



The State of Conservation in North America's Boreal Forest: Issues and Opportunities

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Specialty section:

This article was submitted to
Temperate and Boreal Forests,
a section of the journal
Frontiers in Forests and Global
Change

Received: 14 January 2019

Accepted: 02 July 2020

Published: 30 July 2020

Citation:

Wells JV, Dawson N, Culver N,
Reid FA and Morgan Siegers S (2020)
The State of Conservation in North
America's Boreal Forest: Issues
and Opportunities.
Front. For. Glob. Change 3:90.
doi: 10.3389/ffgc.2020.00090

The North American Boreal Forest biome has been recognized as containing some of the highest proportions of intact, primary forest left on Earth. Over 6 million km² of the Boreal Forest biome is found in Canada (5.5 million km²) and the United States (0.74 million km²) across 10 provinces and territories and one United States state (Alaska). All of it is within the traditional territories of hundreds of Indigenous governments, many of whom are now asserting their rights to make decisions about its future and current land-use including for conservation and development. The biome is considered to be 80% intact and between 8 and 13% formally protected. The North American Boreal Forest biome's intactness has allowed it to retain many globally significant conservation features including long-distance mammal and fish migrations, healthy populations of large predators, one to three billion nesting birds, some of the world's largest lakes and North America's longest undammed rivers, massive stores of carbon and ecological functionality. The biome's forests, minerals, and hydropower potential are also recognized as economic opportunities so that the industrial footprint is rapidly increasing, sometimes without careful land-use planning decisions. Indigenous, federal, state, provincial and territorial governments and conservation organizations have strived over recent decades to recognize the conservation opportunity inherent in such a still-intact landscape, resulting in implementation of some of the world's largest land conservation set-asides. Indigenous governments, in particular, have been at the forefront in developing and implementing world-leading, modern land-use plans that achieve land conservation at massive scales. Supporting efforts to ensure that a high proportion of North America's Boreal Forest biome is protected and remains as intact habitat with unimpeded ecosystem processes should be a priority of the global conservation community. Federal, state, and provincial/territorial governments should support Indigenous protected area proposals, vastly increase financial support

for Indigenous government land conservation and stewardship activities, and should develop new protected area co-management models with Indigenous governments. Governments should also be strongly advocating for raising the global Convention on Biological Diversity protected area goal to at least 30% by 2030.

Keywords: boreal forest, forest conservation, intact forest, indigenous guardians, indigenous-led conservation, indigenous protected and conserved areas, primary forest, protected areas

INTRODUCTION

With the advent of GIS capabilities and the availability of complete global coverage of remote sensing products over the last two decades, identification of the biomes of the world with the least large-scale human impacts has become possible. Notwithstanding the various methodological and definitional questions around how to define and map such areas (Potapov et al., 2017; Venier et al., 2018; Watson et al., 2018) there has been broad consensus that there are five regions of the world that encompass the largest areal extent of forest habitat that has not been subject to large-scale industrial logging, roadbuilding, mining, or other modern industrial land-use impacts. First identified in 1997 (Bryant et al., 1997) and termed “frontier forests” these forest areas have subsequently been mapped under different criteria and terms including “wilderness,” “intact forest” and “primary forest” in a number of other publications and analyses (Sanderson et al., 2002; Mittermeir et al., 2003; Potapov et al., 2008, 2017; Hansen et al., 2013; Mackey et al., 2014; Watson et al., 2016, 2018; Dinerstein et al., 2017). These five regions—the forests of New Guinea and Borneo, the Congo Basin, the Amazon Basin, the Russian Boreal Forest, and the North American Boreal Forest (**Figure 1**) – have all seen major losses in forest area since their original identification in 1997 (Hansen et al., 2013; Haddad et al., 2015; Venter et al., 2016; Watson et al., 2016).

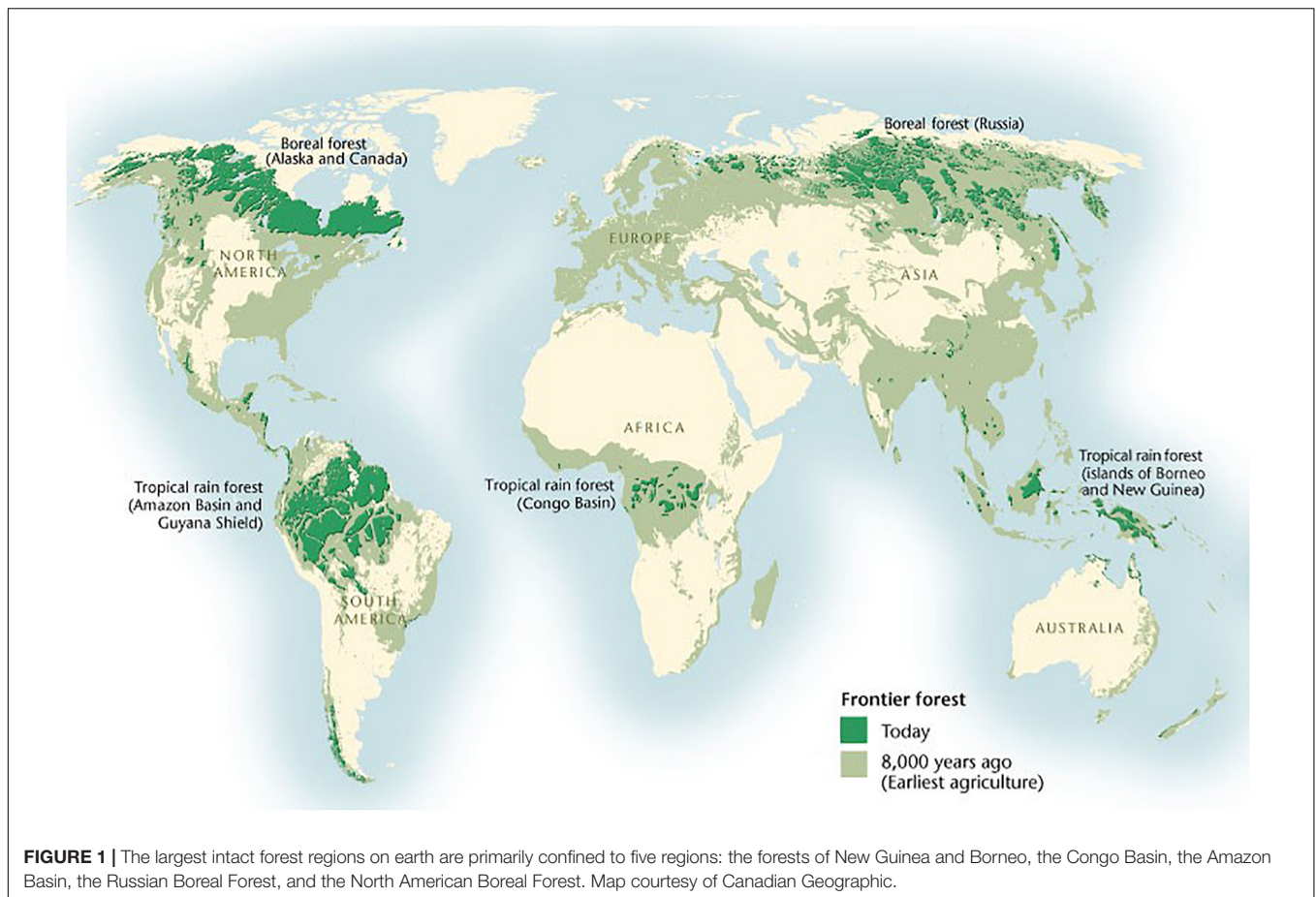
Increasingly, terrestrial protected areas work in these and other regions around the world has focused on increasing protected areas coverage (Dinerstein et al., 2017, 2018; Watson et al., 2018). The first goal that many governments and non-governmental organizations have focused on is reaching the Convention on Biodiversity Target 11 goal of 17% of each nation protected as outlined in the so-called Aichi treaty (Environment and Climate Change Canada, 2016; Canadian Parks and Wilderness Society, 2018; Indigenous Circle of Experts, 2018). Academics and conservation practitioners have also increased awareness for the need to increase protected areas goals to much higher levels in order to achieve the goal of maintaining biodiversity and ecosystem services (Noss et al., 2012; International Boreal Conservation Science Panel, 2013; Wilson, 2016). These higher-level goals are being achieved in certain landscapes as a result of the leadership of Indigenous peoples and often through reconciliation processes that result in strong Indigenous self-government (Indigenous Circle of Experts, 2018; Zurba et al., 2019).

