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The boreal forest as a cultural landscape

Edward A. Johnson[1] and Kiyoko Miyanishi[2]

[1]Biogeoscience Institute and Department of Biological Sciences, University of Calgary, Calgary, Alberta, Canada.
[2]Department of Geography, University of Guelph, Guelph, Ontario, Canada

Address for correspondence: Edward A. Johnson, Department of Biological Sciences, University of Calgary, Calgary, Alberta T2N 1N4. johnsone@ucalgary.ca

Because of its generally low density of humans and few settlements, the circumpolar boreal forest is often viewed as an untouched wilderness. However, archeological evidence indicates that humans have inhabited the region since the continental glaciers disappeared 8,000–12,000 years ago. This paper discusses the ecological impacts that humans have had on the boreal forest ecosystem through their activities in prehistoric, historic, and recent times and argues that the boreal forest has always been a cultural landscape with a gradient of impacts both spatially and temporally. These activities include hunting, trapping, herding, agriculture, forestry, hydroelectric dam projects, oil and natural gas development, and mining. In prehistoric times, human impacts would generally have been more temporary and spatially localized. However, the megafaunal extinctions coincident with arrival of humans were very significant ecological impacts. In historic times, the spread of Europeans and their exploitation of the boreal's natural resources as well as agricultural expansion has altered the composition and continuity of the boreal forest ecosystem in North America, Fennoscandia, and Asia. Particularly over the last century, these impacts have increased significantly (e.g., some hydroelectric dams and tar sands developments that have altered and destroyed vast areas of the boreal forest). Although the atmospheric changes and resulting climatic changes due to human activities are causing the most significant changes to the high-latitude boreal forest ecosystem, any discussion of these impacts are beyond the limits of this paper and therefore are not included.

Keywords: boreal region; ecosystems; forest

Introduction

Although often viewed as a vast untouched wilderness, the circumpolar boreal forest (taiga) region (Fig. 1), which extends roughly between 50° and 70° N latitude, is, in fact, a cultural landscape[1] that exhibits a gradient of human influence. At one end of the gradient are remote areas far from transportation networks such as roads and railways, inhabited largely by indigenous people, and whose ecosystems are still largely unmodified by humans. Figure 2 shows the extent of such "intact" forest landscapes, defined as "essentially undisturbed by human development with an area of at least 50,000 ha,"[2] in Canada and Russia. At the opposite end of the gradient are areas where the natural landscape has been significantly modified or replaced completely by agriculture, cities/towns, and industrial developments. Examples of cities in the boreal include Tromsø, Norway (pop. 63,596); Sudbury, Canada (pop. 157,857); Anchorage, United States (pop. 291,826); and Moscow, Russia (pop. 11,514,300). Between these extremes lie areas that have been partially converted to agricultural fields or whose natural resources are being exploited with varying degrees of effects/impacts on native plant and animal communities through activities such as herding, agricultural fields, strip and open pit mining, oil extraction, tree harvesting, and animal trapping. In all of the boreal regions, there are strong north–south changes in the types of environmental impact (e.g., agriculture being largely confined to the south). In Sweden, only small patches of unlogged forest remain, and in Fennoscandia generally most current forest stands classified as virgin and/or undisturbed have been shown to have had a history

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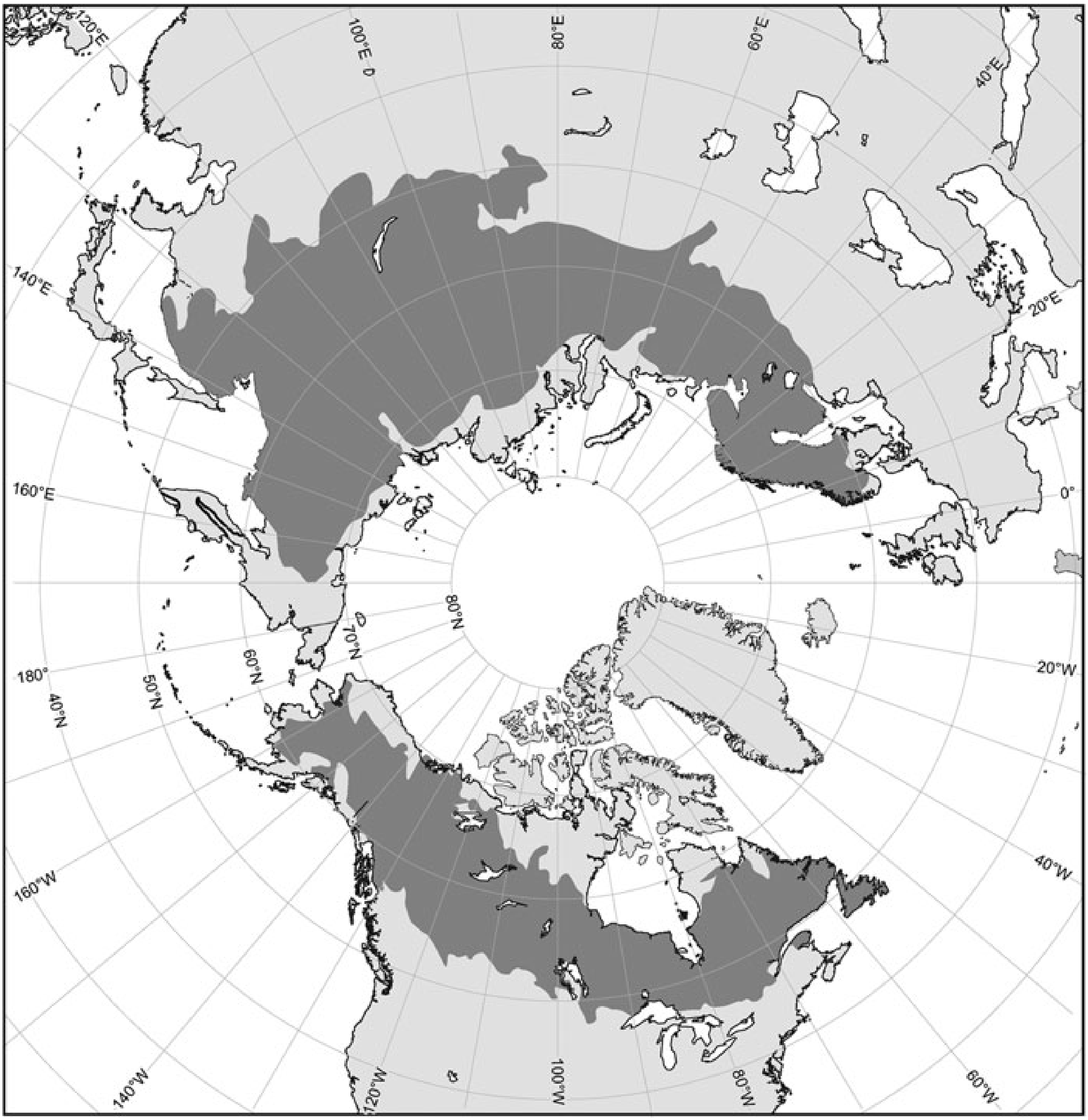

