SINK or SOURCE?

Northern Forests at a Crossroads

AirClim
Air Pollution & Climate Secretariat

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The Air Pollution and Climate Secretariat (AirClim) is a joint venture between four Swedish environmental organisations (Friends of the Earth Sweden, Nature and Youth Sweden, Swedish Society for Nature Conservation, World Wide Fund for Nature Sweden). The purpose is to promote awareness of the problems associated with air pollution and climate change, and to bring about the required reduction in the emissions of air pollutants, including greenhouse gases. The eventual aim is that emissions should be brought down to levels that people and the environment can tolerate without suffering damage.

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SUMMARY

In this report, northern forests are defined as the boreal and temperate forests of industrialised countries in the northern hemisphere. They comprise about 40% of the global forest area, and about the same share of the global forest carbon stock.

All northern forest countries are in Annex 1 of the UN Climate Change Convention (UNFCCC). As non-annex 1 countries can receive financial support for halting deforestation and protecting their forests (under the UN REDD+ programme), they can also be held accountable for progress. The same provisions do not apply to Annex 1 countries. In general it is assumed that forests in Annex 1 countries are not under threat, or at least less threatened than tropical forests.

A key message of this report is that this is a misconception.

Northern forests are experiencing massive losses of ecosystem integrity, biodiversity and carbon storage capacity, and have done so for decades. The main drivers behind this development are climate-induced increases in natural disturbances and unsustainable forest management, including exploitation of the last remaining tracts of old-growth forests, possibly in combination with decreased positive growth effects of warmer climate and CO_2 fertilisation.

Increasing demand - a main driver

An underlying, ultimate driver is the ever-increasing demand for forest products. The consumption of industrial roundwood (for paper and wood products) almost doubled between 1960 and 2010, and is projected to increase by another 75% by 2050. About 75% of the global sawn wood and pulpwood supply comes from northern forests.

Disturbances, such as wildfires and pest outbreaks, are an integral part of northern forest ecosystem dynamics, but have become more frequent and intense in recent decades due to global warming. The frequency and extent of fires are currently higher than at any time over the last 10,000 years. Heat and water stress, which weakens tree resistance, has also caused a dramatic increase in insect outbreaks across the northern forest region. In British Columbia, an unprecedented outbreak of the mountain pine beetle in 2008 affected 37 million hectares of boreal forest. In 2000 and 2001 the Siberian silk moth damaged more than 10 million hectares of larch forest in latitudes where this insect had rarely been observed before. The trends for drought and wind disturbances are similar, and examples of unprecedented disturbance events are manifold. Further increases are projected. At 3^{o}C of mean global warming – which is where we are heading with current climate pledges from the world's governments – the average annual area burned in the Mediterranean region and interior Alaska, for example, is expected to increase by 50% over the next 50 years.

Clear-cut forestry degrades ecosystems

About 75% of the northern forest area is managed for timber production. The prevailing management model, rotation forestry with clear-cut harvesting, is causing ecosystem degradation, threatening biodiversity and is unfit as a management model for climate mitigation. Additional areas are continuously being exploited and degraded.

Less than 10% of the northern forest area is under some level of protection, which is a lower level than in tropical forests (17–26%). About one-third of boreal forests is still largely intact primary or old-growth, but due to a lack of sufficient protection this area is diminishing at an alarming rate. In the temperate region, only about 1% of broad-leaved forests is substantially unaltered and considered old-growth. These forests are strongholds for the natural biodiversity of northern forests

SUMMARY

and generally store large amounts of carbon, sequestered over centuries or even millennia. The remaining northern old-growth forests are estimated to provide at least 10% of the global ecosystem carbon sink.

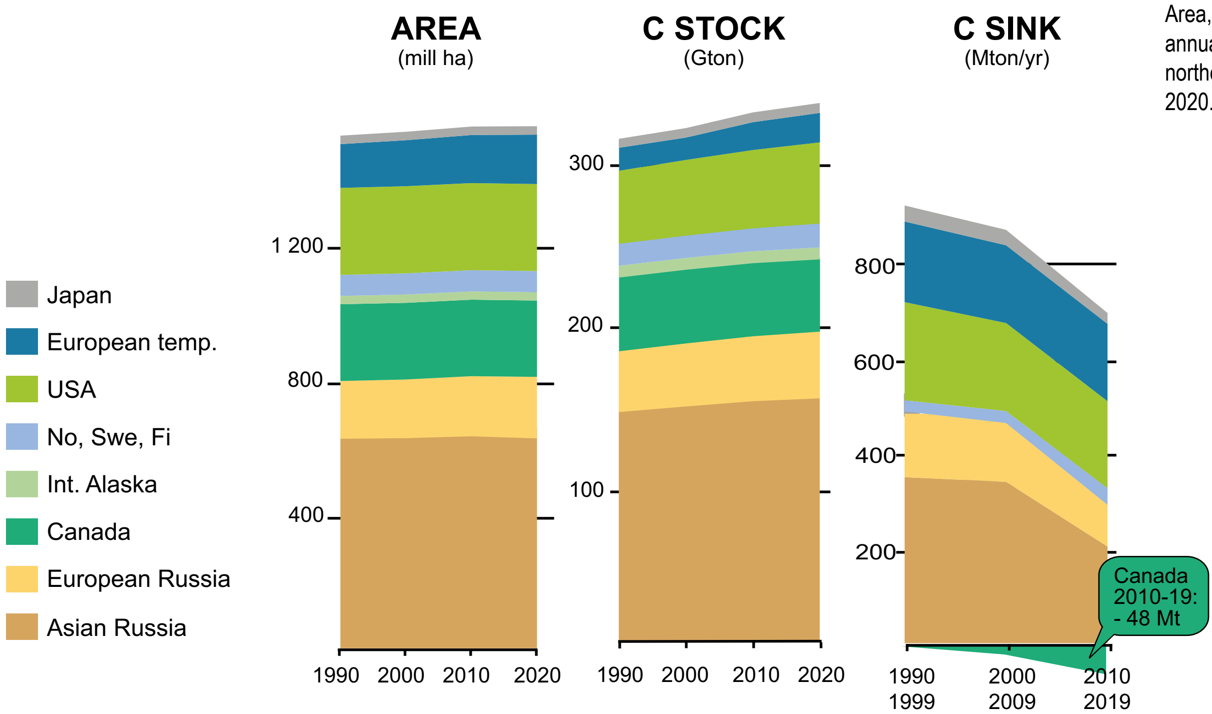
The combined effects of increasing natural disturbances, forestry and insufficient protection for remaining old-growth forests are severe and include loss of forest ecosystem integrity and resilience, a growing biodiversity crisis and depletion of the northern forest carbon sink.