CONSERVATION VALUES OF THE NORTH AMERICAN BOREAL FOREST BIOME THAT MAKE IT A GLOBAL PRIORITY FOR CONSERVATION

North America’s Boreal Forest biome (**Figure 2**) is one of the most intact of these global forested ecosystems (Lee et al., 2003, 2006; Andrew et al., 2012, 2014; Dinerstein et al., 2017; Venier et al., 2018). The biome is estimated to harbor 25% of the world’s remaining intact forests (Aksenov et al., 2002; Lee et al., 2003, 2006). Spanning from Newfoundland and Labrador in the east and across Canada to interior Alaska, it encompasses 6.27 million km². Within its boundaries are some of the largest peatlands, lakes, and rivers in the world (Schindler and Lee, 2010; Wells et al., 2010) and a significant amount of the world’s terrestrial carbon (Carlson et al., 2009, 2010; Tarnocai et al., 2009).

North American Boreal Forest biome peatlands include a wetland that is considered one of the largest in the world, the Hudson Bay-James Bay Lowlands that extend over 370,000 km² (Abraham and Keddy, 2005; Webster et al., 2015). Along with being enormous storehouses of carbon, these wetlands store and filter massive amounts of freshwater (Schindler and Lee, 2010; Wells et al., 2010). Canada’s portion of the Boreal Forest biome is thought to hold a minimum of 208 billion tons of carbon in its trees and other plants, soils, peatlands, as well as under permafrost (Carlson et al., 2009). The biome’s natural capital is worth an estimated \$703 billion annually (Anielski and Wilson, 2009). Ecosystem goods and services are relatively unimpaired across the region due to its large degree of intactness.

The highest densities of trees on earth occur in the global boreal forest biomes and are estimated to support 24% of the world’s individual trees (Crowther et al., 2015). Using Crowther et al.’s (2015) boreal tree density average applied to the North American Boreal Forest biome suggests that the biome holds as many as 500 billion individual trees representing 16% of the world’s total number of individual trees. Many plants species are largely confined to the North American Boreal Forest biome or at least reach their greatest abundance and distributional extent within the biome. This includes many coniferous tree species which are considered characteristic of the North American Boreal Forest biome including *Picea glauca*, *Picea mariana*, *Larix laricina*, *Abies balsamea*, *Pinus banksiana*, *Pinus contorta* var. *latifolia*, and *Abies lasiocarpa* but also characteristic deciduous tree species like *Populus tremuloides*, *Populus balsamifera*, and *Betula papyrifera* (Brandt, 2009).

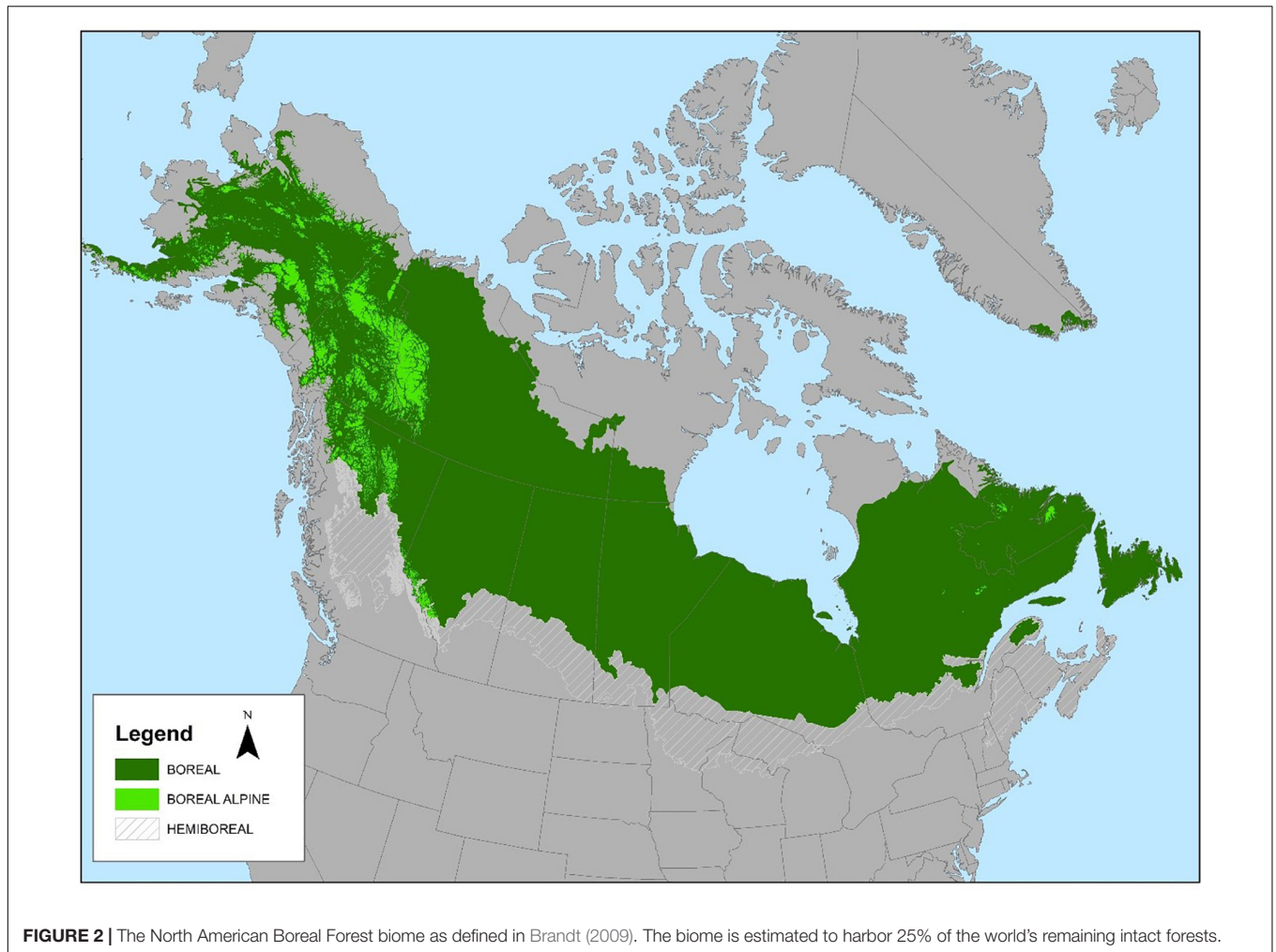


The North American Boreal Forest biome encompasses millions of lakes and ponds (Wells et al., 2010) and Canada's Boreal Forest holds more available freshwater than any other single country on earth (Minns et al., 2008). Freshwater outflows from the North American Boreal Forest biome to marine systems play an important role in driving large-scale ocean currents, moving nutrients, impacting weather patterns and the productivity of marine fisheries across the globe (Aagaard and Carmack, 1989; Woo et al., 2008; Wells et al., 2010). Within the biome are four of the world's ten largest lakes. This includes Great Bear Lake in the Northwest Territories, one of the world's most pristine (Figure 3). Many large lakes here support healthy, age-structured fish populations that includes a significant proportion of larger and older fish that often become scarce under heavy fishing pressure. The largest known individuals of species like lake trout, brook trout, and Arctic grayling have been documented from these lakes (Wells et al., 2010). North America's Boreal Forest biome is rich also in free-flowing, undammed rivers (Figure 4) – more than now occur in the remainder of North America (Dynesius and Nilsson, 1994; Webster et al., 2015). Dams, pollution and water over-subscription have imperiled river biodiversity across much of the world, but rivers in North America's Boreal Forest biome are among the remaining strongholds for populations of many anadromous fish species (Wells et al., 2010). Pacific salmon continue to migrate up the

Stikine, Nass, and Skeena rivers into the Sacred Headwaters of northern B.C. and the Yukon River through Alaska to the Yukon. Anadromous fish ascend the Mackenzie River southward from the Arctic over 1,000 km, some reaching to tributaries in B.C. and Alberta. Atlantic salmon runs along the Atlantic Coast of North America have been lost or are endangered in the United States and southern Canada (Limburg and Waldman, 2009). Yet healthy populations still ascend rivers in the boreal regions of Quebec and Newfoundland and Labrador.

North America's Boreal Forest biome is also home to both Old and New World evolutionary lineages of caribou (Polfus et al., 2017) and migratory and non-migratory lineages of wolves (Musiani et al., 2007) that persist together in the biome. Unfortunately, all populations and forms of caribou that occur in Canada (woodland, mountain, barren-ground) are now listed as Endangered, Threatened, or of Special Concern by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC, 2019) with major harvest restrictions now in place on caribou throughout Canada.

Within the biome are some of Earth's only remaining unfettered large mammal migrations – those particularly of herds of migratory tundra caribou (*Rangifer tarandus*) that can traverse 500–1500 km in an annual migration between boreal forest wintering ranges and tundra summer calving grounds (Hummel and Ray, 2008; Wilcove, 2008; Joly et al., 2019). The Porcupine



Caribou Herd in western Canada and Alaska travels over 1300 km each year as do the Bathurst and Beverly herds of western Canada and the Leaf River Herd of Quebec (Gurarie et al., 2019; Joly et al., 2019). The Western Arctic Caribou Herd of Alaska and the Qamanirjuaq Herd of Canada travel at least 1200 km each year (Joly et al., 2019). Loss of migration corridors threatens many herbivore species across the globe as habitat modification reduces the ability of animals to move across large tracts of intact landscape (Wilcove, 2008; Ripple et al., 2015).