Figure 1. Circumpolar boreal region (adapted from Hare and Ritchie[102]). Reproduced with permission from The American Geographical Society.

of human disturbance and impact.[3,4] Such intensive forest use is not the case in the North American boreal, where much of the forest has not yet been cut for the first time; very little, if any, of the forest has experienced a complete harvest rotation; and large areas are still far from any roads or rail lines. However, even here, the forest has experienced the impacts of exploitation of nontimber forest resources such as fur-bearing animals in the 1700s and, more recently, oil and minerals.

Up to the middle of the last century, ecologists considered the boreal forest as having few species and poorly defined communities because it was thought to be an immature ecosystem that had not had time to reach the maturity of the deciduous forest further south.[5] The traditional ideas of succession and climax did not seem to work in the boreal forest. The boreal ecosystem, particularly in North America, was seen as wilderness. Natural and human disturbances were often not recognized, while

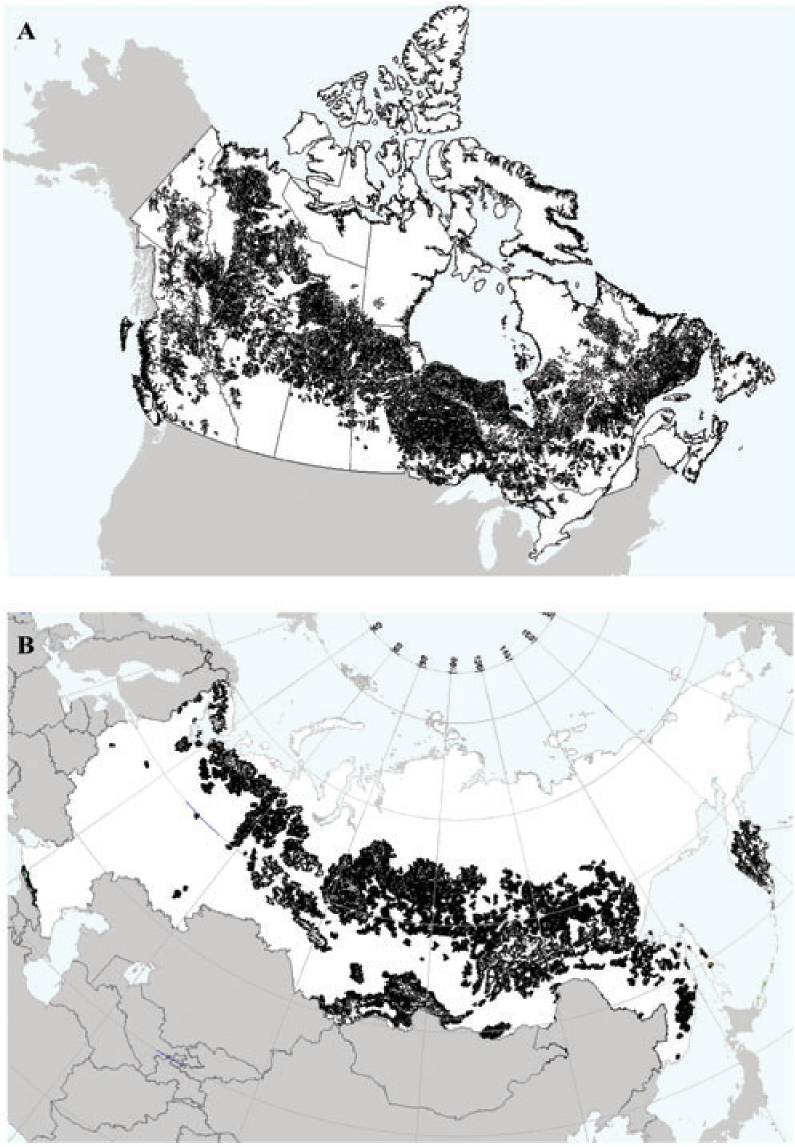

Figure 2. Intact forest of (A) Canada and (B) Russia (adapted from Global Forest Watch).[103–105] Black dots represent areas of at least 50,000 ha essentially undisturbed by human development. Reproduced with permission from Global Forest Watch.

in other situations any disturbance was assumed to be human-caused (e.g., forest fires).[6] Both viewpoints led to myopia of the cultural impact on the landscape.