1,400 red-listed species in Sweden´s forests

In Sweden and Finland, industrial rotation forestry and large-scale clear-cutting have a longer history than in other parts of the northern hemisphere and have transformed 90% of the forest area over the last 70 years. As a result, 1,400 red-listed species in Sweden are considered very negatively affected by forestry. In Finland, 32% of red-listed species (2,113 species) are forest-dwelling. It is reasonable to assume that the effects on forest biodiversity seen in these countries reflect what can also be expected in other parts of boreal forests, unless management practices and intensity changes.

While the net global forest carbon sink increased between 1990 and 2020, the northern forest sink decreased by 23%, and the rate of decline accelerated over the period. Unless this trend is reversed, northern forests may shift from an overall net carbon sink to a carbon source as early as 2060. Passing this critical tipping point would start a process during which part of the huge carbon stock in biomass and soils is released into the atmosphere, causing further warming and further carbon losses in a self-reinforcing loop that results in runaway warming.

Historically, large areas of northern forests (primarily in the temperate zone) have been lost. However, recent human impact on northern forests does not include deforestation to any notable extent. Over the last three decades the extent of deforestation and reforestation has been just 0.3% and 2.3% of the total forest



Area, carbon stock and annual carbon sink of northern forests 1990-2020. (Data from 2.)

area, respectively, and the overall northern forest area has increased by 2%. Nevertheless, governments of northern forest countries are relying heavily on reforestation measures in their national commitments (NDCs) under the Paris Agreement, while very little – if any – attention is paid to the potential for increasing the carbon sink of existing forests. In total, northern forest countries have committed to 160 million hectares of reforestation and afforestation by mid-century – equal to the entire land area used for agricultural production within the European Union. It is unlikely that this can be realised without severe land-use conflicts and complex trade-offs for food security, biodiversity and human livelihood.

A simple explanation for the over-reliance on reforestation and afforestation is that it offers an appealing form of carbon removal for governments and industry. Unlike forest protection and changes to forest management, it does not imply harvest reductions that would affect the supply of raw materials to the industry and energy sectors, and until land is actually allocated for new forests, the land-use conflict may conveniently be overlooked.

Intensified forestry is not an option

Intensifying rotation forestry and increasing harvests is frequently advocated as a strategy to increase the climate mitigation effect of forests. The rationale for this is that harvested wood is supposed to replace fossil fuels and materials – such as steel and cement – that are produced using fossil fuels. In addition, it is assumed that part of the harvested wood will end up as persistent carbon pools in long-lived products (such as wooden buildings). If one tonne of carbon removed from the forest substitutes more than one tonne of carbon emissions from fossil fuels (i.e. a substitution factor of 1.0 or higher), this strategy would be viable. However, recent studies on the substitution effect indicate that the substitution factor is between 0.4 and 0.8, i.e. the climate effect is negative. One reason for this is that only 40% of the roundwood harvested globally is used in long-lived products, and only 44% of carbon in such products remains stored for longer periods than 25 years. This means that from a tonne of carbon removed from the forest today, 830 kg will return to the atmosphere before 2050, and most of it even before 2030. It has actually been shown that a tree left to die and decompose in the forest is a more durable carbon pool than if the same tree is logged, processed and used, given the present product mix.

The carbon cost of timber harvest: 0.8 Gt per year

Wood harvesting and use are not, as often claimed, "carbon neutral". Such claims assume that carbon losses from new harvests are offset by sequestration from the growth of broad forest areas. This is misleading, since the climate consequence of new harvests cannot logically be altered by forest growth that would have occurred anyway. The true carbon cost of present global timber harvesting is 0.7–0.8 Gt per year, and the projected increase in demand would increase this cost by around 0.2 Gt by 2050. Thus, increasing rotation forest management is not a viable climate mitigation strategy.

Bringing greenhouse gas emissions as close to zero as possible is imperative in order to limit global warming to 1.5°C. In addition, negative emissions, i.e. active removals of carbon from the atmosphere, in the range of 2 to 6 Gt per year will be needed. Land ecosystems, especially forests, have the potential to deliver this crucial ecosystem service. It has been estimated that existing forests can store an additional 139 Gt of carbon under appropriate management. Almost half of this potential is in the northern forests. In addition, reforestation measures have the potential to store 87 Gt. For comparison, annual global carbon emissions are around 11 Gt.

