THE IMPACTS OF INDUSTRIAL LOGGING IN THE GREAT NORTHERN FOREST

Greenpeace/Jani Sipilä

EXECUTIVE SUMMARY

The Great Northern Forest, the boreal forest landscape that rings the subarctic, represents nearly one-third of the forest left on Earth. These vast forests are home to a rich diversity of native mammals ranging from reindeer (in Northern Europe and Russia) and caribou (in North America) to wolverines and lynx. Its trees, plants, and soils (including vast areas of peatlands and permafrost) store more carbon than the world's tropical forests.

The Great Northern Forest comprises old growth forest system, with both old growth and new growth resulting from natural disturbances (e.g. fires), and managed forest (i.e. subject to periodic industrially logging). Some of this old growth, particularly in Canada and Russia, exists within large tracts of forest ecosystems with no signs of significant human activity – known as Intact Forest Landscapes (IFLs).

All old growth boreal forest systems have High Conservation Value (HCV). They are complex ecosystems with an abundance of old large trees and dead wood providing habitat for a wealth of species, from birds that nest in the cavities of dead trees, to a host of specialist insects, lichens and fungi. The Great Northern Forest is also home to several hundred Indigenous communities who have governed and stewarded their lands and waters since time immemorial.

The Great Northern Forest is the evergreen crown of the planet. This amazing ecosystem is an important global reservoir of stored carbon and a crucial haven for biodiversity in the face of climate change. To save the beauty and the incredible diversity of life we need to base our relation with the forest on scientific facts. These facts you will find in this report.

FACT: Old growth forests systems are better for biodiversity.

There are substantial differences between a managed boreal forest and an old growth boreal forest, particularly in terms of biodiversity, and with regards to specialist species that depend on old growth. Once an old growth boreal forest has been industrially logged, the complex biodiversity of the old growth forest system is not replaced within a human lifetime, but can take up to 200 years or more. The rotation period in a managed boreal forest (typically 70-120 years) does not allow the forest to develop sufficient old growth characteristics that are so important to biodiversity.

Industrial logging fundamentally damages old growth forests, destroying the results of centuries of complex natural interactions. Many elements of the original forest do recover over time, but many only over time spans far exceeding industrial logging cycles, and some not at all. A forest that is regularly logged (i.e. managed) is poorer in many critical aspects than an old growth forest. Influential actors within the forestry industry wants the public to believe that old growth boreal forest systems are entirely renewable over a short time frame, but this is far from being the case.

Characteristics such as structural complexity, dead wood, and the abundance and diversity of lichens can be destroyed for generations by industrial logging. Species such as the woodland caribou in Canada, heavily dependent on lichens as food source, may be driven out and most likely will never return. In Sweden, the region of the Great Northern Forest with the longest history of large-scale industrial logging, there has been a decline in populations of hundreds of forest species since the introduction of modern, intensive forest management practices in the 1950s, with logging currently believed to be having significant negative impacts on over 1,300 red-listed (i.e. threatened or near-threatened) plants, animals, fungi and lichens.

FACT: Industrial logging is threatening the survival of woodland caribou.

Woodland caribou in Canada act as a key indicator for the health of the forest and the other species that live there. These caribou require large areas of undisturbed coniferous forest habitat to survive, with old growth open lichen woodlands and bogs being their preferred habitats. In Canada, the population is classed as "threatened" because of alarming falling numbers in herd size. Caribou are particularly susceptible to habitat loss from industrial logging because this disrupts sensitive predator-prey dynamics and it takes many decades for the forest to develop sufficiently to allow enough lichen growth to support them. While the areas harvested each year may appear small in an ecosystem as large as the Great Northern Forest, it is the ongoing fragmentation and erosion of old growth habitat, year after year, that jeopardises the survival of woodland caribou. Woodland caribou have already disappeared from approximately half of their historic range in North America coincident with intensive resource exploitation, including logging.

FACT: The impacts of industrial logging are substantially different to those of natural fires.

Industrial logging specifically targets mature and old forest areas, while fire affects forest of all ages, meaning some areas will escape fire and reach much greater ages than in a logging rotation. For example, in one particular Quebec boreal forest landscape with a fire return interval of approximately 300 years, 78% of unmanaged forest consisted of old stands (>120 years old), whilst the managed forest area consisted of only 28% old stands. Put simply, industrial logging is far more efficient and uniform in affecting the older tree stands than fires.

Moreover, losses of forest from industrial logging is, in most cases, additional to losses from fires, meaning the overall forest disturbance has increased. In eastern Canada, it is estimated that industrial logging has increased the annual rate of disturbance by 74% above the natural disturbance regime.

FACT: Old growth forests are better in the fight against climate change.

Old growth forest ecosystems are important in terms of both carbon storage and carbon uptake. More carbon is stored in the trees if they are not subject to industrial logging. As a group of one hundred and ninety scientists recently argued, ***'increasing harvest levels have a negative impact on the climate because the standing forest carbon stock is immediately reduced when harvested. It may take decades to centuries until the former level of the carbon stock is restored by regrowth — especially if old growth forests are clearcut'.*** Modelling of historical forest management across Europe, including Norway, Sweden and Finland, shows that, overall, European forests have released more carbon to the atmosphere than they have taken up over the past 250 years, largely because of the removal of wood from the forest.

The Great Northern Forest holds a high proportion (approx. 95%) of its total carbon in soil. Although responses to logging vary with the type of forest and method of logging, soil carbon is generally reduced by industrial logging because when the trees are cut down the ground warms as it receives more sunlight; this increases the activity of microbes (bacteria and fungi) which break down organic matter in the soil and emit carbon dioxide to the atmosphere. Once lost, the (re-) accumulation of stable soil carbon takes place only slowly and disturbed soil can continue to release carbon for many years following harvest.

The majority of carbon removed by industrial logging from a boreal forest is not stored in long-lived wood products, but released to the atmosphere over a short time scale, where it can contribute to climate change. For Finland and Sweden, analysis shows that less than 4% of the original carbon in wood extracted from the forest remains stored in wood products after 100 years, with the rest released to the atmosphere. Indeed, roughly 60% of the harvested wood is used for pulp and paper and most of this carbon (75%) is released back into the atmosphere over a time scale of only four years.

Whilst managed forests provide a useful and vital resource for timber production, they do not support the full complement of wildlife and ecosystem services (e.g. water quality) provided by old growth forest. There is an urgent need to preserve, and in some cases restore, large areas of the Great Northern Forest to increase its resilience to climate change, protect its carbon stores and maintain biodiversity.

There is a way forward. Greenpeace's vision for the Great Northern Forest is to have greater protection of high conservation value areas and intact forest landscapes. Greater forest protection can co-exist with a responsible logging industry. We are committed to working with Indigenous Peoples and their governments as well as a breadth of stakeholders – policy makers, impacted communities, companies and civil society – to forge long-term solutions for the Great Northern Forest.

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We would like to thank Professor Jay Malcolm for comments on an earlier draft of this report.

WHAT IS THE GREAT NORTHERN FOREST?

Fig. 1 The Great Northern Forest (GNF) consists of vast areas of boreal forest landscapes that stretches from Alaska, through Canada and Scandinavia, all the way to Russia (Copyright: Greenpeace).

The Great Northern Forest, also known as the boreal forest, rings the planet's land surface south of the arctic zone (see Fig. 1), covering parts of Russia, Canada, Alaska (USA), Sweden, Norway and Finland. It represents nearly one-third of the forest left on Earth[1], with about 30% of it classed as primary (or old growth) forest[2].[3] The Great Northern Forest includes over 40% of the world's Intact Forest Landscapes (IFLs).[4] These landscapes include water bodies, such as lakes, and areas of forest subjected to natural disturbances (e.g. wildfires, storm damages, insect outbreaks).[5] Whilst Intact Forest Landscapes generally contain a high proportion of old growth forests, old growth forests also exist outside such areas in smaller fragments[6].[7] Both Intact Forest Landscapes and old growth forests have High Conservation Value (see box on High Conservation Values).

The vast boreal landscapes include the territories of several hundred Indigenous communities[8], who have governed and stewarded the land since time immemorial. Indeed, some of the boreal forest's features today reflect this human interaction, which has "…inextricably tied Indigenous Peoples to the landscapes that sustain and define the diverse Indigenous cultures."[9] In other words, these forests are Indigenous Cultural Landscapes[10] of deep social, cultural and economic value. Respecting the knowledge and rights of these communities is essential for lasting forest protection.

The Great Northern Forest is home to a rich diversity of native mammals ranging from moose and bears, through beavers, wolverines and porcupines, to martens and flying squirrels. Reindeer (Northern Europe and Russia) and caribou (North America) live in the Great Northern Forest and the tundra beyond.[11] Large predators include brown and grizzly bears, wolves and the Siberian tiger.[12] The understory in old growth forests includes a remarkable range and abundance of mosses, lichens and fungi[13], which in turn host an array of insects, providing the basis of food webs.

The boreal forest ecosystem stores an enormous amount of carbon. Altogether, its trees, plants, and soils (including vast areas of peatlands and permafrost) store more carbon than the world's tropical forests.[14],[15] This makes the Great Northern Forest the single largest terrestrial carbon store on the planet. Most of the carbon in the Great Northern Forest is in its soils, with only 5% in the trees themselves.[16]

The composition, in terms of tree species of the Great Northern Forest varies across the region, depending on soil type, climate and the impacts of industrial logging (see How does industrial logging influence tree composition?). The forest is dominated by coniferous species such as pine, spruce, larch and fir, but also in some areas contains deciduous trees, such as poplar (e.g. aspen) and birch.[17] Natural disturbances such as fires and insect outbreaks are an integral part of the boreal forest's cycle of disturbance and regeneration. This means that a natural boreal forest landscape will typically be a mix of old growth forest with other tree stands at various stages of recovery from a disturbance.[18] The frequency of fires varies considerably across the Great Northern Forest. For much of the boreal, fire occurs at an interval of a few centuries, but this ranges from of 50-100 years in the drier, continental parts of the boreal, to practically never in the wettest, coastal parts.[19] However, industrial activities are now adding further disruption to the natural disturbance regime in the Great Northern Forest.[20]

The Great Northern Forest is often regarded as largely unfragmented by human activity. In fact, much is already disturbed, fragmented and degraded. Different regions of the boreal have different histories of large-scale logging, with the longest histories dating back several centuries in Norway, Finland and Sweden[21], to approximately the 1920s in Canada[22] and the end of the second world war in Russia[23]. Historically, as old growth forests in accessible areas became harvested the industrial logging frontier progressively opened up previously inaccessible areas, generally moving northwards. This move towards less accessible areas is largely continuing in Russia[24], and in Canada[25] up to the 'northern limit' of commercial forestry in the latter.[26]. Particularly in Northern Europe, there is now greater emphasis on rotational logging in previously logged forests[27], where areas are industrially logged after an interval to allow regrowth.