In this paper, we will discuss the cultural impact on the ecology of the boreal forest. By *cultural*, we mean the effects that both indigenous and nonindigenous people have had on boreal ecosystems. We focus on the ecological impacts and not social and economic impacts that these activities have had.

Prehistoric boreal cultural landscape

Much of the circumpolar boreal region was covered several times by continental glaciers or by tundra during the Pleistocene. Humans thus had to invade, along with the reinvasion of vegetation and wildlife, as the ice retreated. Palynologists and archeologists have found evidence that much, if not all, of the current circumpolar boreal region was inhabited at some time by humans since retreat of the last continental glaciation. Scandinavia was completely ice free approximately 8,500 years BP, and the oldest archeological sites in northern Sweden and Norway are estimated to be approximately 8,000 and 10,000 years old, respectively.[7–11] The North American boreal became ice free between 11,600 and 8,400 BP, and archeological sites attributed to Paleo Indians in the boreal shield of northwestern Ontario date between 10,000 and 7,500 years BP.[12] In the Russian boreal, human occupation came 13,000 to 12,500 BP.[13]

These early boreal inhabitants who lived primarily by fishing, hunting, and trapping had mostly local impacts.[10] In general, the people inhabiting the boreal regions around the world, such as the Saami in Scandinavia and the Athabasca in North America, were nomadic. The seasonal cycle varied by location, but generally movement was for access to seasonally available foods. The freezing of water had a major influence on travel by allowing a change from water-borne transport by boats and canoes to land transport by snowshoe, toboggan, and dog or reindeer sled. Changes in food and other subsistence materials meant changes in residence and numbers of individuals in the group. Large groups only assembled for short periods at sites of concentrated resources—e.g., fish, water birds, and material for tools. Knowledge of habitat and its distribution on the larger landscape was important for knowing the location and seasonal availability of berries; roots and medicinal plants; animals with small ranges, like the bear and beaver; and nomadic animals like the moose, caribou, and reindeer. All of these activities were done at times of least effort and the best time for success with the tools available made of stone, native copper, wood and other fiber, and animal material. Spring and fall were usually critical times when summer and winter food was less available and people were dependent on dried game meat, berries, and smoked fish. Additionally, firewood was required year round and acquired using only stone tools.

The extent of impacts on ecosystems by indigenous peoples in Fennoscandia was limited before the development of agriculture and the fur trade. They would have exploited their boreal environment by fishing, hunting, and trapping for subsistence. In Europe, numerous archeological sites such as those in Norrland, Sweden, provide evidence of a traditional subsistence hunting culture dating from 8,000 BP that used primarily Eurasian elk (*Alces alces*; a close relative to the North American moose, *Alces americanus*), beaver, and fish.[14] Sometime around 4,000 BP, a change occurred from subsistence hunting to surplus production, presumably for trading for metals.[15] Also at this time, reindeer were added to the traditionally hunted Eurasian elk. Eurasian elk had been widespread from Scandinavia through Russia to Siberia but disappeared from much of Europe from the 11th to 19th centuries.

Prior to the arrival of Europeans in North America, exploitation by indigenous peoples was limited by the tools available, such as bows and arrows, snares, spears, hooks, etc. Furthermore, their social units were relatively small, with several nuclear families forming a hunting group and several hunting groups forming a band of 50–100 people.[16] As a result, their impacts on the fish and wildlife would have been limited. However, there is clear evidence that extinction of megafauna occurred whenever humans first entered areas where the fauna had no previous contact with humans.[17,18] It is also clear that indigenous peoples hunted the megafauna. Further, in areas where this megafauna had previous, long-term contact with humans, extinction was less and slower. So it is possible in the boreal forest of North America and parts of Russia that there could have been a major impact of humans on populations of both large herbivores and predators immediately after the retreat of the continental ice sheet.[19] The evidence of effects of this megafaunal extinction on vegetation and other parts of the trophic cascade is still lacking.

In North America, indigenous people used small controlled fires in selected areas and under specific weather conditions to encourage certain plant species (e.g., berry patches, forage for game animals) as well as to maintain campgrounds and trails.[20,21] Thus, they created small-scale cultural landscapes.[22,23] However, Carcaillet *et al.* could find no evidence of human-set fires in northern Sweden that might indicate management of habitat for game.[24]

Historic boreal cultural landscape

Trapping

In the North America boreal region, the arrival of European fur traders and establishment of their trading posts starting in the 1600s introduced steel and copper tools as well as guns to the indigenous people in exchange for furs. Fur trading started earlier in Fennoscandia and as early as the Middle Ages in parts of Russia but appeared to follow in a general manner the experience of North America.[25]

The fur trade resulted in a major change in the indigenous people's life ways and had a significant ecological impact, first directly on the populations of fur-bearing animals and second indirectly on the forests and ungulate populations. In North America, the indigenous people often had been trading for decades before seeing Europeans because of the use of indigenous middle men as traders far from the European trading posts.[26] However, as the fur trade and trading posts became more widespread, the indigenous people became more settled and concentrated around the trading posts, building more permanent homes, and providing the trading post inhabitants with not only furs but also game meat (largely caribou and moose). Thus, by the early 19th century, census estimates of the indigenous populations around two trading posts in northern Ontario, Canada ranged from 218 to 339.[27] Indigenous people in North American were exposed to European contagious diseases for the first time following European contact and then experienced cycles of epidemics at intervals of less than 30 years until the early 1900s.[28] First contact with European communicable diseases such as smallpox usually reduced populations by more than one half. These epidemics specifically affected the very young and old. This was very disruptive to societies in which the elders were responsible for maintaining the cultural traditions and making important group decisions.