In order to protect and restore the carbon sink of northern forests, as well as their biodiversity and ability to adapt to shifting environmental conditions, including further warming, the following strategies are essential:

▶ **Reduce greenhouse gas emissions rapidly in line with the long-term target of the Paris Agreement**.

Any further increment of warming will increase the extent and intensity of disturbances in northern forests, causing further carbon losses and damage to the resilience of forest ecosystems.

▶ **Ensure efficient protection of at least 30% of all northern forest ecosystems, including all remaining primary and old-growth forests.**

Safeguarding ecosystems and their roles in adaption and mitigation is fundamental to climate resilient development.

In reaching the 30% target, protection of remaining primary and old-growth forests should be a first priority. In addition to the direct negative climate effects of timber extraction, exploitation of these forests will inevitably cause loss of resilience, making them more vulnerable to fire, pests and other disturbances, increasing the risks of further carbon losses. It will also increase the need for future restoration measures.

To be effective, however, the 30% target must be met on a regional scale. A representative, interconnected network of protected, near-natural ecosystms – a green infrastructure – must be planned and implemented all over the northern forest region.

▶ **Halt ecosystem degradation of managed forests and restore their resilience and ability to store carbon**.

Extending the stand volume of existing forests has greater positive short-term effects on the carbon balance than any other possible change in forest management. This can be done by extending the rotation periods, which might be feasible within the framework of rotation forestry and its focus on timber production. It will not, however, improve ecosystem resilience or release the pressure on forest biodiversity more than marginally. Abandoning rotation forestry and clear-cutting and shifting to forest ecosystem management, on the other hand, offers a viable pathway not only to increase the northern forest carbon sink, but also to simultaneously address the biodiversity crisis and strengthen ecosystem resilience.

An overarching principle of ecosystem management is that forestry should minimise its impact on ecosystems. Harvesting is carried out selectively or in very small gaps. Tree species diversity, age distribution and structural diversity should, as far as possible, emulate natural conditions at every specific site. Forests are regenerated naturally. Since forest ecosystem management operates with considerably larger stand volumes than rotation forestry, the carbon stock per area unit is bigger, and a transition to ecosystem management thus utilises a bigger share of the natural carbon storage potential than does rotation forestry.

Shifting from rotation forest management to ecosystem management is in fact a form of ecosystem restoration, conducted within the framework of timber-producing forestry. A rough estimate of the climate mitigation effect of such a transition over the entire managed northern forest area shows the potential to increase the annual carbon sink by about 0.8 Gt, which corresponds to 20% of the present global forest sink.

Ecosystem forest management is probably the most promising solution for achieving sustainable forest management within a context of climate change. ■

1 WHY FOCUS ON NORTHERN FORESTS ?

Almost half of the world's forests are in the northern hemisphere. The circumpolar belt of boreal forests across Alaska, Canada, Scandinavia and Russia comprises about two-thirds of this area. The rest are temperate forests south of the boreal region, most of which are in the USA, Europe and China. All boreal forests in the world and about 80% of temperate forests grow north of the equator.

So far, international policy processes on climate change and biodiversity have focused mainly on tropical forests. Much less attention has been paid to boreal and temperate forests and the increasing threats to the carbon sink and biodiversity of these ecosystems. However, in order to limit global warming to 1.5ºC the climate mitigation potential of all forests globally must be utilised, which in turn means that their capacity to store carbon must be maintained or, when needed, restored.

> ***"It is assumed that forests in annex 1 countries are not under threat, or at least less threatened than tropical forests."***

In a climate policy context there are reasons to focus specifically on the forests of developed countries in the northern hemisphere. The UN Convention on Climate Change (UNFCCC) divides countries into two main groups, more or less reflecting OECD membership (or not) in 1992, when the convention was negotiated. Annex 1 of the Convention includes industrialised countries and "economies in transition" (which in 1992 mainly referred to former members of the Soviet Union and Warsaw pact). All other states, mostly developing countries, that do not appear in Annex 1 are referred to as non-Annex 1 countries.

As developing countries receive financial support for halting deforestation and protecting their forests (under the UN REDD+ programme), they also are held accountable for progress. The same concept does not exist for Annex 1 countries. Even if there are rules for how they report greenhouse gas emissions from the land use sector, there is no real accountability for how they deal with their forests. In general it is assumed that forests in Annex 1 countries are not under threat, or at least less threatened than tropical forests. To address this misconception, which is a main objective of this report, it is useful to deal with the forests of Annex 1 countries separately. In doing so, the expression northern forests is introduced as a common name for boreal and temperate forests in Annex 1 countries of the northern hemisphere.

Defined this way, the total northern forest area is close to 1,600 million hectares, which

REDD stands for Reducing Emissions from Deforestation and forest degradation in Developing countries. The + signifies the role of conservation, sustainable management and enhancement of forest carbon stocks.

Facing page: Intact boreal forest landscape. Muddus National Park, northern Sweden.

ANNEX 1 COUNTRIES IN THE NORTHERN HEMISPHERE

Countries with more than 10 million ha of forest in bold. Countries with less than 1 million ha of forest in brackets.

