Information Ontario. *Caribou Range Boundary*; Land Information Ontario: Ontario, ON, Canada, 2019. Available online: https://geohub.lio.gov.on.ca/datasets/lio::caribou-range-boundary/about (accessed on 14 June 2023).
48. Hermosilla, T.; Wulder, M.A.; White, J.C.; Coops, N.C. Land cover classification in an era of big and open data: Optimizing localized implementation and training data selection to improve mapping outcomes. *Remote Sens. Environ.* **2022**, *268*, 112780. [CrossRef]
49. Hermosilla, T.; Wulder, M.A.; White, J.C.; Coops, N.C.; Hobart, G.W. Disturbance-Informed Annual Land Cover Classification Maps of Canada's Forested Ecosystems for a 29-Year Landsat Time Series. *Can. J. Remote Sens.* **2018**, *44*, 67–87. [CrossRef]
50. Hijmans, R.J. *Terra: Spatial Data Analysis*; The Comprehensive R Archive Network: Ontario, ON, Canada, 2022.
51. R Core Team. *R: A Language and Environment for Statistical Computing*; R Core Team: Vienna, Austria, 2023.
52. QGIS Development Team. *QGIS Geographic Information System*; QGIS Development Team: Rimouski, QC, Canada, 2023.
53. Land Information Ontario. *Forest Resources Inventory Packaged Products—Version 2*; Land Information Ontario: Ontario, ON, Canada, 2022. Available online: https://geohub.lio.gov.on.ca/maps/lio::forest-resources-inventory-packaged-products-version-2/about (accessed on 4 April 2023).
54. Ministère des Ressources Naturelles et des Forêts. *Unité D'Aménagement (UA)—Données Québec*; Ministère des Ressources Naturelles et des Forêts: Québec, QU, Canada, 2023. Available online: https://www.donneesquebec.ca/recherche/dataset/unite-d-amenagement (accessed on 18 April 2023).