It is reported that nearly two-thirds of boreal forests are currently under some form of management scheme, mostly for timber production: 35 to 40% in Canada, 58% in Russia and 90% in Fennoscandia.[28] In Russia a substantial proportion (up to 20%[29]) of logging is illegal.[30] Human disturbance is increasing in all boreal regions as demand for resources increases, leading to the Great Northern Forest becoming increasingly degraded and fragmented[31] by activities such as industrial logging, mining, oil extraction, agriculture and infrastructure development. Importantly, many old growth forests are either being, or have been, converted to forests managed primarily for timber, where they are subject to rotational, industrial logging. Globally, less than 3% of the Great Northern Forest is in formally protected areas, compared with over 25% of tropical forests, although the amount protected varies from region to region.[32]

INDIGENOUS PEOPLES' RIGHTS

The right to Free, Prior and Informed Consent, enshrined in the United Nations Declaration on the Rights of Indigenous Peoples, is the internationally recognized minimum standard for ensuring the survival, dignity and well-being of Indigenous Peoples in the context of resource development within their traditional territories[33]. This means that logging companies operating in the boreal forest should only harvest in or source from an area with the explicit consent of the Indigenous communities that have called that land home for millennia.

Many Indigenous communities participate in the forest products industry and have some level of industrial logging on their territories. However, their right to determine where and how much of this activity takes place is critical. Many Indigenous governments and Peoples are also calling for strong protection of the forests on their land.

Regardless of whether an Indigenous government's choice is for development or conservation, governments, forest companies and environmental organisations must respect their right to make such a determination. Indigenous Peoples must be central to any lasting and socially just solutions on the ground.

WHAT TYPES OF LOGGING TAKE PLACE IN THE GREAT NORTHERN FOREST?

Across the Great Northern Forest, logging practices vary. They have also changed over time, and continue to do so as national regulations and policies are revised.[34] A common logging practice is clearcutting (industrial logging), where all (or nearly all) the trees in an area are cut down at the same time. For example, clearcutting accounted for over 90% of logging in Canada in 2015.[35] In many managed forests, neighbouring areas are clear cut at different times in rotation, leading to a patchwork of forest stands currently being cleared alongside areas of new and older regrowth. Individual clearcuts vary greatly in size: from sometimes even under two hectares in Finland[36], through tens of hectares in Russia[37] to up to over two thousand hectares in some parts of Canada[38]. The rotation period or interval between industrial logging cycles also typically varies from 70 to around 120 years.[39] The trees are taken for timber and/or pulp (mainly for paper products) and the logged area either replanted or left to regrow naturally.

Other forms of logging include selective logging, where individual trees or small groups of trees are harvested, typically of the best timber quality.[40] In Finland, Sweden and Norway, several cycles of thinning are typically carried out on a stand over the decades before a final clearcut.[41] Salvage logging of dead wood sometimes occurs in some regions, particularly after windstorms, forest fires or insect outbreaks.[42] Retention logging, where typically between 5 and 10% of living trees are left within a clearcut is becoming increasingly used in Canada and Sweden.[43]

MANAGED VERSUS NATURAL FORESTS

In the context of the boreal forest, scientific literature generally uses the term 'managed forest' to describe forest subject to periodic industrial logging (typically of between 70-120 years[44]). However, the Canadian government applies the term 'managed forests' to a geographically defined area of forest, which can encompass a range of practices from intense management for timber to extremely little human intervention[45]. In this report, the term 'managed forest' is applied to those forests subject to periodic industrial logging, to differentiate from a natural forest.

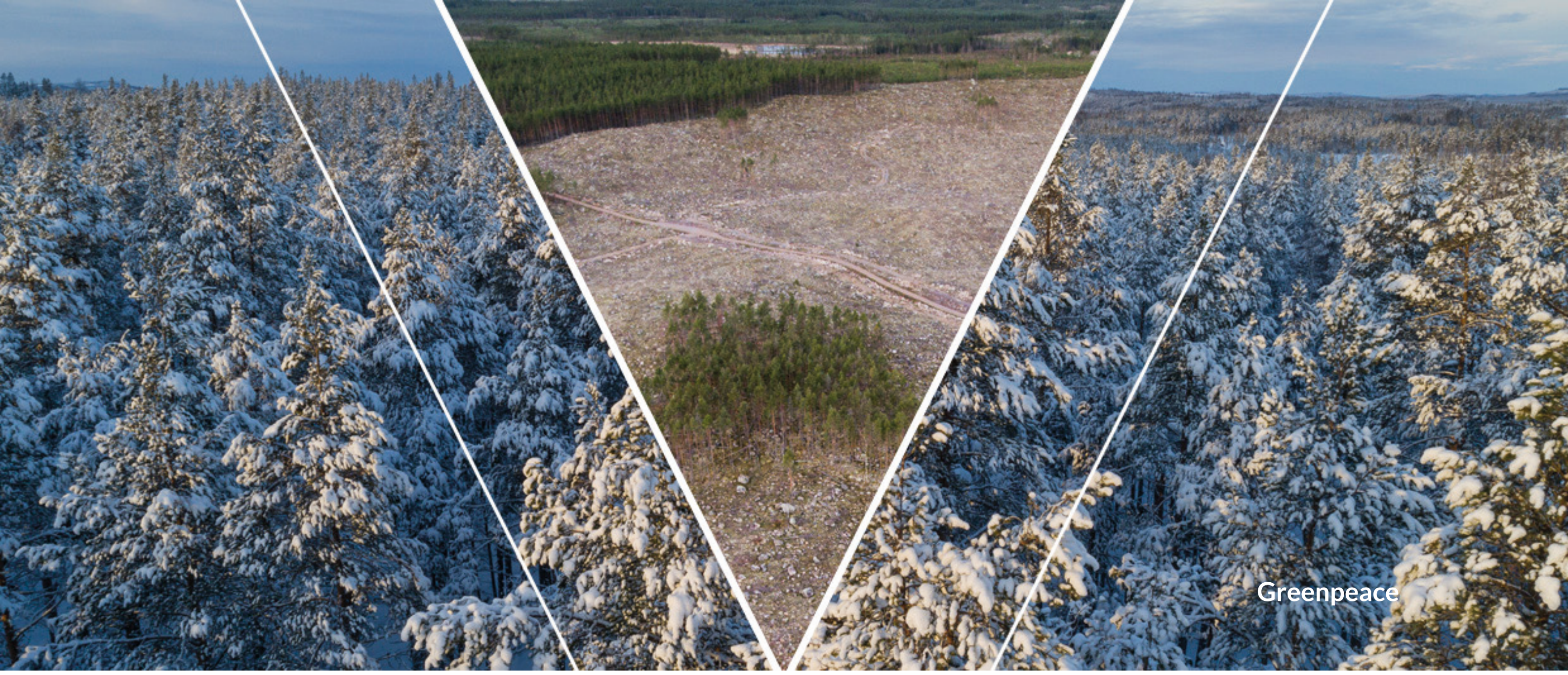
Old growth forests can originate from either managed or natural forests. The key concept of old growth forests is that they exhibit certain characteristics such as abundance of dead wood and lichen that develop over a long period of time, 150 years or more[46]. Thus, although old growth forests may have been historically disturbed by humans, they have recovered sufficiently to display many of the characteristics (and ecological functions) of a mature natural forest. The concept of old growth forest is highly similar to that of a primary forest, where the key concept is that "there are no clearly visible indications of human activities and the ecological processes are not significantly disturbed"[47]. The terms primary and old growth are used interchangeably in this report.

Greenpeace/Risto Sauso

GREENPEACE SUPPORTS RESPONSIBLE LOGGING

Many areas of the Great Northern Forest have a history, in some cases centuries, of managed forestry and have undergone a series of cutting and regrowth cycles. These areas can provide a reliable supply of logs for industry and steady jobs for local communities. Greenpeace supports responsible, certified logging in these areas, subject to Indigenous Peoples' rights and their Free, Prior and Informed Consent. However, managed forestry must go alongside conservation.

Greenpeace's ambition for the Great Northern Forest is for a diverse and resilient forest, with greater protection of high conservation value areas and intact forest landscapes. Greenpeace seeks to join in the collaborative building of conservation plans, with Indigenous Peoples at the center.



HOW DOES INDUSTRIAL LOGGING CHANGE THE FOREST?

The forest created by industrial logging is very different from a forest that is shaped predominantly by natural processes. Old growth boreal forests are complex ecosystems with an abundance of old large trees, large standing dead trees, and a diverse array of dead wood on the forest floor. All these provide habitat for many species, from birds that nest in the cavities of dead trees, to a multitude of insect and fungi species that specialize on dead wood habitats.[48] Industrial logging creates a system managed by regular large-scale human disturbance. Both types of forest have trees but, as explained below, the managed forest that results is not the same as the old growth forest that was cut down.

WHAT IS OLD GROWTH (OR PRIMARY) FOREST?

Naturally, the Great Northern Forest has been, and continues to be, shaped by dynamic processes, notably fire (in most areas), windthrow from storms and insect epidemics. In addition, numerous features of today's boreal forest reflect the long-term interactions with Indigenous Peoples, based on their land-care knowledge and adaptive livelihood practices. Therefore, "primary" doesn't necessarily mean a forest has only old trees, but a variety of characteristics that imply the area is free from industrial disturbance for long enough for traces of the disturbance not to be evident[49].