Austria	Denmark	(Ireland)	(Monaco)	Slovenia
Belarus	Estonia	Italy	(Netherlands)	**Spain**
(Belgium)	**Finland**	**Japan**	**Norway**	**Sweden**
Bulgaria	**France**	Latvia	Poland	Switzerland
Canada	**Germany**	(Liechtenstein)	Portugal	**Turkey**
Croatia	Greece	Lithuania	Romania	Ukraine
(Cyprus)	Hungary	(Luxembourg)	**Russia**	UK
Czechia	(Iceland)	(Malta)	Slovakia	**USA**

ROGER OLSSON

Figure 1. Present and original distribution of northern forests. Grey line shows the approximate boundary between boreal and temperate forests, although this in reality is a wider transition zone. Shaded areas are outside the northern forest area as defined here. *(Map: UN WCMC online database.)*

is 88% of the total boreal and temperate forest area in the northern hemisphere, and 44% of forests globally. About 190 million hectares of temperate forest in the northern hemisphere is in non-annex 1 countries, most of which is in China. The recent history of forests and forest management in China differs a lot from that of the northern Annex 1 countries *(see box next page)*.

Sweden, Russia and the USA have both boreal and temperate forest within their borders, at least according to some definitions and studies. In this study all forests in Sweden and Russia are accounted for as boreal, while all forests in the USA (except Alaska) are considered as temperate. This simplification is of minor, if any, importance when dealing with climate and biodiversity issues in northern forests.

CHINA IS DIFFERENT

Like parts of Europe and the USA, Central China has been extensively deforested for agriculture for centuries. Forest cover decreased from 60% 4,000 years ago to 25% during the 1400s and deforestation continued into modern times.[4] Since the 1980s, however, large areas of abandoned farmland have been reforested under extensive national programmes. As a result, the forest area in China increased by 34 million ha (24%) between 1990 and 2020.[2,3.]

Today, China has 25% of the temperate forests in the northern hemisphere. While the carbon sink in all parts of the northern forest area has at best remained stable over the last three decades, the sink of China's forests has tripled.

Since China is a non-Annex 1 country under the UNFCCC it is not considered as a northern forest country according to the definition used here.

Like other forest regions, northern forests provide a number of critical services to local, regional, and global populations. Mitigating climate change by sequestering atmospheric carbon is just one of them. Air and water purification, timber, game and berries are a few others. Northern forest countries account for around 70% of global production of saw logs and pulpwood.[1]

Boreal forests – an overview

Ecology

Boreal forests grow in high-latitude environments, approximately between 50° and 70° north, where freezing temperatures occur for 6 to 8 months a year. They make up the world's largest land biome, representing about 30% of the global forest area.[6]

Boreal forest ecosystems have evolved under the constraints imposed by a short growing season and severe winters, during which snow cover may last for several months. About one-third of their extent is underlain by permafrost. Compared to other forest biomes, most boreal landscapes are characterised by a low diversity of trees, of which conifers such as spruce, pine and larch species usually dominate, with varying proportions of deciduous species such as aspen, birch and alder.[6,7]

Landscape diversity in the boreal biome reflects (as in all biomes) the influence of site variation, but also the effects of natural disturbances, such as fire, wind throw, insects and drought events, and the resulting processes of ecosystem succession.[7,8] Such disturbances are recurring and sometimes large-scale, but two-thirds are small and do not result in a regeneration phase of even-aged forest (i.e. they are not stand-replacing).[9] The frequency and intensity of disturbances is affected by factors such as climate and forest management.

Human impact and forest management

About two-thirds of boreal forests are under some kind of management, mainly for wood production.[7] Silvicultural practices are similar throughout the boreal forest area. Rotation forestry with clear-cut harvesting is the dominant management model. After harvesting, new forests are often established by planting. Management measures aim to create and maintain even-aged, more or less monoculture-like stands. Rotation periods are typically 100 years or less (Sweden), or a maximum of 150 years (Canada).[10,7] It has been estimated that more than 60% of all stands have been harvested at least once, although this percentage varies regionally.[11] Clear-cutting of old, previously non clear-cut forests with a high degree of naturalness, followed by tree planting and seeding, is a major land use change in the boreal region.[12]

Canada

In Canada, large-scale commercial harvesting began in the early 19th century, focusing on conifer species used for construction, firewood and ship building. Forestry remained largely unregulated until the end of the century, when policy measures to secure sustained yield were introduced. Although clear-cutting and planting are common, forestry has been mostly extensive since the mid-20th century. Forest management continues to operate predominantly under a single-cohort, even-aged management system with low-retention clear-cut harvesting and short rotation cycles.[7]

Boreal forests are primarily state-owned, and harvesting has, until now, involved mainly primary forests rented to forestry companies as long-term concessions. In many regions, the forest industry continues to rely exclusively on primary forests, previously not subjected to organised forest management.[7]

Sweden and Finland

In Sweden and Finland, forest management has a longer history than in Canada. Large forest areas have been exploited by humans since the middle ages for purposes such as charcoal and tar production, firewood, ship-building and slash-and-burn agriculture. As populations grew and the forest industry begun to evolve by the mid-19th century the