The effects of trapping on North American boreal ecosystems are difficult to evaluate since the indigenous populations had already changed to a trapping-for-goods economy when Europeans first contacted them directly. Additionally, a major redistribution of indigenous groups resulted from both epidemic European diseases and the trading economy. Many groups moved into different ecosystems than those they had occupied in pretrading times. For example, many boreal groups moved from the boreal forest into the grassland plains with the arrival of the horse.

However, there is a consensus that trapping-for-trade reduced the populations of the beaver, wolf, bear, and other fur-bearing animals.[26,29–32] There is also some evidence that the moose, deer, and other sources of meat were reduced around trading posts. Carlos and Lewis have presented research that show trapping-for-trade reduced beaver populations in the western boreal of Canada through overharvesting.[33–35] This overharvesting was due to competition between trading companies who raised the prices paid for fur, thus leading to increased harvest by indigenous people. There was little overharvesting in regions where the price of furs stayed lower because of little or no competition between traders. Consequently, if a trading company could control access to the resource commons, it could—if it desired—maintain a sustained yield. But if it had competition for this resource commons from other trading companies, it had to raise the price for furs, resulting in the trappers increasing the harvest to an unsustainable level and causing the fur-bearer populations to decline.

The animals hunted and trapped for trade in the boreal divide roughly into two categories: herbivores (for meat and pelts) and predators (for pelts). The ecological effects of the trapping of these two groups of animals on the rest of the ecosystem are different. Removal of top predators *could* have caused trophic cascades, although evidence from the trapping–trading period is thin and anecdotal.[36] The effects on vegetation in this trophic cascade do not seem to have been commented on by European traders or explorers in their journals or reports. However, the reduction of the beaver would have had significant effects on streams and riparian and adjacent upland vegetation.[37–39] Again, these effects are not seriously commented on in the historic records and not systematically recorded. This is probably a result of the traders not going far from their trading posts and depending on the trappers for information on the state of the trapping region. The state of the ecosystems in the hinterlands was only commented on when large forest fires occurred and when meat was scarce.

Fire seems to have been used by indigenous peoples in specific habitats to improve trapping in areas that did not burn as frequently by wildfires and in small areas to attract game species at certain seasons.[21,40] Records by traders and their employees are often unreliable because of a lack of cultural awareness of the indigenous population. The traders often accused indigenous people of setting fires indiscriminately. In fact, into the 1970s, government agencies still believed that most forest fires in the boreal subarctic were human-caused rather than lightning-caused.[6] At present, we lack systematic information

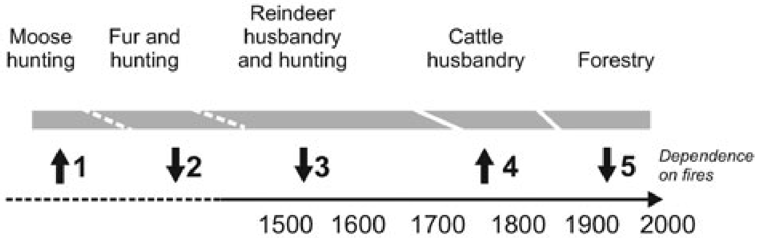

Figure 3. Approximate time frame for the sequence of cultures in the interior of northern Sweden (source: Granström and Niklasson[41]). Reproduced with permission from the authors and Royal Society Publishing.

on most of the ecological effects on boreal ecosystems during the trapping–trading periods in order to draw more general conclusions. Certainly, some effects were widespread if diffuse and thus not apparent to observers interested only in trading and with little environmental understanding or experience in the hinterlands away from the trading posts.

Herding

Herding of indigenous mammals is not common in the boreal forest. Hunters have sometimes used game drives and pit traps when the opportunity presented itself and the animals were gathered into herds, but in general only *Rangifer tarandus* (called caribou in North America and reindeer in Europe) regularly gather into herds and have seasonal migration. Further, only in Fennoscandia and Russia has semidomestication of reindeer occurred. The development of this herding is unknown but seems to have developed from the ease of forming loose attachments to herds for milking and culling for meat. Reindeer and indigenous human populations have occupied the boreal forest and tundra of Fennoscandia and Russia for all of the Holocene. Reindeer are migratory, spending summers in the forest eating herbs, grasses, and deciduous leaves of birch. Starting $\sim$ 2000 BP, Saami people in Fennoscandia shifted to herding of reindeer (Fig. 3) at the same time that their trade in furs was increasing with an emerging market in Europe.[41] Reindeer herding reached its full development in the 1500s. Before this, reindeer were less important than Eurasian elk hunting and fishing.[42] Today, large areas of the boreal forest in Norway, Sweden, and Finland are grazed by semidomesticated reindeer, herded by the Saami exclusively in Norway and Sweden and by both Saami and other groups in Finland. Reindeer populations increased markedly after the 1940s and have increasingly come into conflict with forestry interests.