After a disturbance (e.g. logging or fire), regeneration depends on the forest type[50] but in general, different tree species re-establish themselves at different rates. Some trees are 'pioneers' that sprout quickly from seed, roots or stumps (such as certain pines, birch and aspen[51]), others are 'late succession' species (such as shade-tolerant firs and spruces[52]), which typically grow in established forest, sometimes having persisted as seedlings for many decades[53] until there is a gap caused by an older tree dying. Thus, the regenerating forest may pass through several phases before eventually displaying old growth characteristics, and the exact details of the successional process can be complex[54] (Fig. 2). Old growth forests can also go through multiple phases of such successional events. For example, disturbances on smaller scales than fires (such as windthrow) can provide opportunities for the re-establishment of pioneer species, and a new cycle of ecological succession. Some boreal forest types, e.g. those dominated by black spruce or balsam fir in Canada, are self-replacing with the same species and the main change is increasing structural complexity, rather than a change in tree species as the forest develops old growth characteristics.[55]

As old trees die, they create gaps in the forest for new trees to grow. This "gap dynamic" phase is an indicator of old growth forest. Arkhangelsk Region, NE Russia.
(Copyright: Greenpeace/Tatiana Khakimulina)

Although characteristics of old growth stands are variable depending on the boreal forest type, they generally include[56] an abundance of old and large trees including late-successional tree species. The trees are of uneven ages and there is much dead wood, either standing or on the forest floor, particularly of large diameter standing dead trees and fallen logs. Old growth forests are structurally complex and exhibit a high diversity of habitat features: a high diversity of tree sizes and species, complex three-dimensional structure, and a high diversity of dead wood resources, including with respect to size, species composition, and stages of decay of the wood. [57] The understory in old growth forests includes exceptionally diverse plant life: although typically containing a low abundance of vascular (including flowering) plants, there is a remarkable range and abundance of bryophytes (non-vascular plants such as mosses and liverworts), lichens (both those that grow on trees and those that grow on the ground) and fungi.[58]

The structural complexity of an old growth forest provides habitat for a wealth of animal species.[59] For example, standing dead wood (or snags) provide nesting sites for birds such as hawk owls.[60] The cavities that birds such as woodpeckers excavate in dead or dying trees may be subsequently used by other birds and mammals (e.g. red squirrels or flying squirrels[61]) as nests and dens. In winter, lichen on the ground and on older trees is a major part of the diet of caribou (or reindeer).[62] Lichen is also important as shelter and food for a number of insects and spiders, which are in turn important food sources for birds.[63] Indeed, many species reach their highest abundances in, or may be dependent on old growth forests; examples include the caribou, American marten, Siberian flying squirrel, and Siberian tit (or gray-headed chickadee).[64]

"Natural old growth forests in the [European] Boreal Region are now extremely rare and represent only a tiny fraction of the original habitat which once covered the region. Intensive forestry has removed many of the characteristic features of natural forests: dead and rotting wood, variation in tree size, age and species composition. Yet, these are essential features for maintaining the rich array of forest plants and animals present." - European Commission 2009[65]

Old growth forest either are, or should be, classified as areas of high conservation value (HCV, see box on High Conservation Values) because of their biodiversity (including rare or threatened species), ecosystem services and cultural values.

HIGH CONSERVATION VALUES (HCVs)

According to the HCV Resource Network, 'High conservation values are biological, ecological, social or cultural values which are outstandingly significant or critically important at the national, regional or global level'.[66] The identification and protection of HCVs are part of the principles and criteria or global procurement and investment policies of many certification schemes, private sector organisations and financial institutions.

There are six categories: [66]

HCV 1: Concentrations of biological diversity including endemic species, and rare, threatened or endangered species, that are significant at global, regional or national levels.

HCV 2: Landscape-level ecosystems and mosaics. Intact forest landscapes and large landscape-level ecosystems and ecosystem mosaics that are significant at global, regional or national levels, and that contain viable populations of the great majority of the naturally occurring species in natural patterns of distribution and abundance.

HCV 3: Rare, threatened, or endangered ecosystems, habitats or refugia.

HCV 4: Basic ecosystem services in critical situations, including protection of water catchments and control of erosion of vulnerable soils and slopes.

HCV 5: Sites and resources fundamental for satisfying the basic necessities of local communities or Indigenous Peoples (for livelihoods, health, nutrition, water, etc), identified through engagement with these communities or Indigenous Peoples.

HCV 6: Sites, resources, habitats and landscapes of global or national cultural, archaeological or historical significance, and/or of critical cultural, ecological, economic or religious/sacred importance for the traditional cultures of local communities or Indigenous Peoples, identified through engagement with these local communities or Indigenous Peoples.

HOW DOES AN INDUSTRIALLY-LOGGED FOREST DIFFER FROM AN OLD GROWTH FOREST?

Industrial logging of either an old growth or managed forest disrupts the forest ecosystem in multiple ways. These include fragmentation of animal habitats, breaking food chains and altering water systems. Importantly, industrial logging of a primary or old growth forest often means that it is being converted from a natural forest into a managed forest. That is, once the old growth is cut, the forest may then be cyclically logged, typically every 70-120 years. However, it takes up to 200-300 years for a logged forest to exhibit the characteristics of an old growth forest again (Fig. 2; see "How long does 'old growth' forest take to re-grow"). This means that a managed forest generally does not have time to develop old growth characteristics. Thus, the complex characteristics of old growth are lost and the uniform stands that regrow, and are subsequently logged before they reach the old growth stage, are unable to support the specialist biodiversity of an old growth forest.

Industrial, clear-cut logging removes virtually all the trees in an area, disrupting the forest ecosystem. It can take up to 200-300 years for a forest to fully recover old growth characteristics. In the Great Northern Forest, the typical interval between logging cycles is 70-120 years, so the forest may never recover completely. Montagnes Blanches, Quebec, Canada.
(Copyright: Markus Mauthe/Greenpeace)

Logging, by definition, removes trees from the forest and disrupts the forest ecosystem. Industrial logging of an old growth forest decreases the abundances of older and larger trees. Although the patches from clearcutting may often be smaller than those created by fire or insect damage, industrial logging either is, or has potential to, affect a larger portion of the landscape overall. This results in the landscape having less old growth than under a natural disturbance regime, as there are more trees of a younger age.[67] For example, since the introduction of modern, intensive forest management practices in Sweden in the 1950s, large areas of old growth forest have been industrially logged and the wider forest landscape fragmented. [68] This has led to 60% of Sweden's remaining forest to be under 60 years old. [69]

"Eighty years of forest management in a region [in Canada] where the natural fire cycle is long have strongly modified the landscape by reducing the proportion of old growth forests and modifying forest composition and spatial patterns." - Boucher et al. 2015[70]

In the Great Northern Forest, natural disturbances typically create large amounts of dead wood; for example, downed trees from windthrow and the abundant standing dead trees left after a fire.[71] As well as removing trees, industrial logging reduces the amount of dead wood because the period during which trees are left to die naturally is shortened. This dead wood is vital as food and habitat for many organisms including birds, insects and fungi and as a substrate for many lichens. [72] Indeed, dead wood is regarded as a key ecological indicator of the health of a forest, as the insects that feed on the decaying wood underpin a food web, and it provides nesting sites for many species.[73]

Fallen, dead trees provide a substrate for moss and lichen in old growth spruce forest, Arkhangelsk Region, NE Russia. Dead wood is a key ecological indicator of the health of a forest, but is reduced by industrial logging.
(Copyright: Greenpeace/Tatiana Khakimulina)

The logged area may be replanted, particularly in Sweden[74] and Canada[75] or left to regrow naturally. Replanting, no matter how varied the seed source, cannot replace the complexities of the old growth forest within a human lifetime. Following industrial logging, both replanting and natural regrowth tend to produce uniformly aged younger stands, with trees of a similar age and size[76]. In addition, non-native tree species may be used in replanting. Some of these can outcompete native tree species and become problematic, such as lodgepole pine (a North American species) in Sweden.[77] Conifer-dominated plantings are typically treated with glyphosate based herbicides in some parts of Canada to reduce competition from deciduous species[78], although this practice has ceased in Scandinavia[79]. Application of herbicides can affect the recovery of plants. For example, in Canada, the diversity and abundance of lichens was also affected by post-logging herbicide treatments for at least 40 years. [80]

HOW LONG DOES 'OLD GROWTH' FOREST TAKE TO RE-GROW?

Industrial logging in the Great Northern Forest is not considered to be deforestation by the UN, because trees eventually grow back, even if not in the same species mix.[81] This can lead to the myth that the industrial logging system is sustainable because it doesn't deforest (i.e. the land is not subsequently used for agriculture). However, whilst industrial logging in the Great Northern Forest may not be deforestation, the reality is that it takes many decades for the forest to even come near its original biomass and, if a similar time-scale to recover from fire disturbance is assumed, it takes centuries for its old growth characteristics and biodiversity to recover (see Fig 2 and "Don't young trees replace forest carbon as the forest regrows?").

The low temperatures and long winters of the boreal zone slow the rate of tree growth. This means the Great Northern Forest takes a long time to recover from a disturbance. The relative short history (<100 years) of industrial logging in some parts of the boreal (e.g. Canada) means predictions for forest recovery can only be based on recovery from fire disturbance and evidence from historical logging in the European boreal forest.

Recovery time depends on the characteristics of the forest, with some types of forests, dominated by relatively short-lived species, such as balsam fir in Canada, developing old growth characteristics more quickly (100-150 years) than those dominated by long-lived species, such as spruce in Canada, spruces and larches in Russia, and both spruce and Scots pine in Fennoscandia (200-300 years)[82]. In general, the forest only begins to develop old growth characteristics after roughly 100-150 years.[83] This leads, after up to 200-300 years, into what is termed a "gap dynamic" phase, which is one of the defining features of an old growth boreal forest[84] where older trees die, creating gaps into which younger trees can grow up[85] (Fig. 2). Gaps may also be created by small-scale natural disturbances, such as fire and windthrow. Severe fires can interrupt and reset the succession.[86]

It is only in this "gap dynamic" phase that lichen species can recover their abundance and diversity. This is because some of these species, e.g. tree lungwort[87] depend on processes and habitat structures present only in old growth stands, such as old trees or fallen trees and some species require specific climatic conditions, such as either shade or open gaps and moisture that are only found in old growth stands.[88] For example, it can take more than 130 years for the abundance of tree lichens to recover fully in Sweden.[89]

In Quebec, Canada, it's estimated that differences between harvested and old growth forest would still be seen 200 years after industrial logging.[90] In Sweden, it is estimated that it takes 100-150 years after selective logging for structural characteristics of old growth to return, but that 300 years might be needed to develop a clearly uneven age structure.[91] In conclusion, the typical rotation period in a managed boreal forest (70-120 years), would not allow the forest to fully develop old growth characteristics that are so important to biodiversity.