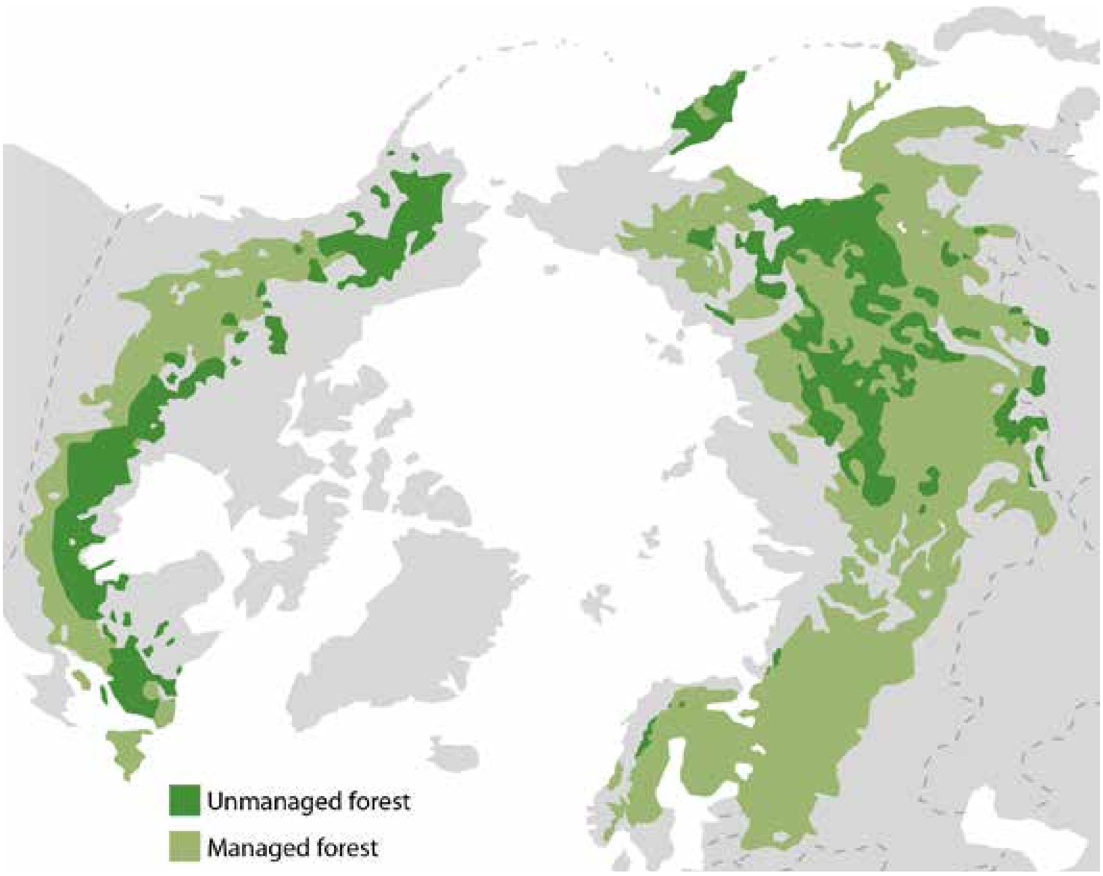


Figure 2. Boreal forests of the world. Unmanaged forests in dark green and managed forests in light green. (Simplified and redrawn from 123.)

timber frontier gradually kept moving northwards. Unregulated selective logging and lack of proper regeneration caused scarcity or even depletion of timber, which in turn sparked fears of permanent loss of forests and a need to regulate forest management. Sweden's first Forestry Act was introduced in 1903. As a result forest resources begun to recover.[7]

Selective cutting was replaced by rotation forestry and clear-cut harvesting over a short transition period by the mid-20th century. This management model was favourable for the rapidly growing and economically important pulp and paper industry, and hence formed a key part of national forest policies, where increased yield was – and still is – the primary goal.[7]

Today, industrial forestry is more intensive and affects a larger part of the forest area in Sweden and Finland than in any other part of the boreal region. Very little primary or old-growth forest remains, and the decrease continues. In Sweden alone, at least 19% of all clear-cuts over the last 20 years have occurred in old forests that were most likely not previously cut and planted or seeded. Old forests have been lost at a steady rate of about 1.4% per year during this period. At this rate no such forests will remain outside protected areas by 2070.[12]

Russia

In Russia, human-forest interactions were historically minimal owing to the lack of roads and the sparse human population in the vast expanses of forest. However, in north-western Russia forests closer to settlements were used in similar ways as in the Nordic countries, including timber harvesting for construction, fuel and charcoal production as well as slash-and-burn for agriculture.[7]

Since the Soviet era, industrial-scale forest use has been dominated by an extensive exploitative model of forest use, aiming at maximising income with only limited interventions. The system applies clear-cut harvesting, continuously extending into new forest territories, and is characterised by harvesting of the most productive and accessible stands and natural unassisted regeneration. It typically involved clear-felling of 50–100-hectare areas – and in many cases substantially larger. However, these areas were not conventional clear-cuts, as uncut patches of various sizes and individual trees of unused species or low quality were left behind. Thinning was in practice executed as selective logging of desired tree species and dimensions. As a result, the quality of forest resources degraded with a decreasing volume of economically accessible forest resources.[7]

As in Canada, however, large tracts of unmanaged primary or old-growth forest still remain in the northern part of the boreal zone *(figure 2)*.

"5–6 percent of the boreal forest area is under some level of protection"

Forests in Russia are owned by the state and leased to private companies. Forest management is regulated by the Forest Code of 2006 (with numerous corrections and amendments) and a number of other federal and regional regulations. The practice of forest leases does not, however, correspond to principles of sustainable management. As a result, the governance and management of forests has deteriorated significantly.[7] Over the last two decades (2000–2016) the ratio of forest regeneration to final felling (by area) dropped from 147% to 74%, which implies that successful forest regeneration is increasingly delayed or even fails after harvesting operations.[13]

Many studies have shown that the officially established national annual allowable cut (about 650–700 million m^3 per year for the last decade) is about twice as high as it should be according to sustainable management principles. As a result, in some parts of the country the amount of available timber resources has become depleted.[7]

Protected areas

5–6% of the boreal forest area is under some level of protection, which is a lower level of protection than in temperate forests (15%) and tropical forests (17–26% depending on source).[4] Large areas of primary and old-growth boreal forest lack any kind of protection, including in the Nordic countries, where very little such forests remain.