Effects on the boreal forest by reindeer grazing depend on their density and seasonal habitat needs. However, in general, when grazing increases in intensity, trampling and changes in composition of lichens, herbs, and deciduous trees occur (den Herder *et al.*[43]). The effects are not always detrimental, but at high reindeer densities and short recurrences of grazing, they can have significant impacts on the ecosystem. The most obvious effect is a more open forest with little intermediate forest canopy. Evidence indicates that fires decreased after reindeer herding began because of the importance of lichens in the diet of reindeer and their slow recovery after fire.[44,45]

Agriculture

Despite the long summer day length, agriculture in the boreal is limited by harsh climate, thin soils, and distance to markets.[46] Consequently, most farming is restricted to mixed crops and animal husbandry. Forestry and trapping are often winter activities for farmers. It seems throughout history the southern edge of the boreal forest was invaded by southern agricultural groups when it was or appeared to be climatically more accommodating or when population and political pressure moved populations.[47] In Fennoscandia, farming began at the end of the 1600s with the spread of farmers from further south into areas traditionally used by Saami. Burning for agricultural clearing increased at this time.[48] During the 1800s, along with emigration to North America, there was increased colonization of the inland boreal areas in Sweden, Norway, and Finland.[46] Unlike in North America, this agricultural settlement included some indigenous Saami who gave up their nomadic reindeer herding to establish permanent farms. However, by the end of the 1800s, many farms were beginning to be abandoned as immigration to America increased.

In the Canadian and Russian boreal, agricultural colonization on the southern edge occurred only in the early 1900s and reached a peak in both regions after the First World War.[47] Again, as in Fennoscandia, by the 1940s farms were being abandoned. In all cases in the southern boreal, it appears that the spread of agriculture into the forest was decided by what farmers thought were favorable forest types that could be cleared for agriculture and favorable locations with respect to roads, railways, and nearby farms for cooperative help. Tchir *et al.* showed that settlers in the Canadian boreal selected higher hill slope positions irrespective of substrate (glaciolacustrine or glacial till).[49] Settlers appear to have used observable attributes such as stoniness, soil texture, and hill slope position rather than soil productivity in making settlement decisions. Thus, the species-richer upper hill slopes of aspen forest (glaciolacustrine) and aspen and white spruce forest (glacial till) were settled first, while the species-poorer lower hill slopes of aspen forest (glaciolacustrine) and white spruce and balsam fir forest (glacial till) were settled later.

Forest clearance for agriculture and colonization had the usual ecological effects in replacing natural or seminatural ecosystems with crops and introduced grasses supported by fertilizer and herbicide and fragmenting the remaining natural landscape. Fencing areas for cattle had the effect seen everywhere on indigenous wildlife populations. In the clearing phase of agricultural settlement, fires spread beyond the agricultural clearings into the intact forests. These settlement fires came at very short intervals, causing tree species composition to change by eliminating species that required longer fire intervals to become sexually reproductive (e.g., white spruce) and increasing species that could regenerate by sprouting (e.g., aspen).[50] These fires often spread tens of kilometers into the adjacent forest. In Canada, Fennoscandia, Russia, and the Baltic countries, agricultural colonization and the resulting increase in fires produced land-use conflicts with the indigenous populations who used the land for trapping, herding, and hunting.

Because these agricultural colonizations were often ill advised for both economic and climate–soil reasons, many farms were abandoned and the areas reverted to forest. The regenerating forests were rarely the same as that before agriculture (notice we did not say *natural* because some areas, particularly in Fennoscandia and Russia, had already been affected by herding and trapping for some time). Often, the regenerating forest‘s composition depends on the kinds of cropping or grazing that occurred on the field before abandonment.[51–53]

The spread of agriculture into the boreal forest often results in the drainage and mining of peatlands with the resulting changes in hydrology and release of methane and carbon dioxide.[54–56]

Contemporary boreal cultural landscape

Forestry

Throughout the boreal forest, indigenous people would have used wood for fires and structures. This impact was usually local and temporary because of seasonal movement; in Eurasia, forests were cleared in slash and burn agriculture.[57] Cutting and logging are not new to the boreal forest, but only in the 1800s did larger industrial forestry start. The principal limitations to the development of industrial forestry in the boreal forest are the slow growth of trees, the limited distribution of "productive" sites often making up less than 40% of the landscape, and access and transport of the wood to distant markets. In fact, much of the remaining intact boreal forest has very low productivity.[1] Early transport of logs to mills was by water and starting in the mid-1800s by permanent or temporary railroads. River transport of floating logs and rafts of logs and damming and sometimes changing or reversing the course of rivers had significant riparian ecological impacts that in many areas persist today and often go unrecognized.[58]

In boreal North America, Fennoscandia, and Russia, early industrial forestry was along the southern edge of the boreal forests. Early logging involved selective cutting of the largest and most easily accessed and transported trees. This logging was done with little knowledge of or concern for changes in forest composition or sustainability. The logging affected species composition by removing large pine and spruce and leaving smaller species, particularly deciduous trees.[59] In Fennoscandia, logging also affected reindeer grazing by reducing lichen cover.[60] While fires increased during clearance for agriculture, they decreased when forestry became more important.[48,61,62]

By the 1900s, industrial forestry was more widespread in North America, Fennoscandia, and Russia, largely due to improved access to markets, the emerging pulp industry, and the simultaneous spread of settlements into the southern edge of the boreal forest. Industrial forestry expanded rapidly after the Second World War in all regions of the *southern* boreal forest. At about this time in North America and Fennoscandia, sustained yield forestry began to be practiced with resulting increase in silviculture treatments, landscape forest rotation age regulation, and single-species plantations. The Soviet system in Russia also saw a major increase in logging in the postwar years with the then-strong centralized control and subsidy.[63]

The ecological effect of this century and a half of increased industrial forestry across the southern edge of the boreal forest has led to younger forests that increasingly reflect the relatively short rotation ages. The shorter rotation age has reduced the area in older "old-growth" forests. However, in boreal North America, unlike Fennoscandia and Russia, most forest leases are still in their first rotation and in areas that have never been cut. Natural disturbances (wildfire and insect outbreaks) are still "harvesting" an important part of industrial forests compared to commercial operations.[64] The importance of fire and insect outbreaks has led to an increase in salvage logging after these disturbances and often results in disruption of the natural regeneration.[65] Replacement of mixed species stands with single-species plantations was very popular after 1945 and has again been used in recent decades to change the composition of the forest to reduce the risk from future insect epidemics.