The lichen, *Lobaria pulmonaria* or tree lungwort, growing on the trunk of a tree. Tree lungwort is an indicator of old growth forest as it requires the humidity and diffuse light characteristic of old growth forests. Arkhangelsk Region, NE Russia. (Copyright: Greenpeace/Evgeny Usov)

REGROWTH STAGES

5-10 YEARS:
Trees are regenerating.

20-30 YEARS:
Young trees are established, and, in mixed woods, pioneer tree species (e.g. deciduous birch and aspen) cover the area.

100-150 YEARS:
The forest has a well-developed canopy. In mixed woods, pioneer tree species are now mature or dying. In both mixed woods and self-replacing conifer forests, late-successional conifers are beginning to grow in the gaps created by the death of this first cohort of trees. Old growth characteristics are beginning to develop: structural complexity is increasing and dead wood is accumulating.

UP TO 200-300 YEARS:
In the absence of further disturbance, the forest becomes structurally diverse with well-developed mosses, liverworts and ground lichens in the understory. Dead wood is abundant. The forest has recovered many of the original old growth characteristics.

Fig. 2. Generalised illustration of the phases of boreal forest regrowth following disturbance. Adapted from Bartels et al. (2016)[92] and Angelstam & Kuuluvainen. 2004[93].

It takes considerably longer for an industrially logged forest to reach full maturity and recover old growth characteristics than is claimed by the logging industry. For example, an illustration (Fig 3) by a major Canadian logging company gives the impression that the forest is effectively grown back after only 20 years.[94] This is far from the case.

> Fig. 3. Illustration of regrowth by a Canadian logging company gives the impression that the forest is fully regenerated after only 20 years. However, it takes considerable longer (up to 200-300 years) before the forest develops old growth characteristics and is considered fully regenerated. Source: Resolute Forest Products website; the section this graphic illustrates is titled ”Our Forests Are 100% Regenerated”.

Logging changes the tree composition of the forest. Once logged, old growth, coniferous forests typically regenerate with a higher abundance of deciduous trees. However, management practices, such as applying herbicides are used in parts of the boreal (e.g. Canada) to promote coniferous tree species. Arkhangelsk Region, NE Russia
(Copyright: Greenpeace/Igor Podgorny)

Industrial logging can change the tree composition of some boreal forests, particularly mixed woods, favouring pioneer species. Widespread changes in tree species composition have occurred in Canada as a result of industrial logging. [96] Although the changes depend on the type of soils and local climate, a trend towards faster growing deciduous trees at the expense of conifers as a result of industrial logging was identified. [97] In particular, aspen and balsam poplar have increased in abundance as these species are fast-growing and can regenerate via suckers sprouting from roots and stumps and widely dispersed seeds. In parallel, the abundance of several commercially important species, such as white pine, red pine and white spruce has decreased.[98] Similarly, in Russia, economically valuable coniferous forests generally convert to deciduous forests after industrial logging.[99]

Changes to tree species can affect the growth (or biomass productivity) of the Great Northern Forest. Several studies have found that a reduction in the diversity of tree species results in a reduction in forest productivity.[100] In addition, old growth forests are considered natural reservoirs of genetic diversity as their gene pool is considered to be superior to younger or managed stands, and the older trees produce more viable seeds.[101] Therefore, maintaining the natural tree composition in old growth forests is vital for the health and productivity of the Great Northern Forest.

"***The ongoing [tree] species loss in forest ecosystems worldwide could substantially reduce forest productivity [or growth] and thereby forest carbon absorption rate to compromise the global forest carbon sink***" - Liang et al. 2016[102]

INDUSTRIAL LOGGING, FRAGMENTATION AND FIRE

Industrial logging fragments a forest. In the Great Northern Forest, fragmentation is sometimes regarded as ephemeral as the trees regrow. However, industrial logging creates fragments of old growth within a matrix of younger forest.[103] This can affect wildlife, especially old growth specialists by forming barriers to movement and isolating species in old growth forest 'islands' (see "What does industrial logging mean for wildlife?"). Fragmentation of old growth forests is an important impact of industrial logging because over 40% of the global area of Intact Forest Landscapes is in the boreal, predominantly in Canada and Russia.[104] Once fragmented by industrial logging, the forest is no longer intact.

Fragmentation of the forest (even if temporary) by industrial logging, causes more of the forest being exposed to harmful 'edge' effects, e.g. reduced buffering against strong winds which can damage trees. [105] The edges produced by industrial logging are more abrupt and lack the complexity of those produced by natural disturbances (e.g. fire).[106] This edge complexity is important for biodiversity as it provides habitat for certain wildlife species, prevents deposition of nutrients and pollutants and reduces the effects of wind.[107]

Industrial logging, even selective logging, requires roads that fragment the forest. These form a network of mostly permanent alteration with no natural equivalent and are increasing in the boreal forest. It's estimated that there are 62,000 km of logging roads in Canada, with more road development planned.[108] In Sweden, a very dense network of forest roads has resulted in 98% of all forest in south Sweden and 75% in north Sweden lying within 1 km of a road, with the development aim to increase the road network so the distance to a road is only 500 m.[109] Although figures aren't available for the extent of logging roads in the boreal forests of Russia, it is set to increase with projected increases in logging.[110]

Roads built for industrial logging fragment the Great Northern Forest, make previously inaccessible areas more accessible and are increasing throughout the boreal. Arkhangelsk region, NE Russia.
(Copyright: Greenpeace/Tatiana Khakimulina)

The building of roads allows access to previously inaccessible parts of the forests. This is likely to increase fire frequency, which generally increases near human activities[111] (although fragmentation can also form fire breaks[112]). For example, in Russia, human activities were found to be responsible for an estimated 87% of ignitions in fragmented boreal forest areas for the period 2002-2005[113], with a similar finding by a more recent study[114]. Similarly, a Canadian study also found that fire frequency increased in previously logged boreal forest because logging residues acted as fuel for lightning initiated fires.[115] Conversely, in Sweden, the fire history of forests is complex, with active human management of fire resulting in alternating periods of fire suppression and prescribed burning since the early 1900s[116]. As a result of fire suppression, in Sweden at least, the forest ecology is considered degraded.[117]

Climate change (higher temperatures and/or lower rainfall, increased drought) is expected to increase the vulnerability of the boreal forest to fires.[118] Effects of climate change are thought to be experienced already, with an increased length of fire season throughout the boreal[119], particularly in Siberia, where the number and extent of fires has increased substantially[120]. The combination of industrial logging, fragmentation and climate change poses a serious threat to much of The Great Northern Forest[121].

"Fire has been the major disturbance process operating in boreal forests since the last Ice Age, mainly because human population density is relatively low in Boreal areas compared with most of the other biomes in the world. However, advancing timber harvest (logging) and other human encroachment has led to an increase in fire frequency in recent years, particularly in Siberia." – Bradshaw et al. 2009[122]

WHAT DOES INDUSTRIAL LOGGING MEAN FOR WILDLIFE?

"Regeneration of an old growth forest often takes centuries and, for some endangered species, the consequences of the destruction of old growth forest may be irreversible[123]" – Open letter to the EU Council by 190 scientists, September 2017[124]

Old growth boreal forests contain many specialist species that depend on old growth characteristics and attain their highest densities in such forests. [125] Industrial logging particularly affects these specialists. For example, 38% of all threatened or endangered (or 'red-listed') species in Finland, 46% in Norway and 51% in Sweden are forest species.[126] Although industrial logging has had a much shorter history in Canada than in Scandinavia, it is considered that industrial logging in Canada's boreal forests has already incurred an "extinction debt" where species may be doomed to extinction in the future.[127]

"About 50% of the [threatened or endangered] red-listed Fennoscandian species are threatened because of forestry...Although logging is considerably more recent in Canada than in Fennoscandia, already 12 out of 17 vulnerable, threatened or endangered forest-dwelling species of wild flora and fauna are considered susceptible to logging in the boreal shield region." Venier et al. 2014[128]

PLANTS, LICHENS, FUNGI AND INVERTEBRATES

To understand how industrial logging impacts wildlife, it is helpful to start at the bottom of the food chain that underpins the majority of insect, bird and mammal life in the forest. The mosses, liverworts and lichens that are characteristic of old growth forests are generally destroyed by industrial logging and, because of their long recovery time, may not recover sufficiently before the next logging cycle. Many of these mosses, liverworts and lichens depend on the presence of dead wood, particularly large fallen logs, which are less abundant in managed forests.[129] Many invertebrates, particularly beetles, also depend on dead and decaying wood.[130] For example, in Sweden approximately 1,000 species of beetles depend on dead wood.[131] The lack of dead wood in managed forests means these invertebrates are at risk of local extinction.[132]

Lichen abundance can be two times higher in natural landscapes than in managed landscapes in Sweden.[133] In Finland, tree lichens are absent in roughly 50% of the forests in a managed landscape, whilst present in the vast majority of forests in national parks in northern Finland.[134] Lichen are vital winter food for woodland caribou and reindeer (see "Woodland (boreal) caribou: an indicator species")

"***The changes in forest age structure in our study area [in Sweden] suggest a significant loss of arboreal [tree] lichen resources since the adoption of modern forest management in the mid-20th century.***" - Kivinen et al. 2012[135]

Plants and lichen provide food, shelter and nest material for many animals, including mammals and birds.[136] Studies show that the richness of plants, fungi and invertebrates is reduced by boreal forest management. For example, by 1997, in Finland, 27% of endangered invertebrates (202 species), and 53% of lichens and fungi (199 species) were considered threatened by forestry[137] and in southwest Finland, where less than 0.5% of the original old growth forest is left, out of 100 beetle species, 73 have already gone extinct[138]. Although industrial logging has existed for less time in Canada than Sweden and Finland, it is thought that similar deleterious effects on the richness of plants, lichen, fungi and invertebrates are inevitable.[139]

BIRDS

"Old-forest specialists account for almost one-third of all birds breeding in older boreal forests in both Finland and Canada. It is these late-successional species that are most likely to be negatively affected by even-aged forest management regimes that truncate the forest age-class distributions" - Venier et al. 2014[140]

Hundreds of bird species,[141] including the Siberian jay, capercaillie, Siberian tit (or gray-headed chickadee), great gray owl, Boreal owl, and Canada warbler are either forest dwellers, or depend on the boreal forest.[142] The Great Northern Forest is a vital breeding ground for billions of birds each year. For example, each spring, between 1 and 3 billion birds begin making their way up to North America's boreal forest, some from as far away as southern South America, to find suitable habitat to breed and hatch their young.[143] It's estimated that over half of all European bird species breed in the boreal,[144] with over 300 species of birds breeding in the North American boreal[145].