Northern temperate forests – an overview

Ecology

The vast majority of the world's temperate forests (80–90%) are in the northern hemisphere. Northern temperate forests grow south of the boreal forests in areas with at least one month of frost (for continental areas) or with one or more months with a mean temperature lower than 18°C (for maritime-influenced areas) and with at least 4 months with a mean temperature over 10°C.[4]

Temperate forests are more varied than boreal forests, in terms of ecology as well as tree species diversity. Six different temperate forest biome types can be found in the northern hemisphere. Broadleaf deciduous forests, mixed with conifers in the north and in mountainous areas, dominate in eastern North America, Europe and eastern Asia. In western North America, evergreen conifers dominate. This biome includes the temperate rainforests of the Pacific Northwest, home of the most massive trees on Earth, the giant redwood. In southern Europe, temperate forests are grading into a mosaic of broadleaf evergreen forests, conifer forests and shrub lands under influence of the dry Mediterranean climate.[4]

As in boreal forests, disturbances are natural elements of forest dynamics in temperate forests, but disturbance regimes are more varied and generally smaller in scale. In areas with a low or moderate degree of disturbances, wind throw is a dominant factor, while wildfires are more common and sometimes large-scale in conifer-dominated forests, where the overall degree of disturbances often is high. Fire is also the dominant disturbance in dry areas, such as the Mediterranean region.[14,15]

Human impact and forest management

Unlike most boreal forests, northern temperate forests have a very long history of human impact. From around 10,000 years ago the expansion of agriculture in Eurasia contributed to early deforestation, and this process continued over millennia. European, North African, and Middle Eastern temperate forests were logged extensively during the Roman Empire, the Middle Ages, and again in the 16th century to supply a growing shipbuilding industry. Further deforestation took place in the 19th century when charcoal was needed to fuel the beginning of the industrial revolution. Two thousand years ago, forests covered 80% of western Europe, while today they cover only approximately 34%. Half of this forest loss took place more than a 1,000 years ago.[4]

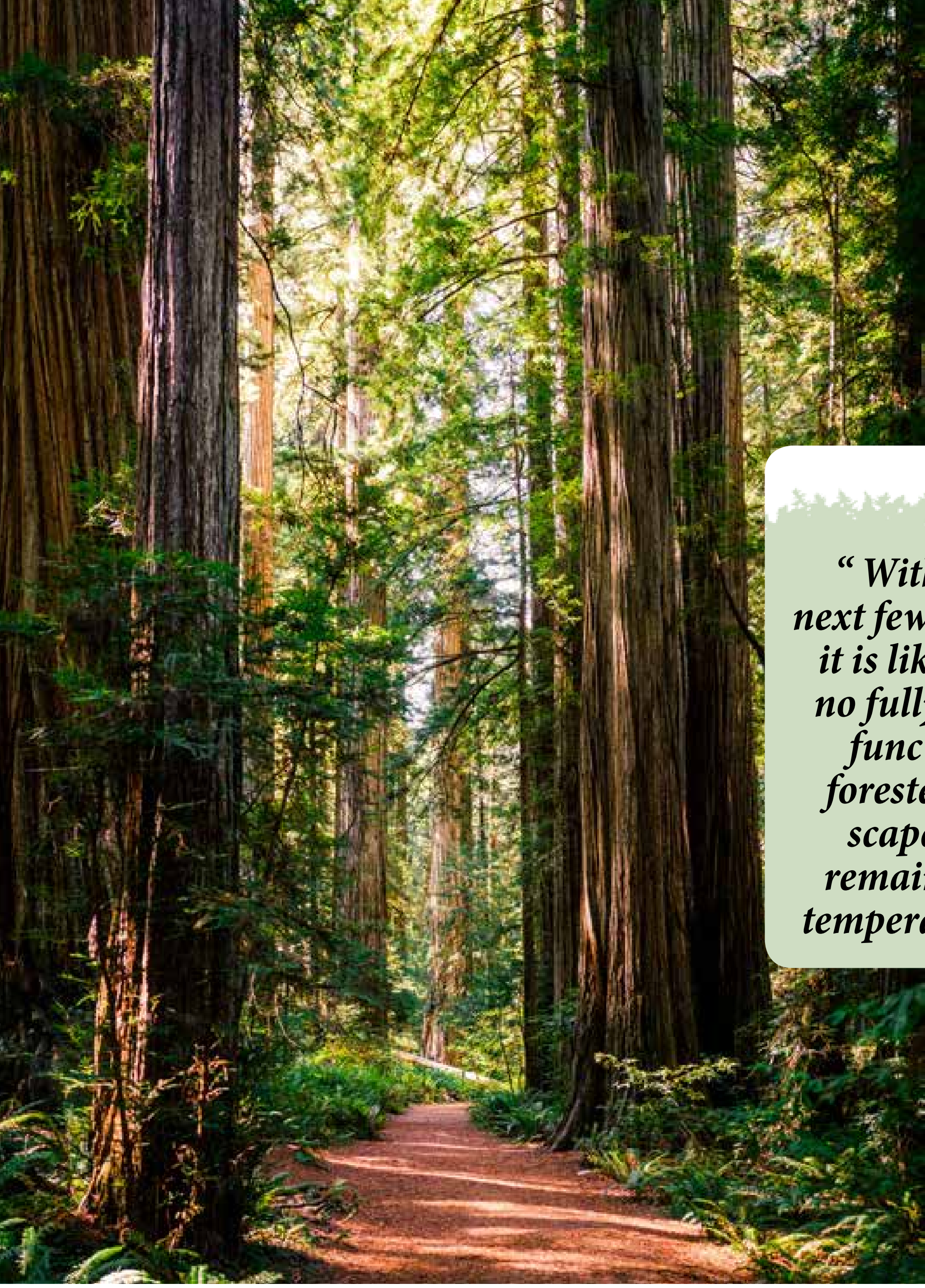
In North America, vast expanses of temperate forests were logged in the 18th and 19th centuries to make room for farming, to produce lumber and to supply fuel for the industrial revolution. Logging increased exponentially by the early 20th century, resulting in even higher rates of deforestation.[4]