Dams and hydroelectric power

In recent decades, the drive to find secure energy sources has led to extensive development of hydropower in the boreal regions. Since the 1950s, the Russians have built 13 hydroelectric dams on the Oh, Yenisei, Lena, and Kolyma Rivers. The James Bay hydroelectric development project in Québec, Canada, begun in 1974, has flooded an area of 177, 000 km^2 (bigger than the state of Florida, United States) and has 11 generating stations. There are other smaller dams in the rest of the Canadian boreal, again mostly built since the 1970s. In Sweden with electric dams, hydroelectric dam construction started in the early part of the 1900s but most occurred after the Second World War.[66] As with some Canadian dams (e.g., Taltson River Dam), some dams in other parts of the boreal were constructed to produce power for mining operations. Along with dam creation, in recent years there have been economic, social, and environmental needs to remove dams and to restore the rivers to their predam flows.[67] Dam removal also has many impacts on ecosystems that had adjusted to conditions with the dam.[68,69]

Ecological effects of dams in the boreal are similar to those in other ecosystems. Dams have not generally changed river discharge, but they have changed the natural discharge patterns with decreased magnitude and timing of spring runoff and peak flows with return times longer than 10 years mostly eliminated.[70–74] Significant effects on the downstream hydrographs have been found in some boreal regions to extend 1,100 km downstream.[75] Dams have resulted in effects on stream chemistry, water temperatures, sediment loads, riparian vegetation, fish populations, and benthic populations.[76–79] Additionally, these dams lead to extensive flooding of forests and are barriers to traditional migration routes of caribou and reindeer. Flooding has created a problem of methylmercury contamination; on flooded lands, biologically unavailable inorganic mercury is converted into a biologically available and toxic form.[80] Dams also require the construction of power lines and road access with the associated ecological effects that such linear disturbances have. All dams have limited life spans before their reservoirs are filled with sediment. This has not always been considered in many dams built into the 1970s.[81]

Dams big and small, natural or human, have effects on the fluvial geomorphology of streams and rivers, both up and down the stream.[82,83] Recent work in geomorphology has shown that changes in flow regime, bank strength, and sediment budgets can have long-term effects on stream morphology and thus ecosystems.[84,85] These effects often extend well upstream and downstream of the dam and pond/reservoir by disrupting the connection of fluvial processes and hillslope processes.[86] In boreal regions, the time of adjustment may be very long, on the order of 1,000 years, although some features, particularly stream width and bar exposure caused by tree and shrub colonization, respond in decades.[84] The interaction with regional water tables and peatlands has indirect effects on biogeochemical cycling, flora and fauna composition, and productivity, both in streams and on adjacent uplands.[87] Since these effects may be slow and subtle, they are often missed or seen as part of the normal variation.

Oil and natural gas development

Oil and gas development are limited to sedimentary basins that can produce oil, natural gas, shale gas, and tar sands. In Alaska, United States, and Newfoundland, Canada, oil and gas are found in the Arctic and Atlantic Oceans, not in the boreal. In Canada‘s boreal, the sedimentary basins are around the western edge of the Precambrian Shield in Alberta, Saskatchewan, and British Columbia. Sweden has very small deposits, mostly as shale gas. Norway's oil and gas deposits are all offshore. Russia has major deposits of oil and gas in Siberia. In all of these areas, there has been extensive exploration, drilling, and production, particularly since the Second World War.

The environmental impacts of oil and gas development occur during exploration seismic, drilling, production and pipeline construction, operation, and closure. The impact of these activities has been reduced in Canada and Alaska in the recent decades because of increased regulatory requirements and technological advances. Traditional 2D seismic required the clearing of forest by bulldozers of sets of ∼eight meter-wide linear corridors at ∼one-half kilometer intervals and then holes drilled at intervals along the corridors in which dynamite charges were set. The charges are used to create seismic waves to map the subsurface features. In recent years, the use of low-impact seismic requires smaller vehicles and reduced forest clearing in construction of seismic lines; additionally, GPS instruments allow surveying with less linear corridors. However, with the need for smaller scale mapping in 3D, a finer grid is often required. Most of the seismic before the 1980s was by traditional methods, so that many areas of the boreal are crisscrossed by seismic lines (e.g., see Fig. 4). In areas with forestry operations, the area cut by seismic lines is often greater than that harvested for trees.[88] Regeneration in seismic lines is slow, primarily because boreal trees are not good at filling gaps of this small size and tree replanting was not done.[89] Seismic lines fragment the landscape; provide access for exotic species; provide corridors for easy predator movement and hunter and recreational access; contribute to soil compaction and topsoil loss from traffic used to construct the corridors; and have impacts on peatlands, wetlands, and streams.

Drilling technology has changed in the last decades, resulting in a reduced footprint of the well site during drilling and afterwards in production. The actual drilling process uses a large number of chemicals, many of which are toxic and carcinogenic. These materials are used as lubricants in the bore hole and are injected into the surrounding rock in order to increase flow through the sediment pores. Most fields required additional wells drilled to allow enhanced recovery. In the past, this led to multiple well platforms and roads, but today directional drilling allows many wells from a common platform, thus reducing the number of well sites and supporting infrastructure. Producing wells must then be connected by pipelines that require further access routes and support roads and clearing for aerial view of the pipeline route. Natural gas requires processing plants near the well fields. This discussion is simplified; oil and gas differ in diameter of their pipelines, regulations, and, in the case of natural gas, if it is shallow or deep deposits.