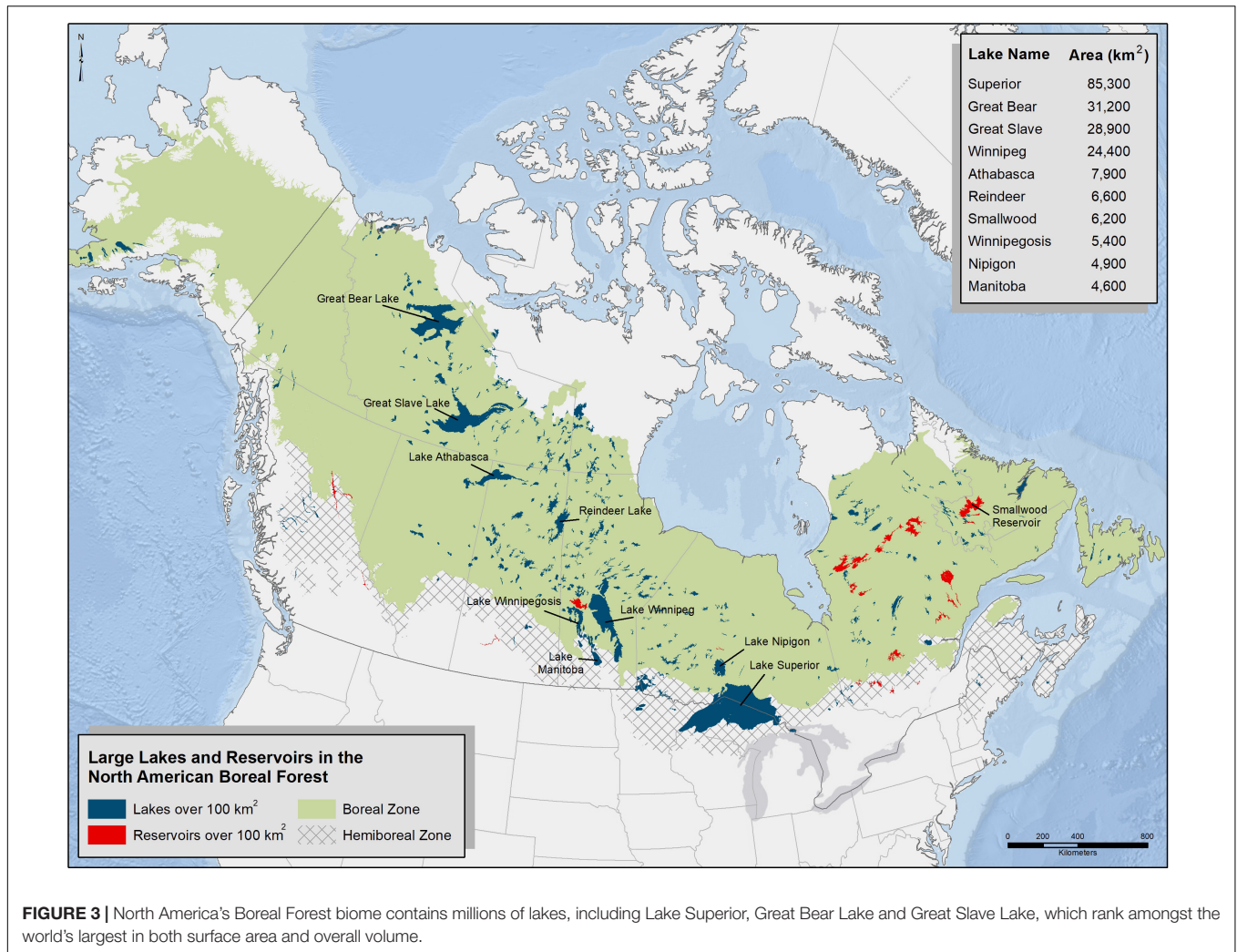
The North American Boreal Forest biome supports significant populations of large carnivores that have been lost from much of their southern range including wolves, grizzly bears, and wolverine (Laliberte and Ripple, 2004; Cardillo et al., 2006; Bradshaw et al., 2009). One of the southernmost populations of polar bears in the world occurs in the Boreal Forest biome in the Hudson Bay and James Bay region where the bears have the unusual habit of maternity denning in the ground (rather than in snow) sometimes hundreds of kilometers inland (Peacock et al., 2010).

Within the North American Boreal Forest biome are a variety of range-restricted mammal species including the Ungava collared lemming (found only in northern Ungava peninsula),

Richardson's collared lemming, singing vole (found only in parts of Alaska, Yukon and the Northwest Territories), Dall's sheep, collared pika, and the American wood bison (Bowers et al., 2004). A subspecies of freshwater harbor seal is separated from the sea and found only in Quebec's Tursujuq National Park (Smith, 1996, 1997; COSEWIC, 2007).

A great abundance of invertebrates, especially insects, occur only or primarily in peatlands and other wetlands and lakes, rivers and streams of North America's Boreal Forest biome. This includes species of chironomid flies, lepidopterans, dragonflies, and beetles (Spitzer and Danks, 2006). Species of dragonfly whose range is primarily within the biome include the Boreal Snaketail, Quebec Emerald, Hudsonian Emerald, Kennedy's Emerald, Boreal Whiteface, Lake Darner, and Zigzag Darner (Cannings and Cannings, 1994; Dunkle, 2000).

Butterflies that are wetland-dependent and that have most of their range confined to the North American Boreal Forest biome include the Bog Fritillary, Titania Fritillary, Disa Alpine, Jutta Arctic, and Cranberry Blue (Opler and Malikul, 1992). Peatlands of the biome support unusual species, like the sphagnum bog cricket (*Neonemobius palustris*), bog katydid (*Metrioptera sphagnum*), the pitcher plant mosquito (*Wyeomyia smithii*),



and the pitcher plant midge (*Metriocnemus knabi*) (Capinera et al., 2004; Spitzer and Danks, 2006).

The North American Boreal Forest biome supports billions of songbirds, millions of waterfowl and shorebirds, and is the last stronghold for globally endangered species like the Whooping Crane (Wells and Blancher, 2011). The intactness of the North American Boreal Forest biome is a critical reason it has remained one of the world's most important breeding reservoirs for migratory birds, supporting an estimated 1–3 billion nesting birds each summer including billions of songbirds and millions of waterfowl and shorebirds (Wells, 2011; Wells and Blancher, 2011). The biome is the last stronghold for the globally endangered Whooping Crane which nests in or near Wood Buffalo National Park straddling the border between Alberta and the Northwest Territories (Wells and Blancher, 2011). Each fall, the biome annually “exports” some 3–5 billion birds once the young have hatched and migrated to populate their wintering ranges, from southern Canada and the United States south through Mexico, the Caribbean, Central America and South America (Robertson et al., 2011; Wells and Blancher, 2011; Wells et al., 2014). At least 96 species are estimated to have at least half

of their North American breeding distribution within the biome and 151 to have at least 25% of their breeding distribution in the biome (Wells and Blancher, 2011). Wetlands within Alaska's portion of the Boreal Forest biome have long been known as an important stronghold for the original wild populations of Trumpeter Swan and these same wetlands are hosting increased densities of nesting waterfowl in recent decades, perhaps three times as many as in the 1950's (Petrie and Reid, 2009).