WHAT IS A FOREST?

According to a common definition, used by the UN Food and Agriculture Organization (FAO) among others, a forest is an area of at least 0.005 km^2 with a canopy cover of 10% or more and in which trees are capable of reaching a minimum height of 5 metres. However, other (higher) minimum values for area and/or canopy cover are used by other organisations and in scientific studies. Tree-covered land that does not meet the minimum criteria for forests is often referred to as woodland or shrub land.[4]

The use of different definitions explains why maps of regional or global distribution of forests are not consistent. It is also a main reason for the considerable differences in forest area figures given in the literature.[4] For example, a recent study based on ground-based measurements and remote sensing data, estimates the total northern forest area as 1,793 million ha in 2020, while the FAO Global Forest Assessment reports a 10% higher figure (1,979 mill ha). Figures outside this range can also be found in the literature.[2,5,4]

In forest management, and sometimes in forest research, forests are delineated into smaller areas – or management units – known as stands. In this way, a forest is seen as a collection of distinct areas, typically ranging in size from a few hectares to several hundred. In each stand, the trees share certain characteristics, usually species, age, size, arrangement, condition, or location – or some combination of these.



SAM/ADOBE STOCK

Temperate redwood forest in USA´s Pacific Northwest.

As a result of this long history of human exploitation, temperate forests globally today cover less than half of their potential extent. Furthermore, only about 1% of the remaining northern temperate broad-leaved forests is substantially unaltered and can be considered old-growth or natural forest. The vast majority are either managed for wood production, have been transformed into plantations or show long-term effects of human land-use practices.[4]

Forest fragmentation, mostly from the urbanisation of the landscape and the continued harvesting of ever more remote forests, decreases the likelihood that remaining forest fragments can maintain ecosystem functionality. Within the next few decades, it is likely that no fully intact, functional forested landscapes will remain in the temperate zone, given current urbanisation trends.[4]

" Within the next few decades, it is likely that no fully intact, functional forested landscapes will remain in the temperate zone"

Protected areas

The area of protected temperate forests globally has increased considerably over the last two decades, and at present about 15% of the remaining temperate forest receives some level of protection. Thus, temperate forests are better protected than boreal forests (5–6%), but not as well as tropical forests (17–26% depending on source). The level of protection varies considerably among regions and countries, from 29% of the broad-leaved deciduous forests in Germany to 15% for conifer-dominated rainforests in North America.

It should be noted, however, that large forest areas classified as protected are plantations or otherwise highly managed forests.[4]

Indigenous peoples and local communities

Across the Northern Forest zone, indigenous peoples and local communities depend on a wide range of forest ecosystem services, both tangible and intangible, for their livelihood, culture and well-being.

The total population of indigenous people in boreal forest countries is about two million, by far the majority in Canada. In temperate USA, almost three million people consider themselves as indigenous (or native American). Part of this population maintains traditional lifestyles, including trapping, hunting, fishing and reindeer herding. The relationship with the land is a foundation of indigenous

	Area	C stock	C sink
	Million ha	Gt	Mt/year
Northern forests	1,577	342	691
-of which boreal	*1,149*	*265*	*324*
- of which temperate	*428*	*76*	*367*
Southern temperate forests	364	61	318
Tropical forests	1,871	468	2,521
Total, global forests	**3,812**	**870**	**3,530**

Table 1. Northern forest area (million ha 2020), stock (Gt 2020) and annual sink (Mt/year) 2010–2019.[2]

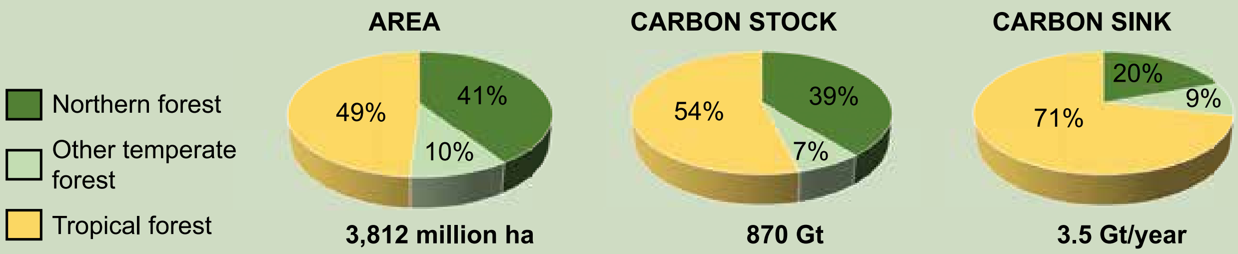


Figure 3. Northern forest shares of global forest area (2020), C stock (2020) and annual C sink (2010-2019 (%). While the northern forest sink has decreased by 25% since 1990, the tropical forest sink has remained stable due to the effect of extensive regrowth, compensating for the loss of intact tropical forest.[2]

peoples' identity and culture. This relationship is increasingly affected by the major transformation of forests driven by climate change and forest management. Although indigenous institutions play an increasing role in forest governance, the consideration of indigenous values and perspectives remains the exception rather than the rule.[16,17,18,19]