55. Ministère des Ressources Naturelles et des Forêts. *Récolte et Autres Interventions Sylvicoles—Données Québec*; Ministère des Ressources Naturelles et des Forêts: Québec, QU, Canada, 2023. Available online: https://www.donneesquebec.ca/recherche/dataset/recolte-et-reboisement (accessed on 4 April 2023).
56. Hermosilla, T.; Wulder, M.A.; White, J.C.; Coops, N.C.; Hobart, G.W.; Campbell, L.B. Mass data processing of time series Landsat imagery: Pixels to data products for forest monitoring. *Int. J. Digit. Earth* **2016**, *9*, 1035–1054. [CrossRef]
57. Land Information Ontario. *Ontario Land Cover Compilation v.2.0*; Land Information Ontario: Ontario, ON, Canada, 2022. Available online: https://geohub.lio.gov.on.ca/documents/7aa998fdf100434da27a41f1c637382c (accessed on 13 April 2023).
58. Ministère de l'Environnement. *Utilisation du Territoire—Données Québec*; Ministère de l'Environnement: Québec, QU, Canada, 2023. Available online: https://www.donneesquebec.ca/recherche/dataset/utilisation-du-territoire (accessed on 13 April 2023).
59. Ministère des Ressources Naturelles et des Forêts. *Carte Écoforestière à Jour—Données Québec*; Ministère des Ressources Naturelles et des Forêts: Québec, QU, Canada, 2022. Available online: https://www.donneesquebec.ca/recherche/dataset/carte-ecoforestiere-avec-perturbations# (accessed on 15 June 2023).
60. Maltman, J.C.; Hermosilla, T.; Wulder, M.A.; Coops, N.C.; White, J.C. Estimating and mapping forest age across Canada's forested ecosystems. *Remote Sens. Environ.* **2023**, *290*, 113529. [CrossRef]
61. Soille, P.; Vogt, P. Morphological segmentation of binary patterns. *Pattern Recognit. Lett.* **2009**, *30*, 456–459. [CrossRef]
62. Vogt, P.; Riitters, K. GuidosToolbox: Universal digital image object analysis. *Eur. J. Remote Sens.* **2017**, *50*, 352–361. [CrossRef]
63. Lesmerises, R.; Ouellet, J.-P.; Dussault, C.; St-Laurent, M.-H. The influence of landscape matrix on isolated patch use by wide-ranging animals: Conservation lessons for woodland caribou. *Ecol. Evol.* **2013**, *3*, 2880–2891. [CrossRef]
64. Bergqvist, G.; Wallgren, M.; Jernelid, H.; Bergström, R. Forage availability and moose winter browsing in forest landscapes. *For. Ecol. Manag.* **2018**, *419–420*, 170–178. [CrossRef]
65. Seip, D.R. Factors limiting woodland caribou populations and their interrelationships with wolves and moose in southeastern British Columbia. *Can. J. Zool.* **1992**, *70*, 1494–1503. [CrossRef]
66. Wittmer, H.U.; McLellan, B.N.; Serrouya, R.; Apps, C.D. Changes in landscape composition influence the decline of a threatened woodland caribou population. *J. Anim. Ecol.* **2007**, *76*, 568–579. [CrossRef]
67. Leclerc, M.; Dussault, C.; St-Laurent, M.-H. Behavioural strategies towards human disturbances explain individual performance in woodland caribou. *Oecologia* **2014**, *176*, 297–306. [CrossRef]
68. Lesmerises, F.; Dussault, C.; St-Laurent, M.-H. Wolf habitat selection is shaped by human activities in a highly managed boreal forest. *For. Ecol. Manag.* **2012**, *276*, 125–131. [CrossRef]
69. Whittington, J.; Hebblewhite, M.; DeCesare, N.J.; Neufeld, L.; Bradley, M.; Wilmshurst, J.; Musiani, M. Caribou encounters with wolves increase near roads and trails: A time-to-event approach. *J. Appl. Ecol.* **2011**, *48*, 1535–1542. [CrossRef]
70. Losier, C.L.; Couturier, S.; St-Laurent, M.-H.; Drapeau, P.; Dussault, C.; Rudolph, T.; Brodeur, V.; Merkle, J.A.; Fortin, D. Adjustments in habitat selection to changing availability induce fitness costs for a threatened ungulate. *J. Appl. Ecol.* **2015**, *52*, 496–504. [CrossRef]
71. Elkie, P.; Green, K.; Racey, G.; Gluck, M.; Elliot, J.; Hooper, G.; Kushneriuk, R.; Rempel, R. *Science and Information in Support of Policies That Address the Conservation of Woodland Caribou in Ontario 2018*; Ministry of the Environment, Conservation and Parks: Ontario, ON, Canada, 2018. Available online: https://www.ontario.ca/page/range-management-policy-support-woodland-caribou-conservation-and-recovery (accessed on 17 April 2023).
72. Land Information Ontario. *MNRF Road Segments*; Land Information Ontario: Ontario, ON, Canada, 2020. Available online: https://geohub.lio.gov.on.ca/datasets/lio::mnrf-road-segments/explore (accessed on 17 April 2023).
73. Statistics Canada. *National Road Network—NRN—GeoBase Series—Open Government Portal*; Statistics Canada: Ottawa, ON, Canada, 2022. Available online: https://open.canada.ca/data/en/dataset/3d282116-e556-400c-9306-ca1a3cada77f (accessed on 17 April 2023).
74. Natural Resources Canada. *Canadian Wildland Fire Information System | Download Data*; Natural Resources Canada: Calgary, AB, Canada, 2021. Available online: https://cwfis.cfs.nrcan.gc.ca/datamart/download/nfdbpoly (accessed on 17 April 2023).
75. Wynne, G.; James-Abra, E. Timber Trade History. In *The Canadian Encyclopedia*; Historica Canada: Toronto, ON, Canada, 2015; Available online: https://www.thecanadianencyclopedia.ca/en/article/timber-trade-history (accessed on 21 August 2023).
76. Thorn, S.; Bässler, C.; Brandl, R.; Burton, P.J.; Cahall, R.; Campbell, J.L.; Castro, J.; Choi, C.-Y.; Cobb, T.; Donato, D.C.; et al. Impacts of salvage logging on biodiversity: A meta-analysis. *J. Appl. Ecol.* **2018**, *55*, 279–289. [CrossRef]
77. FAO. *Global Forest Resources Assessment 2020: Terms and Definitions FRA 2020*; Food and Agricultural Organization of the United Nations: Rome, Italy, 2020.
78. Antonarakis, A.S.; Pacca, L.; Antoniades, A. The effect of financial crises on deforestation: A global and regional panel data analysis. *Sustain. Sci.* **2022**, *17*, 1037–1057. [CrossRef]
79. St-Laurent, M.-H.; Boulanger, Y.; Cyr, D.; Manka, F.; Drapeau, P.; Gauthier, S. Lowering the rate of timber harvesting to mitigate impacts of climate change on boreal caribou habitat quality in eastern Canada. *Sci. Total Environ.* **2022**, *838*, 156244. [CrossRef]
80. Nagy-Reis, M.; Dickie, M.; Calvert, A.M.; Hebblewhite, M.; Hervieux, D.; Seip, D.R.; Gilbert, S.L.; Venter, O.; DeMars, C.; Boutin, S.; et al. Habitat loss accelerates for the endangered woodland caribou in western Canada. *Conserv. Sci. Pract.* **2021**, *3*, e437. [CrossRef]
81. DellaSala, D.A.; Strittholt, J.R.; Degagne, R.; Mackey, B.; Werner, J.R.; Connolly, M.; Coxson, D.; Couturier, A.; Keith, H. Red-Listed Ecosystem Status of Interior Wetbelt and Inland Temperate Rainforest of British Columbia, Canada. *Land* **2021**, *10*, 775. [CrossRef]