Many bird species, such as Siberian jay, Siberian tit, three-toed woodpecker, and great gray owl are old growth specialists.[146] They depend on habitats in old growth forests for food and shelter. For example, they might nest in tree cavities or forage on insects that, in turn, feed on decaying wood, and some have a high preference for certain tree species.[147] These birds are particularly affected by industrial logging, as this removes these old growth characteristics, and changes tree species composition. Birds dependent on old growth characteristics may be replaced by more generalist bird species in the regenerating forest. This means that whilst the overall abundance of birds may not be highly affected, the mix of bird species is altered, including reductions of the specialists that depend on old growth forests.[148] For example, in Ontario, Canada, songbird communities differed between old growth and logged stands for up to 50 years, with half the old growth bird species in the study still absent from the logged stands at this time.[149] Birds that are old growth specialists are also affected by the fragmentation of old growth forests into smaller and increasingly separated patches. This is because suitable habitat becomes increasingly hard to find, and eventually outside the range that a resident bird species can reach, leading to their isolation in old growth fragments.[150]

Both standing and fallen dead wood are an important habitat for insects and other invertebrates, which form the basis of the food chain in the Great Northern Forest. Arkhangelsk Region, NE Russia (Copyright: Greenpeace/Tatiana Khakimulina)

"Bird species of old growth boreal forests in Fennoscandia have steeply declined in numbers during the past 50 years most likely because of habitat loss and fragmentation by commercial harvesting." - Brotons et al. 2003[151]

MAMMALS

A rich diversity of mammals, from caribou, moose, wolves, lynx and Siberian tiger to porcupines, flying squirrels, voles and martens are found in the Great Northern Forest.[152]

Mammals, both large and small are affected by the reduced complexity of industrially-logged forests. In North America, industrial logging has been observed to reduce marten populations for about 40 years until sufficient forest regeneration had taken place.[153] Martens typically reach their highest abundance in old growth habitat and regenerating forest supports fewer martens.[154] A study in Ontario, Canada found that, for red-backed voles, heather voles, red squirrels, northern flying squirrels, short-tailed shrews, and star-nosed moles, there was a reduction in suitable habitat in forests logged 50-60 years ago compared with those that had not been industrially-logged.[155] However, other small mammals such as masked shrews, deer mice and meadow voles and meadow jumping mice tended to increase, depending on forest regeneration. Altogether, the study found that habitats of 40% of bird and mammal species showed marked differences between unlogged forest and forest industrially logged 50-60 years ago, with more species better suited to unlogged forests.

The Siberian flying squirrel lives in the boreal forests of Eurasia, from Finland through Russia to Mongolia and north-eastern China. Its preferred habitat is old growth forest as it tends to nest in tree cavities.[156] The species is in decline over much of its range due to loss of old growth forests caused by industrial logging.[157] It is particularly affected by forest fragmentation as it lives predominantly in trees and is reluctant to cross open ground.[158] This also means that populations living in fragments of old growth forest could become isolated from other populations of flying squirrel and lose genetic diversity, leading to an extinction risk in the forest fragment.[159]

"***The low estimates of population growth rates along with the overall, long-term decline of flying squirrels in Finland suggest that there is an urgent need to reconcile the conflicting ecological and economic goals in forestry in this country to ensure the persistence of the species. Although responses to habitat loss and fragmentation are species-specific, these results raise concern for other, less mobile boreal forest species facing the same problems of habitat isolation and destruction.***" - Lampila et al. 2009[160]

Wolverines were at one time present throughout the entire boreal forest.[161] They occur at low densities and have a very large home range (100 to 500 km^2 for males), which makes them vulnerable to forest fragmentation. Populations can become genetically isolated,[162] and ultimately unviable through forest fragmentation. Wolverines avoid deciduous forest (which typically increases in abundance as the forest regenerates) and noise disturbances, although they do not totally avoid managed forests.[163]

WOODLAND (BOREAL) CARIBOU: AN INDICATOR SPECIES

"***Mounting evidence suggests that forest management (at least as currently practiced [in Canada]) and the maintenance of self-sustaining woodland caribou populations are not compatible.***" Professor Daniel Kneeshaw, Université du Québec à Montréal, 2017[164]

Woodland caribou or reindeer act as a key indicator for the health of the forest and the other species that live there. In North America, they are called caribou and exist in the wild as solitary for much of the year, forming small groups in winter. In Russia, Norway, Sweden and Finland, they are called reindeer and are mainly in domesticated or semi-domesticated herds, although wild populations also exist.[165] Woodland caribou require large areas of mature coniferous forest habitat to survive, with old growth open lichen woodlands and bogs being their preferred habitat.[166] Their sensitivity to the impacts of industrial development serves as a warning that the overall health of the ecosystem is being significantly damaged. Under Canada's Species at Risk Act, woodland caribou are classed as a threatened species[167] with the population decline projected to be greater than 30% in the near term.[168] Some populations in Canada have disappeared while others are now listed as very unlikely to be self-sustaining[169], prompting calls for the government to "set a clear and rapid pathway to effective protection and recovery of caribou across Canada"[170].

Large fallen tree with lichen in the old growth spruce forest, Arkhangelsk Region, NE Russia. Such trees provide surfaces for lichen to grow on. Lichen is a vital food for both European reindeer and North American caribou in winter.
(Copyright: Greenpeace/Tatiana Khakimulina)

The changes in forest structure and species composition caused by industrial logging (see How does industrial logging change the forest?) have a major effect on habitat suitability for caribou. In winter, caribou diet consists predominantly of lichens,[171] in some cases up to 80%[172]. Abundant lichen is an old growth characteristic, as lichens are principally found on older trees and on the ground in forest gaps. Reindeer (Northern Europe and Russia) and woodland caribou (North America) are particularly susceptible to habitat loss from industrial logging because it takes many decades for the forest to develop sufficiently to allow enough lichen growth to support them.[173] This not only affects caribou and wild reindeer, but also domesticated reindeer, whose herders have to be able to access lichen rich forests.[174]

"Circa 30–50% of the potentially good winter grazing grounds for reindeer [in the Swedish study area] has been lost because of intensive forest management during the 20th Century and furthermore the quality of the grazing grounds are considerably impaired." - Berg et al. 2008[175]

Human disturbances, such as industrial logging roads and clearcuts,[176] but also mining and gas infrastructure,[177] destroy caribou habitat and also act as barriers to caribou and reindeer movement. In Canada, such disturbances are well documented to also make caribou more vulnerable to predators. If the old growth forest in the caribou's home range becomes a mosaic with patches of regenerating forest, the home range becomes shared with other animals, such as moose and deer, which are attracted by the abundant shrubs growing on clearcuts.[178] This, in turn, attracts predators that mainly prey on moose and deer, such as black bears and wolves, but will also opportunistically prey on caribou, in particular their calves.[179] This predator-prey interaction is an important impact of industrial logging on caribou, and negatively affects the survival of caribou populations in disturbed forests.[180]

While the areas harvested each year may appear small in an ecosystem as large as the Great Northern Forest, it is the constant erosion of old growth habitat, year after year, that jeopardises the survival of woodland caribou in these areas. Industrial logging is causing a large-scale shift in the age-class of trees towards young stands at the expense of old growth.[181] A recent study projected that, under current rates of industrial logging and fire, the proportion of old forests in western Quebec would reach "a minimum level rarely seen in the natural landscape in the past". [182]

Woodland caribou have already disappeared from approximately half of their historic range in North America,[183] coincident with intensive resource exploitation[184], including logging [185]. For this reason, caribou in Canada are sometimes called the "canary in a coal mine"[186], reflecting the decline in health of the boreal forests in Canada.

In Canada, the federal government science suggests that woodland caribou have less than a 60% chance of being self-sustaining when disturbance (industrial logging and/or fire) exceeds 35% of their range[187], and this disturbance threshold could be even less in many cases[188]. There have been many recommendations for the conservation of large unfragmented areas of old growth forest in Canada to aid caribou survival.[189] It is recommended that planning for caribou survival should be should be on a scale of 10,000-15,000 km^2.[190] Such areas are not found in the regularly-disturbed patchwork landscape resulting from industrial rotational logging, highlighting the need for a network of large-scale protected areas.

"To maintain woodland caribou, therefore, the reserve network should contain multiple protected areas that are at least 10,000-20,000 km^2 (2.5-5 million acres) in size, ideally distributed across the species' range in order to maintain the species' natural distribution" Internationa Boreal Conservation Science Panel[191]

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WHAT ECOSYSTEM SERVICES ARE DISRUPTED BY INDUSTRIAL LOGGING?

"Beyond carbon storage, wetlands, peat ecosystems and boreal forests serve a multitude of important ecosystem functions including purification of water, creation of habitat and generation of a historically valuable resource."
DeLuca & Boisvenue 2012[192]

WATER QUALITY AND QUANTITY

Industrial logging activities can have negative impacts on watercourses. Here, the turbidity ('cloudiness') of a river in the Dvinsky Forest (Archangelsk, Russia) increased due to road construction. (Copyright: Greenpeace/Tatiana Khakimulina)

Boreal forests hold vast amounts of water in their streams, rivers, wetlands, peatlands and lakes. Much of this is considered clean and unpolluted.[193] Industrial logging has major impacts on water systems, particularly from building road networks to access trees and transport logs to mills, which can interrupt water courses. The effects of industrial logging depend on a suite of variables including soil type, closeness of logging to a watercourse, slope and forest type. The removal of trees reduces evapotranspiration but, in Canada at least, does not appear to significantly affect the volume of water in watercourses.[194] In contrast, as described below, industrial logging can impact water quality.