The environmental impacts of oil and natural gas well sites, pipelines, and roads are often very high and often persist for long periods on the boreal landscape.[90] The drilling of oil and natural gas well sites, although now more carefully managed, still uses many hazardous chemicals that have real possibility of leaking above and below ground, producing soil and water contamination. In areas in which forestry; oil and gas development; and other industrial, municipal, and recreational land-use occur, the synergistic ecological impacts are spatially extensive and disruptive of the ecosystem processes of population dynamics of animals, biogeochemical cycles, and biotic community structure and organization.

Tar sands development is more of a mining operation at present than traditional oil and gas drilling. Tar sands mining consists of removing the surface material to get at the sediment layer in which the bitumen is found.[91] The surface material is then replaced. There are also large artificial ponds in which the toxic waste from the extraction process is stored. Large amounts of water are withdrawn from rivers, reducing the annual magnitude and pattern of flow. Ecological restoration of the landscape is

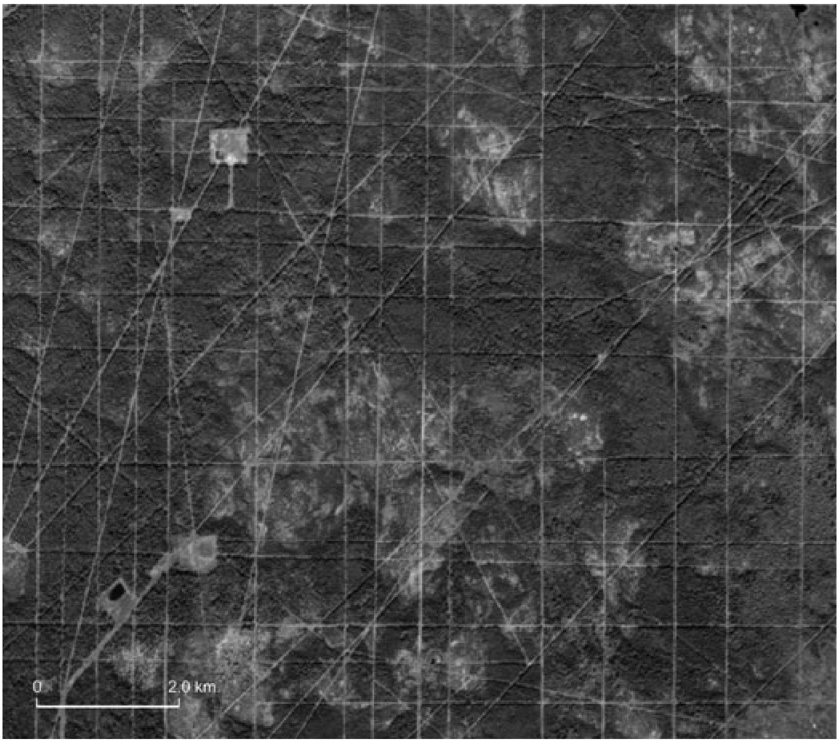

Figure 4. Air photo illustrating the high density of seismic lines (light-colored straight lines) in parts of the boreal forest in Alberta, Canada (source: AS4324, Photo 166, 1992). Reproduced with permission from Alberta Sustainable Resource Development, Air Photo Distribution. Image owned by the Government of Alberta and protected under the Copyright Act of Canada.

not the normal small-scale restoration practiced in recent decades for other human disturbances. Instead, a completely new landscape, not only of vegetation but also of hydrology, soil, and topography, has to be created. The present established area of mineable and deep tar sands in Alberta, Canada is 140,000 km^2. At present, no restoration has been undertaken, although research on how to do this is ongoing. There has also been serious criticism of the method of monitoring the direct and indirect environmental effects.[92] Downwind air pollution from the processing plants has serious impacts on lichens, the winter food of woodland caribou, and on the biodiversity of terrestrial and aquatic ecosystems on Precambrian bedrock. It is estimated that the restoration process to a "functioning ecosystem"[93] of tar sands mining will take hundreds of years. Nothing of this size and scope has taken place before in the boreal forest.

Shale gas development is in the exploration phase and is limited to sedimentary basin.[94] Shale gas requires deep wells and more wells than conventional gas, although directional drilling may reduce the above-ground footprint. The gas is produced by fracturing the sediment to provide passage for the natural gas. The fracturing is done hydraulically and with gas, chemicals, and sand to maintain the fractures. The process requires large amounts of fresh water. Additionally, the carbon footprint will be larger, as CO_2 is a natural impurity in some shale gas deposits. Some of this emission may be reduced by carbon capture techniques. At present, the most obvious impact will be the large use of surface and ground water. Water used will consist of stream and river water, shallow and deep groundwater, and recycled shale gas well water. Use of surface and ground water will certainly have effects on instream flow and the resulting aquatic ecosystems. The effects on hillslope hydrology are not yet clear. What is clear, however, is the conflict with already allocated water rights to other uses, both industrial and domestic.

Mining

Indigenous peoples everywhere in the boreal used rocks and minerals. Chert and other rocks were valued for making stone tools and were often being traded over long distances from specific sources. Native copper was mined 6,000 years ago in boreal Canada; however, mining impact by indigenous peoples would have been insignificant. In most parts of the boreal forest, hard rock mining started in the 1800s and was at first primarily for gold and silver and only later for nickel, asbestos, copper, uranium, iron, and diamonds. Most of this mining is on the Precambrian Shield with its deposits formed often billions of years ago; 80% of all mines in Canada are found in the boreal region.[95] Many mineral deposits in the southern boreal forest were discovered during development for agriculture, roads, and railroad construction. In recent decades, mineral deposits in the northern boreal have been found by more systematic surveys, exploration, and a better understanding of geology and use of geophysical techniques.