Sadly, there are a growing number of Boreal bird species in steep decline with six species considered globally threatened under IUCN Red List and eight Near Threatened. Boreal-dependent birds like the Rusty Blackbird, the Olive-sided Flycatcher, and Canada Warbler have shown declines in abundance of more than 50% over the last half-century. All three are now on Canada's list of Threatened or Special Concern species and Olive-sided Flycatcher appears on Audubon Alaska's Redlist (Warnock, 2017). Boreal-breeding waterbirds are also featured on that list, including the eastern populations of Barrow's Goldeneye and Harlequin Duck, the western populations of Horned Grebe, and Yellow Rail, Hudsonian Godwit and Red-necked Phalarope (Wells et al., 2014). The

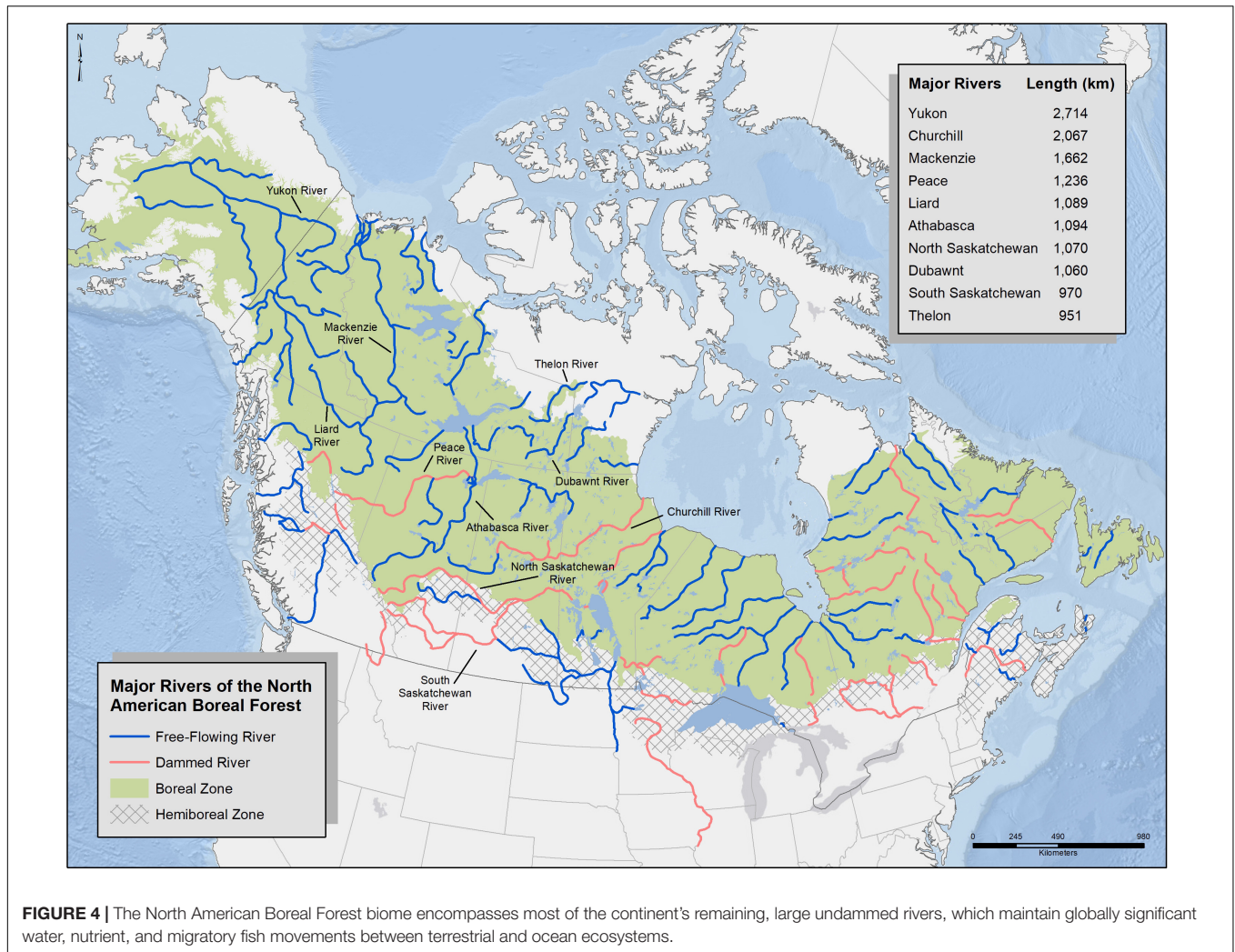


FIGURE 4 | The North American Boreal Forest biome encompasses most of the continent's remaining, large undammed rivers, which maintain globally significant water, nutrient, and migratory fish movements between terrestrial and ocean ecosystems.

candidate species for future inclusion on that list include a number of shorebirds that are dependent on Boreal wetlands for breeding, including Lesser Yellowlegs, Semipalmated Sandpiper, Short-billed Dowitcher, Stilt Sandpiper, and Pectoral Sandpiper (COSEWIC, 2019). Many other Boreal-breeding species have seen steep declines in the last 50 years, including Black Scoter (listed as Near Threatened on the IUCN Red List), Surf, and White-winged Scoters, Lesser Scaup, Long-tailed Duck (listed as Vulnerable on the IUCN Red List), Blackpoll Warbler, and even well-loved backyard feeder birds like White-throated Sparrow and Dark-eyed Junco (Wells, 2007; Slattery et al., 2011; Sauer et al., 2015; Wells et al., 2016, 2018). Many of the species in steep decline on Alaska's Watchlist are found seasonally within Alaska's Boreal Forest biome (Warnock, 2017).

GOVERNANCE AND POLICY CONTEXT OF THE CANADIAN BOREAL FOREST

Virtually all of North America's Boreal Forest biome is considered (at least by non-Indigenous governments) to be under the

dominion of federal, provincial and territorial governments as so-called "crown land" in Canada (Bone, 2000). Decisions about the management of that land have historically largely been under the control of provincial and territorial governments (Frideres and Rowe, 2010) in Canada. Indigenous governments, on the other hand, consider their traditional territories within the region to be sovereign lands for which they should have complete authority or co-authority with federal, provincial, and territorial governments. In some regions, these lands were never under a historic treaty and some areas of Canada remain without even a modern-day treaty (Bone, 2000). In other regions, there are historic treaties that are sometimes invoked by federal, provincial or territorial governments to suggest that all Indigenous land management rights were extinguished (Long, 2010). Recent legal cases have challenged the latter view and have been supported, at least in part, by court rulings including at the Canadian Supreme Court (Ariss and Cutfeet, 2012).

Provincial and territorial governments as opposed to the federal government, in the Canadian confederation system, hold the rights to make decisions about the use of crown lands. One of the types of land uses granted by provinces and

territories that encompasses much of the southern half of the Boreal Forest biome is for industrial scale logging (International Boreal Conservation Science Panel, 2013). Often long-term land tenures to single logging companies cover vast areas, larger than some United States states. These tenures give those companies the rights to harvest logs and build roads, bridges and other infrastructure in order to do so. Mining companies and oil and gas companies can similarly license claims for areas of the boreal forest for exploration (Wells et al., 2010). If exploration has indicated a substantial mineral deposit, then those companies can apply for the right to develop mines or oil extraction facilities. Hydropower corporations in Canada are largely all public-private corporations. These entities must also be granted rights to develop dams, roads, transmission line corridors and other infrastructure within Boreal Forest lands. Historically, Indigenous peoples were rarely consulted on the management of their lands including the granting of rights to resource extraction companies to operate on their traditional territories (Ariss and Cutfeet, 2012; Indigenous Circle of Experts, 2018) or the designation of protected areas (Indigenous Circle of Experts, 2018). In the last two decades, more engagement and consultation of Indigenous governments and communities has begun taking place. But the degree of authority in land use decisions that any particular Indigenous government or community has over the use of its traditional territory varies greatly across Canada depending especially on the views of the provincial or territorial government and bureaucratic leadership and the level of pressure exerted by resource extraction industries in that region.

GOVERNANCE AND POLICY CONTEXT OF THE ALASKA BOREAL FOREST

The Alaska portion of the Boreal Forest biome is managed by the federal government (51%), Native Corporations (24%), state and local governments (25%), and private landowners (0.4%). Federal lands in the Alaska Boreal Forest biome are primarily managed by the Bureau of Land Management. The Bureau of Land Management is governed by a multiple-use mandate, seeking to balance a host of resources. This is outlined in federal statute 43 U.S.C. §1732(a) which states: “Multiple use means the management of the public lands and their various resource values so that they are utilized in the combination that will best meet the present and future needs of the American people,” and includes “the use of some land for less than all of the resources.” The resources to be managed specifically include, but are not limited to “recreation, range, timber, minerals, watershed, wildlife and fish, and natural scenic, scientific and historical values.” In addition, the Bureau of Land Management is required to “give priority to the designation and protection of Areas of Critical Environmental Concern,” which are areas that receive special management “to protect and prevent irreparable damage to important historic, cultural, or scenic values, fish and wildlife resources or other natural systems or processes. . .” (Federal Land Policy and Management Act, 43 U.S.C. § 1712[b][3], 1702[a]).

Management for the Bureau of Land Management Boreal Forest lands in Alaska is defined in Resource Management Plans that govern land use for decades at a time. These Resource Management Plans are based on ongoing inventories of existing resources and identify which lands will be managed as Areas of Critical Environmental Concern or for other special purposes, as well as which lands will be available for oil and gas leasing and which lands will be recommended for withdrawal from mining (Federal Land Policy and Management Act, 43 U.S.C. §§1711, 1712). Based on its perception of the multiple use mandate, the Bureau of Land Management is generally reluctant to set aside lands for protection or to close them to leasing or other forms or development. For example, the Kobuk-Seward Record of Decision and Approved Resource Management Plans did not close any of the 11.9 million acres under consideration to oil and gas leasing (Bureau of Land Management, 2016). Nonetheless, many existing Resource Management Plans in Alaska do contain some Areas of Critical Environmental Concern that protect cultural and subsistence values for Tribes (e.g., Bureau of Land Management, 2008a; Bureau of Land Management, 2008b). In addition, much of the Boreal Forest lands, close to 50 million acres, were withdrawn from mining and leasing pursuant to the Alaska Native Claims Settlement Act, subject to later actions by the Bureau of Land Management and the Department of the Interior to revoke those withdrawals (Alaska Native Claims Settlement Act, 43 U.S.C. § 1616[d][1]).