Forests naturally supply organic matter and nutrients to streams.[195] However, industrial logging can increase the temperature, flow and turbidity (cloudiness) of streams, and even rivers and lakes. It can also increase the release of nutrients (such as nitrogen and phosphorus) from soils, upsetting the delicate chemical balance of boreal water bodies,[196] with implications to biodiversity as the type of plants change in response to increased nutrients. The increase in nutrients following industrial logging may be short-lived in the case of soluble nutrients (e.g. chloride, potassium, nitrate), but other, less soluble nutrients (e.g. calcium, magnesium) may show longer-term changes (over 3 years).[197] Industrial logging near streams and rivers results in waters that are lacking shaded areas, raising water temperatures.[198] Shade from direct sunlight is important for aquatic organisms and industrial logging can increase the exposure of aquatic organisms to higher levels of damaging ultraviolet radiation from direct sunlight.[199] Whilst some of these effects may be short-term and localized, more research is needed on the possible long-term impacts of industrial logging on water quantity and quality at the local and also landscape scale. [200]

SOIL STRUCTURE AND NUTRIENTS

Logging can cause soil erosion[201] and disturbs soil structure[202]. Whilst soils disturbed by logging may release nutrients to waters, the overall nutrient content of soils may change little, as only a small portion of the soil's nutrients are affected. [203] Any changes in soil carbon and nutrients, such as nitrogen, phosphorus, magnesium, calcium and iron, from logging are highly variable and depend on, amongst other factors, soil type, tree species mix and the type of logging, with partial harvest reducing impacts compared to clearcut.[204] Soil becomes damaged due to compaction during logging. This can affect water run-off and hinder the growth of understory vegetation during recovery.[205] Importantly, logging generally results in losses of soil carbon, which are described below in "How industrial logging worsens climate change".

"Logging disturbance in boreal forests can clearly alter biogeochemical processes in soils by changing forest composition, plant uptake rates, soil conditions, moisture and temperature regimes, soil microbial activity, and water fluxes." - Kreutzweiser et al. 2008[206]

DOES INDUSTRIAL LOGGING HAVE THE SAME IMPACT AS NATURAL FOREST FIRES?

Fires are part of the natural dynamics of much of the Great Northern Forest. Fires differ in their severity, with destructive stand-replacing fires thought to be more common in North America than Fennoscandia.[207] However, even in North America, the role of stand replacing fires in producing uneven aged forest is considered to be over-estimated and the effects of gaps as forest mature, storms, and insects underestimated.[208] Not all fires destroy all trees. Some fires may be of low intensity, allowing trees to survive, especially old Scots pine trees in the European boreal zone, which become less sensitive to fire as they age.[209]

The impacts from industrial logging are substantially different to those from fire: industrial logging specifically targets mature and old forest areas, while fire affects forest of all ages, meaning some areas will escape fire and reach much greater ages than in a logging rotation. For example, in one particular boreal forest landscape in the North Shore region of eastern Quebec with a fire return interval of approximately 300 years, 78% of unmanaged forest consisted of old (>120 years old) stands whilst the managed forest area consisted of only 28% old stands.[210] Similarly, it is estimated that, in the absence of industrial logging, forests over 100 years old (i.e. 100 years since fire) should cover an average of 49% of the boreal landscape in Canada, those over 200 years, 27% and those over 300 years, 16%.[211] In contrast, a forest that is harvested on a 100-year cycle will have an average age of 50 years and no stands older than 100 years. In summary, industrial logging is far more efficient and uniform in affecting the older tree stands than fires.

"Low-frequency fire landscapes are naturally dominated by a matrix of old growth forests interspersed with irregularly shaped patches of younger forests originating from fire or other intense disturbances. In comparison, managed landscapes under an even-aged regime are typically composed of a higher proportion of young stands, are more fragmented, have a greater amount of edges and smaller, simpler and more isolated patches of old growth forests." - Boucher et al. 2015[212]

Tree species composition may be altered in a forest recovering from industrial logging compared to fire. [213] Several conifer species, such as black spruce, will open their cones during a fire, seeding the burnt area, and becoming the dominant species.[214] With industrial logging, the regeneration is dominated by other trees, e.g. balsam fir in eastern Canadian boreal forests, because the seeding from fire-released tree seed (spruces and pines) is absent.[215]

The structure of the regenerating forest following industrial logging and fire differs. The edges produced by industrial logging are more abrupt and lack the complexity that is important for biodiversity.[216] After a fire, dead wood is abundant with snags and standing burnt trees. These provide food sources and habitat for invertebrates and hence birds and mammals. However, after industrial logging, dead wood and snags tend to be absent and the ground cover is dominated by grass and shrubs.[217] In Canada, this lack of dead and burnt wood was found to change the composition of bird species for at least 20 years, away from those that use burnt areas, such as the keystone woodpecker species, towards those that favour more unforested, open country.[218] In Sweden[219], fire is considered important for tree regeneration, as over-dominance of certain understory species (e.g. black crowberry) inhibit seedling establishment. In addition, logging does not produce charcoal, which assists establishment of certain tree species. Logging and soil preparation are considered to not provide the same ecological benefits as fire. [220]

Moreover, losses of old growth forest from industrial logging is, in many cases, additional to forest losses from fires[221], meaning the overall forest disturbance increases, a principle well reflected by the Canadian Government's Woodland Caribou Recovery Plan.[222] In the managed forests of Quebec, Canada, a study found that industrial logging had increased the annual rate of disturbance by 74% above the natural disturbance regime.[223]

HOW INDUSTRIAL LOGGING WORSENS CLIMATE CHANGE

'***The evidence is that Canadian boreal logging is actually making the climate change problem worse. Given the importance of drastically reducing greenhouse gas emissions as soon as possible in order to avoid catastrophic climate change, to my mind it is a much better climate change strategy to leave as much carbon as possible stored in the existing primary forest.***' – Professor Jay Malcolm, University of Toronto, 2017[224]

The trees and soils of the Great Northern Forest, which include peatlands and areas of permafrost, are the single largest carbon store on Earth's land surface.[225] Although carbon is taken up during tree regrowth, logging reduces carbon storage in the forest ecosystem by removing trees (which store carbon in their wood) and causing erosion and losses of soil carbon to the atmosphere.

The Great Northern Forest is currently accumulating carbon overall[226], although this sink is at risk in the future with climatic changes[227]. Conversely, modelling of historical forest management across Europe, including Norway, Sweden and Finland, shows that, overall, European forests have released more carbon to the atmosphere than they have taken up over the past 250 years.[228] One key factor leading to this release of carbon from forests is the increased proportion of forests under human management. This is because the removal of wood from the forest releases carbon that would otherwise be stored within trees, leaf litter, and also dead wood and soil as the tree dies and decays.

"In Europe, two and a half centuries of land-use change increased the forest area by 10% and has put over 85% of the forests under management, but it has failed to result in net CO_2 removal from the atmosphere, because wood extraction released carbon otherwise stored in the biomass, litter, dead wood, and soil carbon pools." – Naudts et al. 2016[229]

Managed forest in Canada is also considered to be taking up carbon.[230] However, it has not yet been possible to estimate carbon uptake in unmanaged forests in Canada[231] so the difference in carbon uptake and storage between a regularly industrially logged forest and a natural, unlogged forest (dominated by natural disturbance processes) cannot be assessed. Nevertheless, it is evident that industrial logging has reduced, and is still reducing, the age of trees in the Great Northern Forest.[232] For example, since the introduction of modern, intensive forest management practices in the 1950s in Sweden, large areas of old growth forest have been industrially logged[233], resulting in over 60% of Sweden's remaining forest under 60 years old. Similarly, a recent study projected that, under current rates of industrial logging and fire, the proportion of old forests in western Quebec would reach "a minimum level rarely seen in the natural landscape in the past".[234] The carbon contained in the Great Northern Forest is likely to be reduced as a result of this large-scale reduction in tree age.

A recent analysis considered industrial logging across Canada's boreal forest to be a major source of carbon dioxide emissions. Rates of industrial logging were found to be outpacing the recovery of carbon in the forest. That is, carbon dioxide emissions associated with clearcutting Canada's boreal forest are currently greater than the carbon dioxide absorbed by areas that were industrially logged in the past and are in the process of regenerating. The analysis estimated that this causes, on average, the release of more than 26 million tonnes (Mt) of carbon dioxide a year (calculated to be equivalent to nearly 5.5 million passenger vehicles).[235]

SOIL CARBON

Boreal forests contain a large proportion (approx. 95%[236]) of ecosystem carbon in their soils. Therefore, even a small change in soil carbon can have considerable impacts on the total amount of carbon released to the atmosphere.[237]

Different harvesting methods in different forest types have different levels of impact, with clearcutting having a greater effect than selective logging.[238] In general, soil carbon is reduced by industrial logging because when the trees are cut down, the ground warms as it receives more sunlight; this increases the activity of microbes (bacteria and fungi) which break down organic matter in the soil and emit carbon dioxide to the atmosphere. At the same time, removal of vegetation means less new organic matter, such as dead leaves, entering the soil for microbes to feed on.[239]

Once soil carbon has been lost, (re-)accumulation of stable soil carbon takes place only slowly [240]. Studies differ in their findings. One study in Canada found that the soil carbon had recovered 10 years after logging[241], whilst another study, also in Canada, identified soils as sources of carbon to the atmosphere for over 20 years following harvest[242]. Soil is one of the least well understood carbon pools of the boreal forest ecosystem and more research is needed to better assess soil carbon changes during harvesting.[243]

Doesn't industrial logging increase carbon uptake?

"Increasing harvest levels have a negative impact on the climate because the standing forest carbon stock is immediately reduced when harvested. It may take decades to centuries until the former level of the carbon stock is restored by regrowth — especially if old growth forests are clearcut" – Open letter to the EU Council by 190 scientists, September 2017[244]

It used to be thought that only young trees took up carbon as they increased in size. However, it has now been shown (including for boreal forests) that old growth forests continue taking up carbon[245] for up to several centuries, well beyond the point at which they reach commercial maturity. In the Great Northern Forest, although the carbon uptake into living trees slows, carbon is thought to still be accumulated into the soil[246], contributing to old growth boreal forest ecosystems not only being a major carbon store, but in addition a small carbon sink.[247] However, one study found a decrease in carbon stocks, as the forest reaches the old growth stage, thought to be associated with the death of the first cohort of trees (Fig. 2).[248] Nevertheless, it is evident that old growth forests are not only important in terms of carbon storage, but also in terms of carbon uptake. This means that, rather than industrial logging and regrowth being carbon neutral over a typical industrial logging cycle (approximately 100 years), more carbon is stored in the trees if they are not logged, as can be seen in Fig. U.[249] In general, models that consider industrial logging followed by regrowth as carbon neutral do not take the accumulation of carbon by mature trees into account.[250]

Difference in carbon storage between a protected (unharvested) and regularly harvested forest area

Fig. 4 Differences in carbon storage between an unlogged and regularly logged forest area from an initial state of post-disturbance. Changes in carbon stored in the regularly (approx. 100 years) logged scenario is shown in red, whilst that in the unlogged scenario is in blue. The cyclical nature of industrial logging and regrowth does not allow as much carbon to be stored as the unlogged scenario, which matures to old growth. An absence of natural disturbance (e.g. fire) is assumed in both scenarios. Adapted from Holtsmark 2012[251] and Keith et al. 2014[252].