Hard rock mining is done by open pits and by underground excavation, producing large amounts of waste rock (tailings). For example, about 1 tonne of copper is produced for every 99 tonnes of waste. Waste rock is often remined later using more efficient and more toxic chemicals. The waste rock often contains sulfide, heavy metals, and other contaminants from the processing methods and deposits. In most mines, the waste is the major source of most heavy metal in streams and rivers. The large aboveground footprint of open pit mines is the most obvious environmental impact both locally and regionally, particularly on the above-ground and below-ground hydrology.

Igneous and metamorphic rocks containing sulfide minerals produce sulfuric acid when exposed to air and water with the help of *Thiobacillus ferroxidans* bacteria. The acid is then carried by rain and drainage into watersheds. This process can go on for long periods (e.g., thousands of years) until the sulfides are weathered out. The low pH and chemicals used in the mining process also release heavy metals from rocks.

Both open-pit and below-ground mining require large machinery and associated processing facilities. Isolated mines, as is the usual case in the boreal, require roads and rail access often over great distances. Additionally, considerable power is required to run the dragline, transport vehicles, and associated extraction facilities. Further, shipping heavy minerals such as copper and nickel require transport methods that can carry heavier loads. Mines also use large quantities of surface water in extraction and processing. The gross water use for the extraction stage of metal mining in Canada is estimated at 2,542 million m^3 per year.[95]

The environmental impact of hard rock mining, although limited to a smaller footprint, has a much longer term effect, even when the mines themselves have relatively short lifespans. Sudbury, Ontario, Canada has one of the longest running hard rock mining operations (starting in the 1880s) and also has research documentation on its impacts on vegetation, water, air, and soil. The mines around Sudbury cover an elliptical area with a width of 200 kilometers. The deposit was formed by a meteor impact 1.85 billion years ago. This deposit accounts for two thirds of the world's nickel-bearing sulfide ore. By the late 1960s, the impact of sulfur dioxide air pollution from the three Sudbury smelters was evidenced by an inner zone barren of vegetation with a steep gradient of resistant plants out from this zone.[96,97] Extensive research has been done on the soil chemistry, soil organisms, and vegetation effects across these sulfur dioxide-impacted areas; research has also been done on vegetation recovery and genetic selection for plants tolerant of the acidity.[98] The lesson learned from this example is that recovery is slow and it is better to provide strict regulation in order to minimize impact from the beginning.

Conclusions

The boreal region has probably always been a cultural landscape impacted by humans since the Pleistocene ice retreated. However, the impact has varied depending on the closeness to large population and commercial centers. What closeness means has depended on the cost and demand for the natural resources. The boreal cultural impact must be considered in the framework of its severe climate with associated short growing season, low soil nutrients, slow ecosystem recovery, and often permafrost.

In the first phase of cultural impact, only local indigenous populations were important, and these populations were small and dependent primarily on local subsistence hunting and gathering. There is possibly one exception to this statement in North

America, where the Pleistocene migration of humans from eastern Asia was into a landscape in which the resident fauna had not previously encountered humans. Although there is some debate on the exact impact of this human invasion, it is clear that many species of large mammals, both predators and herbivores, became extinct in the millennium after human arrival in North America.[99] The result of this extinction must have been a major change in the trophic cascade. Thus, in a very important way, the impact of the arrival of the first humans in boreal North America could have been as important as the impact that started after the arrival of Europeans.

The second phase of cultural impact is marked by the arrival of commercial enterprise and increasingly large population centers close enough to allow exploitation of natural resources. This phase is marked by the use of the boreal regions across the globe as hinterlands or sources of natural resources. This hinterlands–heartland continuum first occurred in Europe and eastern Russia and then in North America and western Russia. The boreal regions have never become heartlands because the climate is not conducive to agriculture except on its southern margin and not conducive to settlement because of the infrastructure required to deal with the cold climate. Further, the boreal region has generally been far from commercial markets, although this has diminished as demand for limiting resources has increased and offset the transportation cost. As a consequence, human populations in the boreal have consisted of two separate groups: those who tried to maintain their indigenous life ways and those that are there as government employees from the heartland or for resource exploitation.[100] Up to now, this second group has been the source of most of the ecological and environmental impact in the last three centuries.

The boreal has always had a boom or bust economy during this second phase, starting with the fur trade and continuing today with timber, minerals, oil, and gas. This has been primarily due to the fluctuation in price of these natural resources in distant markets and changing demand (e.g., beaver hats and in recent years the collapse of the fur coat market). Additionally, hard rock mines have a fairly short lifespan of decades, as do some hydroelectric reservoirs. All of these economic effects marginalize indigenous populations and lead to an exploitation strategy that has not encouraged sustainability and care for ecosystem services. Further, the populations of boreal regions are small, so their political influence as commercial and population centers is not great.

The effect of these forces has resulted in an increasing rate of environmental impact on boreal regions. Unfortunately, we can probably not say that North America, being later in the development of its boreal region, will trace the same history as, for example, the Fennoscandian boreal, due to the increasing globalization of natural resource demand.

Of course, throughout this paper we have ignored the largest cultural impact on the boreal in the form of global warming by greenhouse gases.[101] Boreal regions of the world are, along with the Arctic, experiencing the largest change in climate from greenhouse gas warming. This and other atmospheric changes, such as increased acid precipitation, will create a new ecosystem that is not like any of the past in the boreal; in fact, the ecosystem will likely no longer be boreal.

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Conflicts of interest

The authors declare no conflicts of interest.

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