82. Cyr, D.; Gauthier, S.; Bergeron, Y.; Carcaillet, C. Forest management is driving the eastern North American boreal forest outside its natural range of variability. *Front. Ecol. Environ.* **2009**, *7*, 519–524. [CrossRef]
83. Bergeron, Y.; Cyr, D.; Drever, C.R.; Flannigan, M.; Gauthier, S.; Kneeshaw, D.; Lauzon, È.; Leduc, A.; Le Goff, H.; Lesieur, D.; et al. Past, current, and future fire frequencies in Quebec's commercial forests: Implications for the cumulative effects of harvesting and fire on age-class structure and natural disturbance-based management. *Can. J. For. Res.* **2006**, *36*, 2737–2744. [CrossRef]
84. Bergeron, Y.; Gauthier, S.; Flannigan, M.; Kafka, V. Fire Regimes at the Transition between Mixedwood and Coniferous Boreal Forest in Northwestern Quebec. *Ecology* **2004**, *85*, 1916–1932. [CrossRef]
85. Boucher, Y.; Perrault-Hébert, M.; Fournier, R.; Drapeau, P.; Auger, I. Cumulative patterns of logging and fire (1940–2009): Consequences on the structure of the eastern Canadian boreal forest. *Landsc. Ecol.* **2017**, *32*, 361–375. [CrossRef]
86. Löfroth, T.; Birkemoe, T.; Shorohova, E.; Dynesius, M.; Fenton, N.J.; Drapeau, P.; Tremblay, J.A. Deadwood Biodiversity. In *Boreal Forests in the Face of Climate Change: Sustainable Management*; Girona, M.M., Morin, H., Gauthier, S., Bergeron, Y., Eds.; Springer International Publishing: Cham, Switzerland, 2023; pp. 167–189. [CrossRef]
87. Martin, M.; Boucher, Y.; Fenton, N.J.; Marchand, P.; Morin, H. Forest management has reduced the structural diversity of residual boreal old-growth forest landscapes in Eastern Canada. *For. Ecol. Manag.* **2020**, *458*, 117765. [CrossRef]
88. Venier, L.A.; Walton, R.; Thompson, I.D.; Arsenault, A.; Titus, B.D. A review of the intact forest landscape concept in the Canadian boreal forest: Its history, value, and measurement. *Environ. Rev.* **2018**, *26*, 369–377. [CrossRef]
89. Potapov, P.; Hansen, M.C.; Laestadius, L.; Turubanova, S.; Yaroshenko, A.; Thies, C.; Smith, W.; Zhuravleva, I.; Komarova, A.; Minnemeyer, S.; et al. The last frontiers of wilderness: Tracking loss of intact forest landscapes from 2000 to 2013. *Sci. Adv.* **2017**, *3*, e1600821. [CrossRef]
90. Hansen, M.J.; Franklin, S.E.; Woudsma, C.G.; Peterson, M. Caribou habitat mapping and fragmentation analysis using Landsat MSS, TM, and GIS data in the North Columbia Mountains, British Columbia, Canada. *Remote Sens. Environ.* **2001**, *77*, 50–65. [CrossRef]
91. Johnson, C.A.; Drever, C.R.; Kirby, P.; Neave, E.; Martin, A.E. Protecting boreal caribou habitat can help conserve biodiversity and safeguard large quantities of soil carbon in Canada. *Sci. Rep.* **2022**, *12*, 17067. [CrossRef]
92. Leblond, M.; Boulanger, Y.; Pascual Puigdevall, J.; St-Laurent, M.-H. There is still time to reconcile forest management with climate-driven declines in habitat suitability for boreal caribou. *Glob. Ecol. Conserv.* **2022**, *39*, e02294. [CrossRef]
93. Chazdon, R.L.; Brancalion, P.H.S.; Laestadius, L.; Bennett-Curry, A.; Buckingham, K.; Kumar, C.; Moll-Rocek, J.; Vieira, I.C.G.; Wilson, S.J. When is a forest a forest? Forest concepts and definitions in the era of forest and landscape restoration. *Ambio* **2016**, *45*, 538–550. [CrossRef]
94. EU. *European Parliament Legislative Resolution of 19 April 2023 on the Proposal for a Regulation of the European Parliament and of the Council on Making Available on the Union Market as well as Export from the Union of Certain Commodities and Products Associated with Deforestation and Forest Degradation*; European Union: Brussels, Belgium, 2023.
95. Newbold, T.; Hudson, L.N.; Hill, S.L.L.; Contu, S.; Lysenko, I.; Senior, R.A.; Börger, L.; Bennett, D.J.; Choimes, A.; Collen, B.; et al. Global effects of land use on local terrestrial biodiversity. *Nature* **2015**, *520*, 45–50. [CrossRef]
96. Ontario Ministry of Natural Resources. *Forest Management Guide for Boreal Landscapes*; Ontario Ministry of Natural Resources: Peterborough, ON, Canada, 2014.
97. FAO. *Global Forest Resources Assessment 2020: Main Report*; FAO: Rome, Italy, 2020.
98. Ministry of Natural Resources. *The State of Canada's Forests: Annual Report*; Ministry of Natural Resources: Peterborough, ON, Canada, 2022.
99. Puettmann, K.J.; Wilson, S.M.; Baker, S.C.; Donoso, P.J.; Drössler, L.; Amente, G.; Harvey, B.D.; Knoke, T.; Lu, Y.; Nocentini, S.; et al. Silvicultural alternatives to conventional even-aged forest management—What limits global adoption? *For. Ecosyst.* **2015**, *2*, 8. [CrossRef]
100. Bergeron, Y.; Harvey, B.; Leduc, A.; Gauthier, S. Forest management guidelines based on natural disturbance dynamics: Stand- and forest-level considerations. *For. Chron.* **1999**, *75*, 49–54. [CrossRef]
101. Girona, M.M.; Morin, H.; Gauthier, S.; Bergeron, Y. *Boreal Forests in the Face of Clmate Change: Sustainable Management*; Spinger: Berlin/Heidelberg, Germany, 2023; Volume 74.