"*Old growth forests are usually carbon sinks. Because old growth forests steadily accumulate carbon for centuries, they contain vast quantities of it. They will lose much of this carbon to the atmosphere if they are disturbed, so carbon-accounting rules for forests should give credit for leaving old growth forest intact.*" – Luyssaert et al. 2008[253].

Don't young trees replace forest carbon as the forest regrows?

Some early models predicted that industrial logging can be carbon neutral, but this is questionable for boreal forests as industrial logging reduces the overall age of the forest in a landscape[254], and the time for regrowth is so long[255]. It takes 70-120 years before a stand of trees in the boreal forest is commercially mature and harvested again.[256] Industrial logging, therefore, incurs a "carbon debt" as the large stocks of carbon in the original forest ecosystem are replaced by the smaller carbon stocks of the growing managed forest.[257] Gradually, this debt can be paid off provided that the use of wood products results in a net removal of carbon from the atmosphere.[258] Unfortunately, however, this period of debt repayment is estimated to be 100 years or more, even under the assumptions that wood resources are devoted entirely to replacing the use of fossil fuels, e.g. coal[259]. This time lag is important as it is vital that emissions of greenhouse gases (such as carbon dioxide) are reduced immediately, rather than emitting further greenhouse gases and expecting them to be sequestered by forest regrowth over the next century.[260]

As discussed in "Does logging have the same impact as natural forest fires?", fire is an important natural driver of the Great Northern Forest ecosystem but industrial logging is, in most cases, additional to fires. Although fire may result in similar carbon losses to industrial logging, and can be over large areas, fire frequency and intensity is variable, whilst industrial logging is systematic.[261] Therefore, with fire, some stands will escape fire and reach much greater ages than in a logging rotation, eventually fully recover the carbon stored in the trees.

Large tracts of natural forest are also known to be more resilient to climate change than second-growth and degraded forests.[262] Measures that protect natural forest, therefore, not only preserve the forest that is of high conservation value, but also safeguard the forest that is likeliest to remain healthy and thus to continue storing globally significant amounts of carbon in the long term.

Many studies[263] have concluded there is an urgent need to preserve (and in some cases restore) large areas of the Great Northern Forest to increase its resilience to climate change, protect the carbon stores within the trees, soils, peats and permafrost, and to maintain biodiversity, in particular to maintain predator-prey relationships. Such areas can coexist with responsibly logged areas of managed forests.

Isn't carbon stored in wood products?

Only forest carbon stocks provide the additional benefit of protecting biodiversity on this planet. Harvested wood products do not. Nonetheless, wood is a valued material that has been used by humans for millennia. For example, wood is traditionally used as fuelwood, although there is concern that modern, large-scale use of biomass from forests is unsustainable.[264] Wood products are durable and have many advantages over synthetic materials such as plastic and cement. They are used for many purposes, for example in house construction. However, many products from industrial logging are only used for a short amount of time, e.g. paper and tissue. Wood products do store carbon from forests, but this fact tells us little about how much is being stored and for how long.

Many models indicating that industrial logging and regrowth in the boreal forest has an equal or better carbon balance compared to an unlogged forest consider the carbon stored in wood products.[265] However, to act as significant carbon stores, the wood products must last a long time. International guidelines, adopted by the United Nations, on how harvested wood products can be used in national carbon accounts have been devised.[266] These suggest specific half-lives for the main forest product categories (i.e. the number of years it takes before one-half of the material has emitted its stored carbon again) (Table 1). The half-life of paper is very short at only 2 years, and even the half-life of sawn wood (that would be used in buildings or furniture) is of the order of a few decades: half, or less than half, the length of a typical rotation cycle for industrial logging of 70-120 years. Some studies consider further carbon storage by wood products in landfill sites at the end of their lifetime.[267] Carbon storage in landfill is likely to be highly variable depending on management of the site, and some, at least, will decompose to produce carbon dioxide and – even worse – methane[268], a gas with much stronger climate impact compared to carbon dioxide[269]. Furthermore, many countries, particularly in Europe, are increasingly using incineration to dispose of waste rather than landfill and incineration results in this carbon being released to the atmosphere immediately.[270]

Wood from an industrially-logged forest is used for a variety of purposes: fuelwood, pulp and paper, and sawn wood that may be used for building construction or for other solid wood products, such as furniture. The relative proportions of the final uses for harvested wood from Sweden, Finland and Canada (Table 1) show that a high proportion from boreal forests is used for short-lifespan products such as fuelwood or other energy production, newsprint and tissue, which are consumed quickly and do not store carbon long term. In both Sweden and Finland, the majority of the harvested wood is used for pulp (mainly for paper products) with a very short half-life of 2 years, whilst in Canada there is a higher proportion used as fuelwood/other energy production (Table 1). In Sweden and Canada, approximately a third goes to wood products with a half-life of 35 years, and in Finland it is closer to a quarter. In the three boreal countries shown, the largest use of harvested wood is for products with a short lifespan: fuelwood/energy production or pulp and paper.

Figure 5 shows the typical carbon flows following harvest in Sweden and Finland. Approximately 25-30% of the biomass is the residue of branches and needles in the crown and also the stump that are not extracted as timber by industrial logging.[275] These areeither left in the forest (for example, Finnish forest management recommendations are that 30% are left in the forest), or are used for the production of bioenergy.[276] Using the data in Table 1 for Sweden and Finland, analysis

CARBON FLOWS FOLLOWING TREE HARVESTING IN FINLAND AND SWEDEN

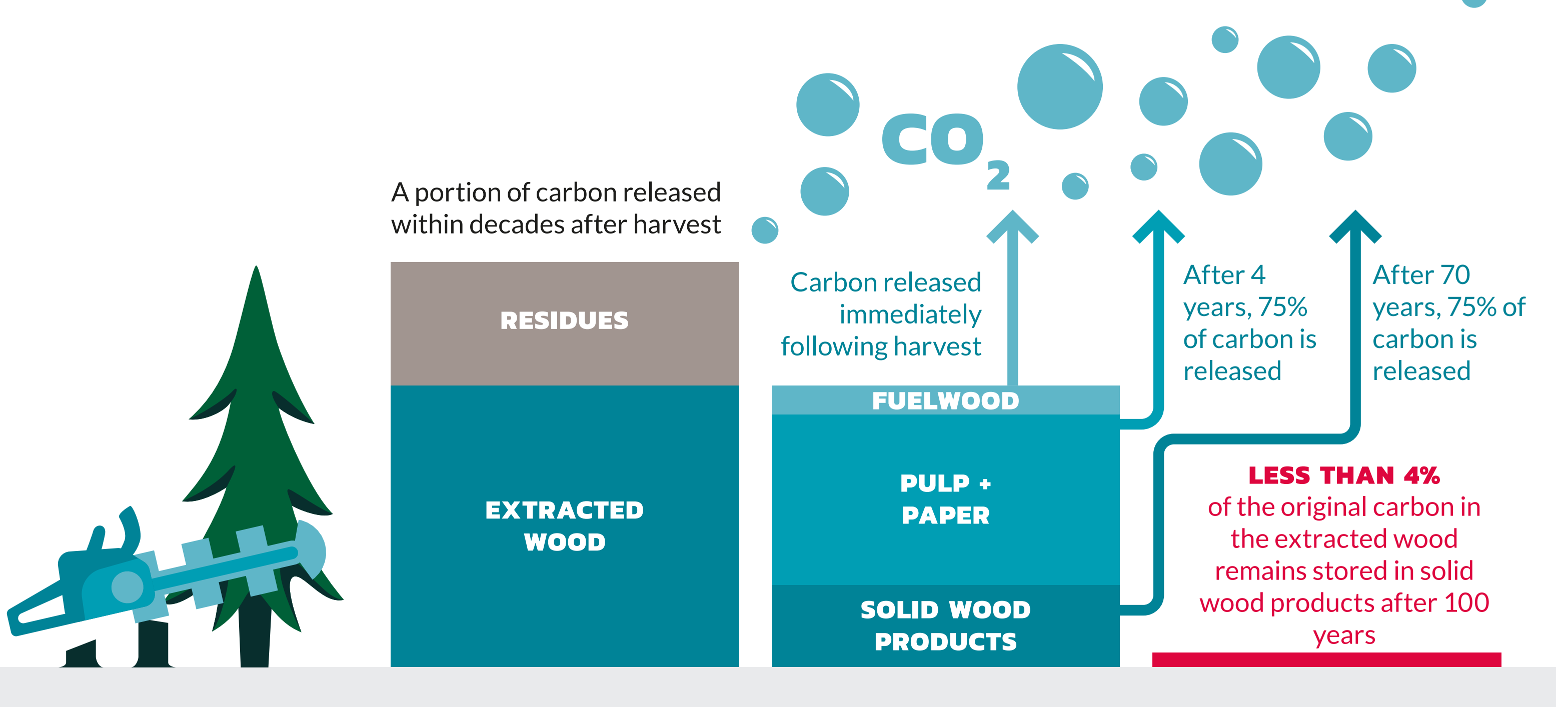

Fig. 5. Carbon flows following tree harvesting in Sweden and Finland. Data from Table 1, with the relative proportions of forestry products averaged between Finland and Sweden. 25-30% logging residues are assumed, after Liu & Westman (2009). [277]

shows that less than 4% of the original carbon extracted from the forest remains stored in wood products after 100 years, with the rest released to the atmosphere. For the approximately 60% of harvested wood used for pulp and paper, most of the carbon (75%) in the harvested wood is released back into the atmosphere over a time scale of only four years (Fig. 5). Therefore, the majority of carbon from industrial logging in a boreal forest is not stored in long-lived wood products, but released to the atmosphere where it can contribute to climate change.

Table 1 Uses of harvested wood in Sweden, Finland and Canada with associated IPCC default half-lives.