INDIGENOUS LEADERSHIP IN BOREAL FOREST LAND-USE PLANNING AND LAND CONSERVATION

In recent years in Canada, Indigenous governments have increasingly been asserting more decision-making authority over their lands (Ariss and Cutfeet, 2012). One of the ways that this has been accomplished has been by Indigenous nations developing leading edge comprehensive land-use plans for their traditional lands (International Boreal Conservation Science Panel, 2013). These plans consolidate the Indigenous government’s vision for the future of their lands and include protected lands as well as lands that may be available for resource development under the oversight of Indigenous governments through their laws, policies and regulations.

In some areas, these plans have led Indigenous governments to declare certain areas as off limits to resource development activities sometimes through a declaration of an Indigenous protected or conserved area (Ariss and Cutfeet, 2012; Indigenous Circle of Experts, 2018). Conflicts have arisen when a provincial or territorial government ignores the declaration and grants permits for private industry to operate within the area designated by the Indigenous government as off-limits to such activity. Those conflicts can result in actual on-the-ground standoffs with Indigenous blockades of access roads and/or may begin a string of protracted legal battles that can be financially debilitating for the Indigenous government (Ariss and Cutfeet, 2012).

THE CHALLENGE FOR NON-GOVERNMENTAL CONSERVATION ORGANIZATIONS

For non-governmental conservation organizations (NGCO), the political landscape is a complicated one within which to operate. In essence, both Indigenous and provincial or territorial governments control or strongly influence land use decisions across the Boreal Forest biome. NGCOs must develop and maintain supportive partnerships with many distinct and independent Indigenous governments and with provincial or territorial government officials to understand the intricacies of reinforcing Indigenous-led conservation actions and not overstep the Indigenous government's leadership.

CURRENT CONSERVATION STATUS OF THE NORTH AMERICAN BOREAL FOREST BIOME

Large tracts of North American Boreal Forest ecosystems remain intact not by design, but rather as the outcome of the inaccessibility of access (Andrew et al., 2012). The historical and current difficulty in accessing these lands has also made it one of the last industrial development frontiers on earth. The area protected is estimated to be only between 8 (Andrew et al., 2014) and 12.7% (Lee and Cheng, 2010; Carlson et al., 2015) and development and land-use management decisions are underway at an increased rate. Yet estimates do not yet reflect gains made in the last 2 years in creating new, large-scale protected areas in Canada's Boreal Forest region.

The overall areal extent of the North American Boreal Forest biome considered intact or relatively free of industrial anthropogenic impacts (including forestry, mining, oil and gas, hydropower, and infrastructure but not including climate change) has been estimated at 80–83% (Lee and Cheng, 2010; Lee et al., 2010; Andrew et al., 2012; Powers et al., 2013; Smith and Cheng, 2016). An area of contention in global analyses of areal extent of intact forest is whether areas impacted by forest fires should be considered as part of the anthropogenic footprint (Venier et al., 2018). Most forest fires in the North American Boreal Forest biome have historically been considered to be lightning-caused (Veraverbeke et al., 2017) and part of the long-term ecological history of the biome (Brandt et al., 2013; Venier et al., 2018). Very large forest fires have historically occurred across much of the North American Boreal Forest biome. In recent decades, the size and frequency of fires has increased, especially in the Alaskan and western Canada portions of the biome, perhaps to a level that has not occurred in the last 10,000 years (Kelly et al., 2013).

In contrast, in the Russian Boreal Forest biome most forest fires are generally considered to be human caused. Most experts now agree that the area burned in forest fires in the North American Boreal Forest should not be considered part of the anthropogenic footprint since most large fires are in remote areas lacking industrial infrastructure and these burned over areas will

regrow and remain intact. However, because of the inclusion of areas burned by forest fires, several global analyses have suggested that the North American Boreal Forest biome has lost forest cover in recent decades at exceptionally high rates (e.g., Hansen et al., 2013; Haddad et al., 2015). An estimated 399,000 km² of the Canadian portion of the North American Boreal Forest biome was impacted by forest fires between 1985 and 2010 (White et al., 2017), amounting to 9% of the Canadian portion of the biome. If this were considered part of the anthropogenic footprint, the area considered intact would be lowered to approximately 74%.

A 1987 study reported that, of the "frontier forests" of North American (most in the Boreal Forest biome), 26% were under moderate or high threat (Bryant et al., 1997). An expert review of the state of all of North America's ecoregions categorized two southern Boreal Forest ecoregions as in Critically Endangered condition, one as Endangered, and an additional seven Boreal Forest ecoregions as Vulnerable (Ricketts et al., 1999).

As these studies reflect, the loss and fragmentation of intact ecosystems of the North American Boreal Forest biome is increasing as industrial access infrastructure is established from south to north. This is clear from the fact that while northern portions of the biome like the Taiga Plains ecozone are substantially intact (78% of the ecozone consists of intact landscapes of 10,000 ha or larger), substantial disturbance has occurred in southern portions like the Boreal Plains ecozone which is only 36% intact (Lee et al., 2006). In the southern portion of the North American Boreal Forest biome, estimates of the amount of no-longer-intact habitat range up to 66% (Ricketts et al., 1999) encompassing 1.77 million km². Lee et al. (2006) demonstrated that less than fifteen percent of the 710,000 km² Boreal Plains ecozone (the portion of the southern Boreal ranging from the eastern foothills of the Canadian Rockies to south-central Manitoba) was in forested landscapes that were still large and intact. More than 4,000 km² of the southern Boreal Forest biome within Saskatchewan and Manitoba and over 24,000 km² of the Boreal Forest biome within Quebec was impacted between 1900 and 2000 by forestry, road-building, and other infrastructure development (Stanojevic et al., 2006a,b).

FOREST INDUSTRY IMPACTS IN THE NORTH AMERICAN BOREAL FOREST BIOME

Forestry practices differ across international boundaries within the North American Boreal Forest Biome but forestry clearly has impacted more area of the Boreal Forest biome than any other industrial activity. A third of the North American Boreal Forest biome is tenured (leased) for forestry in Canada (Carlson et al., 2015). As of 2003, an estimated 61% of the 1.6 million km² Canadian commercially managed portion of the North American Boreal Forest biome had been logged at least once – an area of over 1 million km² (Venier et al., 2014) or 16% of the entire biome (note that this does not include any portion of Alaskan boreal that was logged). Using Landsat time series, White et al. (2017) estimated that 104,000 km² were disturbed by harvest in boreal ecozones of Canada between 1985 and

2010 while 399,000 km² were impacted by wildfire during the same period. A remote sensing analysis in 2013 estimated that 240,000 km² of Canada's portion of the Boreal Forest biome showed visible forest cutblocks (Pasher et al., 2013; Webster et al., 2015). A number of declining and Canadian federally listed Boreal Forest dependent birds species show major overlap with the most heavily impacted southern portion of the Boreal Forest biome (Wells, 2011) as does the Canadian federally threatened Woodland Caribou (Environment Canada, 2008, 2011; International Boreal Conservation Science Panel, 2011).

In the eastern Canadian part of the North American Boreal Forest biome, the pace and scale of forest harvest has increased in recent decades. Combined with increased size and frequency of forest fires, this is diminishing the amount of older age forest on the landscape to critically low levels (Cyr et al., 2009; Venier et al., 2014; Gauthier et al., 2015; Bergeron et al., 2017). Similarly, only 16.5% of old growth was estimated to be remaining in the managed portion of the Boreal Forest biome in Ontario and only 10% in Alberta (Venier et al., 2014).

The Alaska portion of the Boreal Forest biome has experienced limited timber harvest that has been concentrated near communities with infrastructure. Less than 5% of the total timber harvested in Alaska comes from Boreal Forests (Wurtz et al., 2006). Forested boreal lands make up 47 million hectares of land (roughly the size of California) in interior Alaska. Most timber extraction occurs in mature stands of white spruce where volumes are highest, with much of this harvest being devoted to local wood product needs. During the late 1980's and early 1990's, many high-quality white spruce logs were exported to Pacific Rim countries from state and private lands in the Boreal Forest. However, changing global markets largely ended these exports and the likelihood of future log exports from Alaska's interior forests appears small. Timber harvest in Alaska's Boreal Forest remains low due to distance from markets, low population densities, and lack of accessible timber lands for harvest.