Supplementary Materials

Assessing the cumulative impacts of forest management on forest age structure development and woodland caribou in boreal landscapes: a case study from two Canadian provinces

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Table S1: Availability of Ontario FRI data for all FMUs in the study region.

FMU_CODE	FMU_NAME	Public	Year	# Polygons	Notes
966	Pic Forest	Y	2008	107052	MarathomBlock in V2
421	Pineland Forest	Y	2011	35471	
177	Dog River-Matawin Forest	Y	2012	84051	
350	Kenogami Forest	N			Productive Forest Area retrieved from (Arbex Forest Resource Consultants Ltd. 2016)
535	Dryden Forest	Y	2015	25733	
438	Gordon Cosens Forest	Y	2012	150813	
120	Trout Lake Forest	Y	2013	9,697	
35	Black Spruce Forest	Y	2015	94557	
816	Lake Nipigon Forest	Y	2014	145330	
930	Romeo Malette Forest	N	2005	59,294	Not currently publicly available. Productive Forest Area retrieved from (Arbex Forest Resource Consultants Ltd. 2019)
574	Missinaibi Forest	Y	2014	130240	Combination of Martel and MagpieForest in V2
280	Timiskaming Forest	Y	2014	131947	
994	Whitefeather Forest	N			Productive Forest Area retrieved from (ArborVitae Environmental Services Ltd. 2018)
390	Nagagami Forest	Y	2014	34623	
615	Algoma Forest	Y	2013	139959	
840	Red Lake Forest	Y	2010	24005	
702	Lac Seul Forest	Y	2015	82789	
406	Boundary Waters Forest	Y	2010	189513	Combination of Crossroute and Sapawe in V2
415	Ogoki Forest	Y	2010	113330	
60	White River Forest	Y	2010	65820	
175	Caribou Forest	Y	2012	52335	