	Half-life[a] (Years)	Sweden[b]	Finland[c]	Canada[d]
Fuelwood/other energy production	0	8 %	12 %	29 %
Pulp (for paper)	2	58 %	60 %	25 %
Wood panels	25	0	0	11 %
Solid Wood Products	35	34 %	27 %	35 %

Notes: a) Default value half-lives from IPCC guidelines[271]. IPCC guidelines consider biomass for bioenergy to be burnt within the year and the carbon not stored. b) Skogsindustrierna 2015[272] c) Finnish Forest Industries 2015[273] d) Chen et al. 2013[274]

LARGE SCALE PROBLEMS NEED LARGE SCALE SOLUTIONS

The scale of the problem is large scale, but not unsolvable. A recent Canadian study projected that the proportion of old forests in western Quebec would reach "a minimum level rarely seen in the natural landscape in the past" and "the situation could become even more critical with the projected increases of fire with climate change".[278] The boreal forest in Russia lost over 4% of its intact forest landscape in just 13 years (2000-2013).[279]

Since the introduction of modern, intensive forest management practices in the 1950s, in Sweden's portion of the Great Northern Forest, large areas of old growth forest have been industrially logged and the wider forest landscape fragmented.[280] This has led to population declines in hundreds of forest species,[281] with industrial logging currently believed to be having significant negative impacts on over 1,300 red-listed (threatened or near-threatened) plants, animals, fungi and lichens.[282] With over 60% of Sweden's remaining forest under 60 years old[283] and therefore not mature enough to be harvested,[284] there is intense timber industry pressure on the remaining areas of older forest.

There is an urgent need to protect the remaining old growth of the Great Northern Forest, to protect intact landscapes (predominantly in Canada and Russia) and to restore and enlarge existing fragments (predominantly in Northern Europe) by allowing mature forests to reach old growth stage.

Greenpeace is not alone in calling for increased protection. One hundred and ninety EU and US scientists recently wrote to the EU Council demanding that 'all remaining old growth and high conservation value forests need to be protected to safeguard biodiversity and carbon stocks'.[285] Similarly, the International Boreal Conservation Science Panel has called for a network of large protected areas with no less than 50% of a region protected from development in Canada, in accordance with Free Prior and Informed Consent of Indigenous Peoples. [286] Large protected areas can coexist with a thriving, responsible logging industry outside these areas.

CONCLUSION

"A forest consists of more than its trees. For example, if an original natural forest with its myriad wildlife plant and animal species is replaced by a forest with only a fraction of those species, then it is reasonable to my mind to say that the forest in its original condition has been destroyed." – Professor Jay Malcolm, University of Toronto, 2017[287]

All old growth boreal forest systems are of High Conservation Value. They are complex ecosystems with an abundance of old large trees and dead wood providing habitat for a wealth of species, from birds that nest in the cavities of dead trees, to a host of specialist insects, lichens and fungi. The Great Northern Forest is also home to several hundred Indigenous communities who have governed and stewarded their lands and waters since time immemorial.

Contrary to common myths, industrial logging fundamentally damages old growth forests, destroying the results of centuries of complex natural interactions, carving old growth forests up into ever smaller fragment. Furthermore regular industrial logging prevents the recovering forest from reaching its pre-existing maturity. Many elements of the original forest do recover over time, but many only over time spans of up to 200 years or more, which far exceeds industrial logging cycles of 70-120 years, and some elements may not recover at all. Characteristics of old growth forests such as structural complexity, abundant dead wood, the abundance and diversity of lichens and presence of specialist species and can be destroyed for generations. Industrial activities, such as logging, could cause species such as the woodland caribou in Canada to be driven out and never return to their original habitat. The forestry industry wants consumers to believe that boreal forests are entirely renewable over a short time frame, but this is far from being the case.

The trees and soils of the Great Northern Forest, which include peatlands and areas of permafrost, are the single largest carbon store on Earth's land surface. Although carbon is taken up during tree regrowth, industrial logging reduces carbon storage in the forest ecosystem by removing trees (which store carbon in their wood) and causing erosion and losses of soil carbon . The main uses of wood from many boreal forests are short-lived products, such as fuelwood and paper, which release most of their carbon back to the atmosphere over only a few years. Managed forests do not store the same amount of carbon as unlogged forests, which continue to take up carbon for centuries. Old growth forest ecosystems are important in terms of both carbon storage and carbon uptake. They are a strong ally in our fight against climate change.

This review has shown how there are substantial differences between a managed boreal forest and an old growth boreal forest. Whilst managed forests provide a useful and vital resource – that of timber production, they do not support the full complement of wildlife, carbon storage and ecosystem services provided by old growth forest. **There is an urgent need to protect the remaining old growth of the Great Northern Forest, to protect intact landscapes (predominantly in Canada and Russia) and restore and enlarge existing fragments (predominantly in Northern Europe) by allowing mature forests to reach old growth stage.**

Greenpeace's ambition for the Great Northern Forest is a diverse and resilient forest with more and larger protected areas. Governments must increase the protection of High Conservation Value forests, including Intact Forest Landscapes, from industrial logging and other destructive activities. Furthermore Greenpeace strongly advocates for the restoration of 500 million hectares of native forests globally by 2030. This exceeds the restoration targets of the CBD Aichi target 15 and the New York Declaration of Forests . Saving the Great Northern Forest - the green crown of the Earth - is critical for the future of our planet.

GLOSSARY

BASAL AREA: the area of a given section of land that is occupied by the cross-section of tree trunks and stems at the base.

BOREAL: one of the three main forest zones in the world located in northern regions, characterised by the predominance of conifers.

CANOPY: cover of branches and leaves formed collectively by the crowns of adjacent trees.

DISTURBANCE: significant change in the structure or composition of ecosystems, species communities, or populations through natural or human-induced events such as industrial logging, fire, or mining. When a forest is referred to as 'undisturbed', this excludes minor small scale alterations in that may have been carried out by groups such as Indigenous Peoples.

FENNOSCANDIA: also known as Fenno-Scandinavia, or the Fennoscandian Peninsula, is the geographical region including Finland, Norway and Sweden, as well as Murmansk Oblast, much of the Republic of Karelia, and parts of northern Leningrad Oblast in Russia.

FIREBREAK: a break in the vegetation that prevents or slows the spread of a fire.

HCV: High Conservation Value - see box for description.

INDIGENOUS CULTURAL LANDSCAPES (ICLS): These are "living landscapes to which Indigenous Peoples attribute social, cultural, and economic value because of their enduring relationship with the land, water, fauna, flora and spirits, and their present and future importance to their cultural identity. An ICL is characterized by features that have been maintained through long-term interactions with the landscape based on land-care knowledge, and adaptive livelihood practices. They are landscapes over which Indigenous peoples exercise responsibility for stewardship."[288]

IFL: intact forest landscape; unbroken expanses of natural habitat (both forest and non-forested) within the current forest zone. These areas need to show no signs of significant human disturbance and to be large enough that all native biodiversity can be maintained, including viable populations of wide-ranging species – in practice they are defined as larger than 50,000 hectares (500 km^2). IFLs include natural disturbances, such as fire, with a decision rule is applied to forest fires to delimitate between natural and human-made fires areas.[289] 'Disturbed' areas include settlements, roads and areas visibly affected by industrial logging, agriculture or other activities, e.g. mining.[290]

KEYSTONE SPECIES: A species whose existence is essential to the integrity of the ecological community. If lost, it causes a disproportionate effect on other species[291]. For example, if the three-toed woodpecker were to be lost from boreal forests, it would adversely impact other bird and mammal species who use the tree cavities excavated by the woodpecker as nest sites[292].

MANAGED FOREST: this term is generally used in scientific literature to indicate a forest subject to cyclical industrial logging. However, in Canada, the government uses 'managed forest' to describe all forests allocated by the government to the logging industry, much of which has not yet been logged. In this document, we use the first meaning. See page 10 for further detail.

OLD GROWTH: used in this report to be equivalent to primary forest (see Primary Forest).

PRIMARY FOREST: defined by the UN FAO[293] as forests of native species, in which there are no clear indications of human activity and ecological processes are not significantly disturbed. Used in this report to be equivalent to old growth forest.

SNAGS: standing dead trees or branches held above the ground

STAND: a group of trees of similar species composition and age structure or growth, either naturally occurring or as a result of logging.

Succession: changes in species composition in an ecosystem over time, often in a predictable order

UNDERSTOREY: the lower level of vegetation in a forest. Includes shrubs, herbaceous plants, ground vegetation such as mosses, and smaller trees.

WOODLAND CARIBOU: in this report, the term 'woodland caribou' generally refers to the boreal population of *Rangifer tarandus caribou*

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[4] 43.8% of the global area of Intact Forest Landscapes is in the boreal biome, Potapov et al. 2008. See also IFL Mapping Team, 2017.

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[10] The term “Indigenous Cultural Landscapes” (ICLs) refers to “living landscapes to which Indigenous peoples attribute social, cultural, and economic value because of their enduring relationship with the land, water, fauna, flora and spirits, and their present and future importance to their cultural identity. An ICL is characterized by features that have been maintained through long-term interactions with the landscape based on land-care knowledge, and adaptive livelihood practices. They are landscapes over which Indigenous peoples exercise responsibility for stewardship.” Definition adopted by Forest Stewardship Council Canada 2016.

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[261] Cyr et al. 2009; Kuuluvainen 2009.

[262] Gauthier et al. 2015.

[263] Bradshaw et al. 2009; Wells et al. 2014; Moen et al. 2014; Rompré et al. 2010.

[264] Schulze et al. 2012.

[265] E.g. Kurz et al. 2013; for a discussion, see Pukkala 2017.

[266] IPCC 2014b.

[267] E.g. Kurz et al. 2013; Chen et al. 2013.

[268] Keith et al. 2014; Chen et al. 2013.

[269] IPCC 2013, Ch. 8.

[270] Seltenrich 2013.

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[275] Liu & Westman 2009.

[276] Peltola et al. 2011.

[277] Liu & Westman 2009.

[278] Bergeron et al. 2017.

[279] Potapov et al. 2017.

[280] Ahlkrona et al. 2017; Östlund et al. 1997.

[281] Larsson 2011.

[282] ArtDatabanken 2015.

[283] Sveaskog AB 2017.

[284] For example, SCA Skog uses a rotation period of 80–120 years in its operations in the north of Sweden, SGS 2016.

[285] De Wever 2017.

[286] Badiou et al. 2011.

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Greenpeace International
Ottho Heldringstraat 5
1066 AZ Amsterdam
The Netherlands

enquiries@greenpeace.org
www.greenpeace.org