MINING AND OIL AND GAS INDUSTRY IMPACTS IN THE NORTH AMERICAN BOREAL FOREST BIOME

A variety of other types of industrial disturbances occur within the North American Boreal Forest biome. In the western Canada portion of the biome, oil and gas extraction and exploration are rapidly increasing. As many as 22,800 oil and gas wells were drilled in 2004 and there were 222,000 active and abandoned well sites as of 2011 (Brandt et al., 2013). There are now at least 441,000 km of pipelines and 1.7 million km of seismic lines (1.75–10 m wide cleared corridors for deploying equipment to search for oil and gas deposits) set primarily in the Alberta portion of the North American Boreal Forest biome (Lee and Boutin, 2006; Brandt et al., 2013; Dabros et al., 2018). The industrial footprint from the oil and gas industry in Canada's portion of the Boreal Forest biome as of 2003 was estimated at 460,000 km² or approximately 8% of Canada's portion of the biome (Anielski and Wilson, 2009). Habitat that would have supported an estimated 58,000–402,000 breeding birds has

already been lost within Alberta's oil sands region (Timoney and Lee, 2009) and future accumulated losses have been estimated into the tens of millions (Wells et al., 2008).

Mining may be one of the most damaging of the natural resource extraction industries to both the environment and local communities. Effects include cumulative impacts, disruption of ecological and social systems, and lasting contamination. Because many of these impacts occur over decades or centuries, the ways that mining activities impact the broad ecological landscape and environment is often not widely acknowledged. Eighty percent of Canada's mines occur within the Boreal Forest biome (Wells et al., 2010). There were 108 mineral, metal, and coal mines in the Canadian portion of the North American Boreal Forest biome as of 2009 and 1300 or more abandoned mines (Brandt et al., 2013). Although there is no existing estimate of the impact to waterways of abandoned and active mines in Canada's portion of the Boreal Forest biome, at least 3,000 such sites are known to occur within 1 km of a stream, river, or lake into which they have the potential to leach contaminants (Wells et al., 2010).

The biggest anthropogenic challenges, other than climate change, for Alaska's Boreal Forest biome, come from proposed development projects that include infrastructure for large-scale mining operations and access to currently roadless landscapes. Some of these projects will threaten the ecological integrity of existing protected areas (Wilson et al., 2014). The proposed Ambler road would develop a 400 km route through western Alaska Boreal Forests, cross three major salmon-producing rivers (including two Wild and Scenic designated rivers), and bisect the southern portion of Gates of the Arctic National Park. The proposed road would allow access and spur development for at least twelve individual mines that would create the largest mining district in Alaska and one of the largest mining districts in the world's Boreal Forest biome (Guettabi et al., 2016). Global development scenarios suggest oil, gas, mining, and renewable energy development in Alaska will concentrate across regions of the Boreal Forest biome (Oakleaf et al., 2019). Four of Alaska's six largest operating mines and six of the seven largest, proposed mining projects occur within the Boreal Forest biome (Spengler, 2013).

HYDROPOWER PROJECT IMPACTS IN THE NORTH AMERICAN BOREAL FOREST BIOME

Large hydropower projects in Canada, many developed in the 1970s and 1980s, have inundated millions of hectares (Wells et al., 2010; Cheskey et al., 2011), especially in parts of the eastern Boreal Forest biome. For example, 1.1 million hectares of terrestrial habitat were lost to five reservoirs established in the La Grande River region of central Quebec (Gauthier and Aubry, 1996). According to Brandt et al. (2013) there were 713 large dams (>5 m in height) and another 290 smaller dams in Canada's portion of the Boreal Forest biome as of 2011. The total surface area of hydropower impoundments was estimated at 50,724 km². Most of this surface area was formerly terrestrial habitat (Wells et al., 2010; Lee et al., 2011).

Large, proposed hydropower projects in Alaska would bring significant changes to Alaska's Boreal Forest biome. The Susitna-Watana Hydroelectric project would destroy over 20 km of spawning habitat for Arctic grayling and impact 100 km of salmon spawning habitat. The dam created by the project would be the fifth largest concrete dam in the world. Proposed dams and both claimed and surveyed mining claims encompass a significant portion of Alaska's Boreal Forest, indicating the potential for large-scale industrial development in a currently intact ecological region larger than the size of California.

ROAD NETWORK AND AGRICULTURE IMPACTS IN THE NORTH AMERICAN BOREAL FOREST BIOME

Roads and associated infrastructure threaten the ecological integrity of large portions of North America's Boreal Forest biome. Between 1959 and 1970, over 6,000 km of new permanent roads were built in Canada, largely in the Boreal Forest biome (Bone, 1992). A vast network of hundreds of thousands of kilometers of logging roads still span Canada's southern Boreal Forest biome – at least 51,000 km (ten times the driving distance between Montreal and Vancouver) in Quebec alone. In addition, there are over 1,200 km of new or upgraded roads under consideration in Quebec's northern regions (Government of Quebec, 2011). In British Columbia, there are now over 600,000 km of resource roads with an estimated 10,000 km of new roads added every year (Forest Practices Board, 2015).

In Alaska's portion of the Boreal Forest biome, the 577 km Dalton Highway was built in 1974 to serve the oilfields on Alaska's Arctic coastline. It bisects Boreal Forest and has accelerated the degradation of permafrost in the region and shifted plant community composition due to the accumulation of road dust. The extent of the degradation footprint from the road extends 115 km² along the road corridor (Farmer, 1993; Connor and Harper, 2013). The Red Dog Mine haul road in northwestern Alaska has impacted birds, mammals and vegetation communities in the region through heavy metal contamination and road dust pollutants (Hasselbach et al., 2005; Neitlich et al., 2017). Even the Denali Park Road, which extends through Denali National Park and allows limited vehicle traffic, has shown degradation of wilderness characteristics within the national park along the road corridor (Burrows et al., 2016).

Land use conversion for agriculture is significant in some parts of the Boreal Forest biome. In the western Canadian Province of Saskatchewan, deforestation rates for agriculture can reach 1% per year (Hobson and Bayne, 2000). Parts of the biome in Alberta, Manitoba, and northeastern British Columbia have also experienced significant conversion to agriculture.

POLICY CHANGE IMPACTS IN ALASKA'S BOREAL FOREST

In Alaska, current government actions by the Department of Interior and the Bureau of Land Management are putting the

ecological and subsistence functions of Alaska's Boreal Forest lands at even further risk. The Bureau of Land Management is preparing revised Resource Management Plans that govern millions of acres and proposes to remove all protections for Areas of Critical Environmental Concern while declining to designate any new Areas of Critical Environmental Concern, despite its statutory obligation. For instance, in the Bering Sea Western Interior Resource Management Plan, the Bureau of Land Management has proposed to remove Areas of Critical Environmental Concern protection from approximately 1.9 million acres (769,000 ha) and refused to give protection to an additional 4.2 million acres (1.7 million ha) that the agency found merited such protection (Bureau of Land Management, 2019). Further, the United States Department of the Interior has issued Public Land Orders revoking withdrawals on nearly 2 million acres (809,000 ha) of Boreal Forest lands (Rait, 2019; Rowland-Shea et al., 2019).

CLIMATE CHANGE IMPACTS IN NORTH AMERICA'S BOREAL FOREST BIOME

While large areas of the North American Boreal Forest biome are being rapidly transformed by industrial activities, the biome is also undergoing major impacts from climate change (Price et al., 2013; Gauthier et al., 2015; Wells et al., 2018). Books, reviews and thousands of pages of government reports are published annually on the changes underway and expected from climate change in the Boreal Forest biome. While these are important (and we summarize some of the major impacts below), we focus in this review on impacts from land-use change activities and policies and actions related to large landscape conservation.

Mean annual temperatures across the biome are projected to be higher by 4–5°C by 2100 with an increase in droughts significant enough to cause tree mortality in the western portion of the biome coupled with increased size and frequency of forest fires and the severity of tree-killing insect outbreaks (Price et al., 2013). Climate warming may initially increase boreal tree growth but after an average 2°C temperature increase is reached, tree growth is expected to decrease as a result of warming and drying (D'Orangeville et al., 2018). The areal extent of the North American Boreal Forest biome is predicted to shrink by 25% by the end of the century (Rehfeldt et al., 2012). More than half of birds dependent on forested habitats within the biome are projected to decline by 2100 as a result of less favorable climate conditions (Wells et al., 2018).

Climate change is also accelerating ecological changes across the Boreal Forest biome. In Alaska, over 50% of these forests have low biomass production due to underlying discontinuous permafrost that leads to stunted timber growth. White spruce is vulnerable to permafrost degradation and may be replaced by grasslands and deciduous trees. Black spruce recruitment is declining due to shortened fire-free periods of time. Drought stress, insects, and displacement of conifers by deciduous species are driving ecological regime shift through much of the Boreal Forest biome. Boreal Forests in Alaska are expected to resemble the mixed deciduous-conifer forests of southern Canada as early

as 2040 (Mann et al., 2012) and in Canada there is evidence that deciduous species are already becoming more prominent in the southern extent of the Boreal Forest and that shift may be exacerbated by modern forestry practices (Cyr et al., 2009; Cadieux et al., 2020).