796	Lakehead Forest	Y	2009	71040	
230	English River Forest	Y	2013	90111	
490	Whiskey Jack Forest	Y	2008	71079	
644	Kenora Forest	Y	2015	93772	
130	Wabigoon Forest	Y	2010	68703	
210	Spanish Forest	Y	2013	101544	
601	Hearst Forest	Y	2007	131932	
110	Abitibi River Forest	Y	2011	244279	
680	Northshore Forest	Y	2013	106305	
443	Wabadowgang Noopming Forest	Y	2014		Part of the Lake Nipigon Forest in V2

Table S2: Quebec southern ecoforest inventory data codes for the ORIGINE attribute, with designations assigned for this study.

Code	**Description**	**Assigned As**
BR	Brûlis total	Fire
BRD	Brûlage dirigé	Fire
CBA	Coupe par bandes	Harvest
CBT	Coupe par bandes finale	Harvest
CDV	Coupe avec protection des tiges à diamètre variable	Harvest
CEF	Coupe d'ensemencement finale	Harvest
CHT	Chablis total	Wind
CIF	Coupe progressive irrégulière phase finale	Harvest
CPE	Coupe progressive d'ensemencement (coupe finale)	Harvest
CPH	Coupe avec protection de la haute régénération et des sols	Harvest
CPR	Coupe avec protection de la régénération	Harvest
CPT	Coupe avec protection des petites tiges marchandes et des sols	Harvest
CRB	Coupe de récupération dans un brûlis	Harvest
CRR	Récolte des tiges résiduelles et des rebuts	Harvest
CRS	Coupe avec réserve de semencier	Harvest
CS	Coupe de succession	Harvest
CT	Coupe totale	Harvest
DT	Dépérissement total	Dieback
ENM	Ensemencement avec mini-serres	Plantation
ENS	Ensemencement	Plantation
ES	Épidémie grave	Disease
ETR	Élimination des tiges résiduelles	Harvest
FR	Friche	Development
P	Plantation	Plantation
PLB	Plantation de boutures	Plantation

PLN	Plantation à racines nues	Plantation
PLR	Plantation avec semis en récipients	Plantation
PRR	Regarni de régénération pour constituer l'équivalent d'une plantation	Plantation
REA	Régénération d'aire d'ébranchage	Harvest
RIA	Régénération de site d'infrastructure abandonnée	Development
RPS	Récupération en vertu d'un plan spécial d'aménagement	Harvest
VER	Verglas grave	Ice
BRU	Brûlage dirigé	Fire
CIF	Coupes progressives irrégulières phase finale	Harvest
CPHRS	Coupe avec protection de la haute régénération et des sols	Harvest
CPI_RL_F	Coupe progressive irrégulière à régénération lente phase finale	Harvest
CPPTM_DIS	Coupe avec protection des petites tiges marchandes discontinue	Harvest
CPPTM_U	Coupe avec protection des petites tiges marchandes uniforme	Harvest
CPRS_BA	Coupe avec protection de la régénération et des sols par bandes	Harvest
CPRS_DA	Coupe avec protection de la régénération et des sols en damier	Harvest
CPRS_PA	Coupe avec protection de la régénération et des sols en parquets	Harvest
CPRS_T	Coupe avec protection de la régénération et des sols par trouées	Harvest
CPRS_U	Coupe avec protection de la régénération et des sols uniforme	Harvest
CPR_U-F	Coupe progressive régulière uniforme finale	Harvest
CTSP_BA	Coupe totale sans protection par bandes	Harvest
CTSP_DA	Coupe totale sans protection en damier	Harvest
CTSP_PA	Coupe totale sans protection en parquets	Harvest
CTSP_T	Coupe totale sans protection par trouées	Harvest
CTSP_U	Coupe totale sans protection uniforme	Harvest
CTX	Ancienne coupe totale sans référence cartographique, dont l'année de réalisation	Harvest
PL	Plantation	Plantation
RECUP_C-T	Coupe de récupération totale après chablis	Harvest
RECUP_F-T	Coupe de récupération totale après feu	Harvest
RECUP_I-T	Coupe de récupération totale après épidémie d'insectes	Harvest
RECUP_M-T	Coupe de récupération totale après maladie	Harvest