Several recent publications have outlined the regions within the Boreal Forest biome that are predicted to be important future climate change refugia for a variety of wildlife and plants and the factors that are important in determining what areas will show rapid change and what areas will show slower changes (Stralberg et al., 2018, 2020a,b).

A VISION FOR THE FUTURE OF THE NORTH AMERICAN BOREAL FOREST BIOME

The recognition of the increasing pressure for industrial resource development led a Canadian senate subcommittee in 1999 to describe the Canadian portion of the North American Boreal Forest biome as “under siege” (Sub-Committee on Boreal Forest of the Standing Senate Committee on Agriculture and Forestry, 1999). The senate subcommittee suggested that management of these lands was not living up to government commitments to sustainable management and ecosystem protection (e.g., Canada’s Forest Accord and National Forest Strategies). A forward-thinking recommendation of the subcommittee was for the establishment of industrial footprint thresholds – an idea that has been proposed and debated in the context of protecting the remaining herds of Threatened Woodland Caribou in Canada’s portion of the Boreal Forest biome (Environment Canada, 2008, 2011; Festa-Blanchet et al., 2011; International Boreal Conservation Science Panel, 2011). Significantly, the senate subcommittee pointed out that recognition and protection of Indigenous rights and participatory land-use planning were critical to the region’s future.

A coalition of Indigenous governments, conservation non-governmental organizations, and forward-thinking industry soon came together after this to form the Boreal Leadership Council (BLC). The BLC has promoted a vision for maintaining the special ecological and cultural values of the Boreal Forest biome within Canada (Carlson et al., 2015). They published this collaborative vision in 2003, describing the idea of an approach to land-use within the biome that would balance conservation and industrial activities with a suggestion that half or more of the biome should be considered for some form of protected area status (Boreal Leadership Council, 2003; Carlson et al., 2015). The need to significantly raise targets for protected areas goals in order to represent all native ecosystems, maintain populations of native species in natural patterns of abundance, maintain ecological processes, and maintain resilience to climate change (Noss and Cooperrider, 1994; International Boreal Conservation Science Panel, 2013; Carlson et al., 2015) is now widely acknowledged and discussed by both scientists and policymakers (Schmiegelow et al., 2006; Noss et al., 2012; International Boreal Conservation Science Panel, 2013; Locke, 2013; Wilson, 2016; Dinerstein et al., 2017).

CONSERVATION SUCCESSES AND OPPORTUNITIES IN CANADA

Fortunately, large conservation gains have been and continue to be made in North America’s Boreal Forest biome through innovative, collaborative efforts of Indigenous, provincial, territorial, and federal governments and NGCO. Over 450,000 km² of protected areas have been formalized in Canada’s portion of the Boreal Forest biome since 2000 and 400,000 km² of forest tenures had been certified through the Forest Stewardship Council (Carlson et al., 2015). In partnership with provinces and territories, the Canadian federal government has embarked on an ambitious effort to reach its Convention on Biodiversity-Aichi obligation of protecting at least 17% of its terrestrial landscape by 2020 (Wulder et al., 2018) through, among other things, establishing a \$500 million Nature Fund, including a \$175 million Target 1 Challenge Fund. A significant proportion of Challenge Fund support has been used to assist Indigenous and provincial/territorial governments in developing protected areas proposals. Because of its relative intactness, lands in the Boreal Forest biome of Canada make up the vast proportion of these proposals.

CONSERVATION OPPORTUNITIES IN ALASKA

In Alaska, National Wildlife Refuges, and National Parks and Preserves make up the current protected areas of the Boreal Forest biome. Over 12 million hectares within the Boreal Forest biome were protected under the Alaska National Interest Lands Conservation Act in 1980. These land protections included subsistence rights for Indigenous Peoples within Alaska, but did not convey management or ownership to Indigenous Peoples. In fact, Alaska’s 229 Federally recognized Tribes do not have equal land rights to those of Native Corporations, or state and federal government. Even with the current political structure, Indigenous Peoples have engaged in land use management planning efforts to establish Areas of Critical Environmental Concern and other types of protected areas within management plans. In Alaska, species-based co-management groups govern specific wildlife populations, but they do not have authority over land management decisions. For example, the Western Arctic Caribou Herd Working Group makes management recommendations for the Western Arctic Caribou Herd and the Alaska Migratory Bird Co-Management Council makes recommendations to inform state and federal wildlife guidelines for migratory birds. However, the conservation of species must include the conservation of species’ habitats, and thus, the co-management models that have been built by species-specific co-management boards should be expanded to include land units for conservation. Although these efforts have not resulted in permanent protection for specific places, the opportunity exists to build new collaborations and secure protections for Alaska’s Boreal Forest biome that are consistent with the requests of Indigenous governments and communities across the region.

INDIGENOUS-LED CONSERVATION

Indigenous governments across the Boreal Forest biome of Canada are leading in many of the most modern, cutting edge land and wildlife management plans and models in the world (International Boreal Conservation Science Panel, 2013; Wells et al., 2013; Carlson et al., 2015). Land-use plans developed by Indigenous governments cover vast regions involving hundreds of thousands of hectares of habitat (Wells et al., 2014). The recommendations for protected areas and sustainable development zones in these landscape plans are some of the most significant conservation efforts ongoing in North America and the world. In 2018, the Canadian federal government announced \$175 million in new funds (Target 1 Challenge Funds as mentioned above) to support new protected areas proposals, including those led by Indigenous governments. New Indigenous land-use plans and protected areas proposals (often termed Indigenous Protected and Conserved Areas) for areas within the Boreal Forest biome continue to be announced and developed.

EXAMPLE INDIGENOUS LARGE-SCALE LAND-USE PLANS AND PROTECTED AND CONSERVED AREAS PROPOSALS

The Łutsël K'e Dene First Nation in the Northwest Territories is implementing a conservation plan for their traditional territory. On August 21st 2019, the Łutsël K'e Dene First Nation signed an agreement with the Parks Canada Agency and the Government of the Northwest Territories to permanently protect 26,376 km² of boreal lands. The entire area, called Thaidene Nënë, is an Indigenous Protected and Conserved Area. Parts of it are also designated as a national park, territorial park and wildlife conservation area (S. Nitah, personal communication).

The Dehcho First Nation in the southwestern part of the Northwest Territories finalized a sophisticated land-use plan in 2006 for their more than 200,000 km² traditional territory (Dehcho Land Use Planning Committee, 2006). While negotiations with the Government of the Northwest Territories and the Canadian federal government are still ongoing, the original Dehcho plan called for more than 100,000 km² of protected lands (International Boreal Conservation Science Panel, 2013; Wells et al., 2013). In October 2018, Dehcho leaders and federal government representatives held a signing ceremony to designate the Edézhíe Dehcho Protected Area and National Wildlife Area. Spanning 14,249 km² of Boreal Forest, Edézhíe marked the first Indigenous protected and conserved area established since Canada laid out its pathway process to protect at least 17% of lands and freshwaters by 2020.

The Sahtúgot'ine Dene in the Northwest Territories proposed and established the Tsá Tué Biosphere Reserve in 2016. The Biosphere Reserve encompassed more than 90,000 km² of area including Great Bear Lake (one of the world's largest and most pristine) and its watershed. More recently the Sahtúgot'ine Dene have proposed creating an Indigenous protected and conserved area in their traditional territory.

In Yukon, the Peel River Watershed Land Use Plan which was developed through a many-year process involving a number of First Nations as well as conservation organizations and the Yukon Government, was approved in 2019 requiring 55,000 km² of new protected areas be formally established in coming years (Government of Yukon, 2019).

In Manitoba and Ontario, several First Nations that developed and implemented land-use plans for their traditional territories, worked with the governments of Manitoba and Ontario to be granted World Heritage status under the name of Pimachiowin Aki (the Land that Gives Life). They protected 29,040 km² of intact forest within the southern portions of the Boreal Forest biome in eastern edge of Manitoba and western Ontario (Davidson-Hunt et al., 2012; Wells et al., 2013). In northern Manitoba, the Sayisi Dene First Nation has proposed protection of the entire 50,000 km² of the Seal River watershed, a 260 km free-flowing river whose watershed is free of any large-scale industrial development. Other Indigenous governments and NGOs are working toward creating a marine protected area at the mouth of the Seal River to protect important beluga calving habitat and other marine protected areas in western Hudson Bay (Labun and Debicki, 2018).

In Ontario the Moose Cree First Nation has submitted a proposal to protect an additional 5,080 km² of the North French River watershed (of which 1,583 km² is currently protected) that flows north into James Bay (Canadian Parks and Wilderness Society, 2018).

In Quebec, the Cree Nation has completed a comprehensive protected areas proposal (Cree Nation Government, 2015) with community proposals for more than twenty large, new protected areas together totaling about 80,000 km² in extent (Cree Nation Government, 2019b). A new agreement was signed in 2019 between the Cree Nation and the Canadian federal government to launch a feasibility assessment for considering a new national marine conservation area in Eastern James Bay (Cree Nation Government, 2019a). A marine protected area had been proposed in 2009 off the central east coast of James Bay by the Wemindji First Nation (Mulrennan and Scott, 2019).

The Innu Nation in Labrador developed a Forest Ecosystem Strategy Plan that directs that more than 50% of the 71,000-km² agreement area be protected for ecological or cultural values – an area of 35,000 km² (Forsyth et al., 2003; Wells et al., 2014).

Although technically north of the Boreal Forest biome in Alaska, there is an opportunity for a new United States model of co-management or Indigenous leadership in protected area management for the Arctic National Wildlife Refuge (Arctic Refuge). The Arctic Refuge was established in 1960 and expanded in 1980 in Alaska. Adjacent to the Arctic Refuge are Ivvavik National Park and Vuntut National Park in Canada. The Porcupine Caribou Management Board, which includes Alaska Native Tribes, Canada First Nations, federal, state and provincial governments, was established in 1987 to fulfill the international treaty obligations to protect the Porcupine Caribou Herd within these protected areas. These landscapes have been proposed as an international Arctic Wilderness area with an emphasis of continuing to protect a land base for the Gwich'in and Inupiat cultures (Miller, 1995) and to protect the ecological integrity

of habitats and migration corridors for the Porcupine Caribou Herd. Adoption of such a new co-management model in Alaska could be an important step toward establishment of other new co-managed protected areas within Alaska's Boreal Forest biome.

INDIGENOUS GUARDIAN PROGRAMS

Increasingly, Indigenous governments across the North American Boreal Forest biome region are also developing programs to train and equip Indigenous people from their own nations to serve as on-the-ground guardians. Indigenous guardians fulfill a wide range of duties including land and people management, biological monitoring, safety and enforcement, and education within their traditional territories and protected areas using both Indigenous knowledge and western science. Often termed "Indigenous ranger" programs in Australia, such efforts already employ about 840 full time equivalent Indigenous people managing protected areas in Australia (Woinnarski et al., 2014) and the Australian government has committed another \$700 million to support rangers until 2028. One of the earliest modern examples of this approach in Canada was initiated by the Haida Gwaii in 1981 under the name of the Haida Watchmen Program (M. Richardson, personal communication). Since that time, the program has expanded to other First Nations and is now collectively called the Guardian Watchmen Program (Coastal First Nations–Great Bear Initiative, 2018). There are now about 60 Indigenous Guardian programs operating across Canada. The Łutsël K'e Dene First Nation, for instance, established the Ni hat'ni Dene (the "Dene Watching the Land") program in 2008 that trains and employs young people from the community in Indigenous knowledge, scientific monitoring and visitor education and safety duties (Łutsël K'e Dene First Nation, 2018). In 2017, the Canadian Federal government committed \$25 million to help support existing and establish more such guardian programs. By the end of 2020, more than 70 existing and new programs will have received financial support for guardian programs.

CONSERVATION RECOMMENDATIONS FOR NORTH AMERICA'S BOREAL FOREST BIOME

- Land-use decisions across the North American Boreal Forest biome will determine its ecological future. Those decisions must be led by Indigenous governments and communities. This is consistent with Free Prior and Informed Consent (FPIC) principles that state that Indigenous peoples have the right to determine and develop priorities and strategies for the development or use of lands and waters or other resources within their traditional territories (Boreal Leadership Council, 2012).
- Federal, provincial and territorial governments should make large-scale, multi-year investments in providing financial resources for Indigenous governments and communities to train and hire Indigenous land-use

planners, managers, and on-the-land guardians. Such programs can fill existing gaps in ecological data particularly in remote northern regions where data are most sparse.

- Federal, provincial and territorial governments should make large-scale, multi-year investments in providing financial resources for Indigenous governments and communities for the planning, development, and management of Indigenous protected and conserved areas. This will be essential for Canada to meet both its current and any future conservation commitments, including the Government of Canada's 2019 Speech from the Throne commitment to protect 25% of lands and waters by 2025.
- To maintain the full complement of all plant and animal species and associated ecological processes, at least 50 percent of the North American Boreal Forest biome should be within a network of protected areas free of large-scale industrial disturbance, including from forestry, mining and exploration activity, oil and gas extraction and exploration, agriculture and hydropower production (International Boreal Conservation Science Panel, 2013; Wells et al., 2014). Industrial development that does occur must be carried out at the highest sustainability standards and only with Indigenous government consent and oversight.
- The protected area networks must include very large landscapes – ideally on the order of 10,000–30,000+ km² (2.5–7+ million acres) in size – connected to allow wildlife populations to survive and to ensure the full range of habitat diversity and ecosystem functions that will serve as biodiversity reservoirs in the face of climate change (International Boreal Conservation Science Panel, 2011).
- Conservation of lands must accommodate Indigenous traditional uses of the land and should be managed or co-managed by Indigenous governments and guardians. In all conservation areas, there should be protection of traditional values and uses, including hunting, trapping, gathering plants for food, materials, medicines and spiritual and ceremonial practices.
- Planning must take into account the cumulative impacts of development over meaningful time periods (i.e., decades to a century). This is necessary to ensure that the full consequences of land use are understood and addressed. Given the unprecedented speed of climate change impacts to ecological systems, especially in northern regions, the viability of wildlife populations is dependent on managing land use to maintain large, intact habitat areas and landscape connectivity.
- While Alaska has examples of species-specific co-management plans, such a co-management model must be applied to Indigenous protected areas or ecosystem-based plans that can be implemented through Indigenous resource management, such as the approach originally envisioned for the Arctic National Wildlife Refuge.
- In Alaska, the foregoing recommendations generally apply. However, they will also need to be implemented in a manner that addresses the challenges of current

land ownership and management within the state. The federal agencies, as well as the State of Alaska, can and should use their management flexibility to enter into co-management arrangements for landscapes and set up Indigenous guardian programs, similar to those employed in Canada. They should undertake an effort to identify the best places for management with Indigenous governments and communities immediately. The opportunity to protect large, intact Boreal Forest landscapes in Alaska will require coordination among diverse stakeholders, investment in Indigenous governments and communities, and recognition of the issues that have resulted from the history of colonization across the United States.

CONCLUSION

The North American Boreal Forest biome is one of the last, large intact landscapes remaining on Earth. The intactness of the biome has allowed it to retain globally significant conservation values and features and ecological functions. As the human industrial footprint and climate change impacts continue to degrade ecosystems and increase the loss of biodiversity on the planet, the protection of the North American Boreal Forest biome becomes even more essential. Maintaining its massive terrestrial carbon storehouse is critical to preventing further carbon from being released into the atmosphere (Bradshaw et al., 2009; Carlson et al., 2009; Bradshaw and Warkentin, 2015). The biome will also become increasingly important as a place of refuge for species forced northward by inhospitable climate further south (Stralberg et al., 2015, Stralberg et al., 2017). Further, the best insurance for maintaining resilience of plant and animal communities to climate change will be the maintenance of intact ecosystems and robust populations (Wells et al., 2018). Species that must shift ranges northward to survive will have their best opportunity to do so when unimpeded by fragmented habitat full of human-made barriers. Careful land-use planning now that conserves very large parts of the North American

Boreal Forest biome will provide the best likelihood of survival for countless species, including humans. The most significant land-use planning and conservation proposals underway across the biome are led by Indigenous governments. Governments, non-governmental organizations, academics and indeed the public at large, should be finding ways to support and encourage Indigenous-led land-use planning, Indigenous guardians and Indigenous protected and conserved areas.

AUTHOR CONTRIBUTIONS

JW, ND, NC, FR, and SM contributed to the writing and editing of the manuscript. All authors contributed to the article and approved the submitted version.

ACKNOWLEDGMENTS

We thank the organizers of several international conferences for an opportunity to present some of the content and concepts reflected in this manuscript including the Intact Forests in the 20th Century conference in Oxford, United Kingdom, in June 2018 and the International Boreal Forest Research Association “Cool Forests at Risk” conference in Laxenburg, Austria in September 2018. We also thank the current and former staff and board of the Boreal Songbird Initiative for their support over many years including Lane Nothman, David Childs, Marilyn Heiman, Kelly Frawley, Jen Cerulli, Meredith Trainor, and Alecia Wells. Thanks to James Guindon, Lindsay McBlane, and Kevin Smith of Ducks Unlimited Canada for GIS support and Valerie Courtois, Emily Cousins, and Cathy Wilkinson and several reviewers for comments on earlier versions of the manuscript. General program support has come from millions of members and donors of the National Audubon Society and Ducks Unlimited, Inc., as well as foundations including the Pew Charitable Trusts and the Hewlett Foundation.

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

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