Northern forests as carbon sinks

All land ecosystems store carbon in living and dead biomass and in the soil. Globally, forests account for 91% of total land ecosystem carbon sequestration, and 39% of the forest carbon pool is in northern forests.[2] Overall, this carbon pool continues to grow, which means the northern forests are a net carbon sink. Over the last decade (2010–2019) the magnitude of this sink has been about 0.7 Gt annually, which is about 20% of the global forest sink.

At the global scale, forests store about the same share of the carbon stock in living biomass and the soil, about 45% each. The remaining fraction is stored in deadwood and litter. There are however big and important differences between forest biomes in this respect. While tropical forests store 52% of their

SINKS, SOURCES, POOLS AND FLUXES

Carbon sinks are processes that remove carbon from the atmosphere, including for example primary production from plant photosynthesis. Such processes are also referred to as carbon sequestration.

Carbon sources are processes or activities that release carbon into the atmosphere, for example combustion of fossil fuels, the respiration of living organisms or decomposition of organic matter.

A forest ecosystem is a net carbon sink if the uptake of carbon through photosynthesis is bigger than the release of carbon from respiration, decomposition and other processes.

Carbon pools or carbon stocks are reservoirs of carbon stored somewhere, for example in living biomass or a defined area of forest soil.

Carbon fluxes are the exchange of carbon from one pool to another.[23]

The units used to quantify sinks, sources and stocks in this paper are **gigatonnes (Gt)** or **megatonnes (Mt)**. One Gt is 1,000 Mt or 1,000,000,000 (one billion) tonnes .

Emissions of greenhouse gases are often reported as carbon dioxide, CO_2. One tonne of carbon corresponds to 3.6 tonnes of CO_2.

Table 2. Northern forest carbon stock 1990–2019 (Gt C).
No, Swe, Fi = Norway, Sweden and Finland.
Temperate Europe includes all EU Member States except Sweden and Finland (which are in the boreal region), plus UK, Switzerland, Belarus and Turkey. (Data from 2).

	1990	2000	2010	2020
Boreal:				
Asian Russia	145	148	152	153
European Russia	39	40	41	42
Canada	47	47	47	46
Interior Alaska	7	7	8	8
Other (No, Swe, Fi)	14	15	15	16
Subtotal boreal	**252**	**257**	**262**	**265**
Temperate:				
USA	46	48	49	51
Europe	14	14	17	18
Japan	6	6	6	6
Subtotal temperate	**66**	**67**	**73**	**76**
Total northern	**318**	**325**	**335**	**342**

carbon in living biomass and 25% in the soil, the situation is quite the opposite in northern forests; 25% is stored in living biomass and 62% in soils.[2] Including the vast areas of more or less treeless peatlands in parts of the boreal region would increase the soil fraction of the total carbon stock to 95%.[20]

One reason for this difference between ecosystems is that most boreal soils are nutrient poor, which means that trees have to invest a large part of their carbon resources below ground in fine roots, root exudates and mycorrhiza to secure their supplies. According to one study from spruce-pine forests in Sweden, only about 14% of the carbon sequestered was allocated to stem growth.[21] In addition, decomposition of organic matter is slower in the cooler climate of high northern latitudes, which means that organic soil carbon slowly accumulates in the top soil of growing forests. Undisturbed old-growth forests continue to accumulate soil carbon for centuries and thus contain large quantities of it.[22] The difference between tropical and northern forests in this respect is of profound importance for their role in climate mitigation and must be taken into account when evaluating different management options.

2 NORTHERN FORESTS IN A WARMING WORLD

Climate change in the northern forest zone

Present global warming (2023) is about 1.3°C compared to pre-industrial levels.[24] Northern forest regions have been warming faster than this global mean temperature and climate models consistently show that this effect will be even more pronounced in the future. At 3°C of mean global warming by 2100 - which is where we are heading with current climate politics - the northern forest zone would experience annual mean temperatures of up to 6°C above pre-industrial levels (*figure 4*).[25,26]

The faster pace of warming at high latitudes is often attributed to the melting of sea ice: as it disappears, it is replaced by a growing expanse of dark ocean water that absorbs sunlight rather than reflecting it. Decreased snow cover on land areas changes the ratio of absorbed to reflected sunlight - the albedo - in the same way. Other important factors that are not as well understood also contribute to the above-average warming at northern latitudes.

Seasonal variations further amplify the effects of mean temperature increases. For example, while northern and eastern European winter temperatures will rise more than summer temperatures, the Mediterranean region will experience the largest summer warming. This has already increased the frequency and intensity of high-temperature extremes and droughts in the area, and these events are projected to increase further.[23]

Projections for North America predict continued increase in intense heatwaves, diminished snowpack, extreme precipitation and intense storms. Cold season precipitation

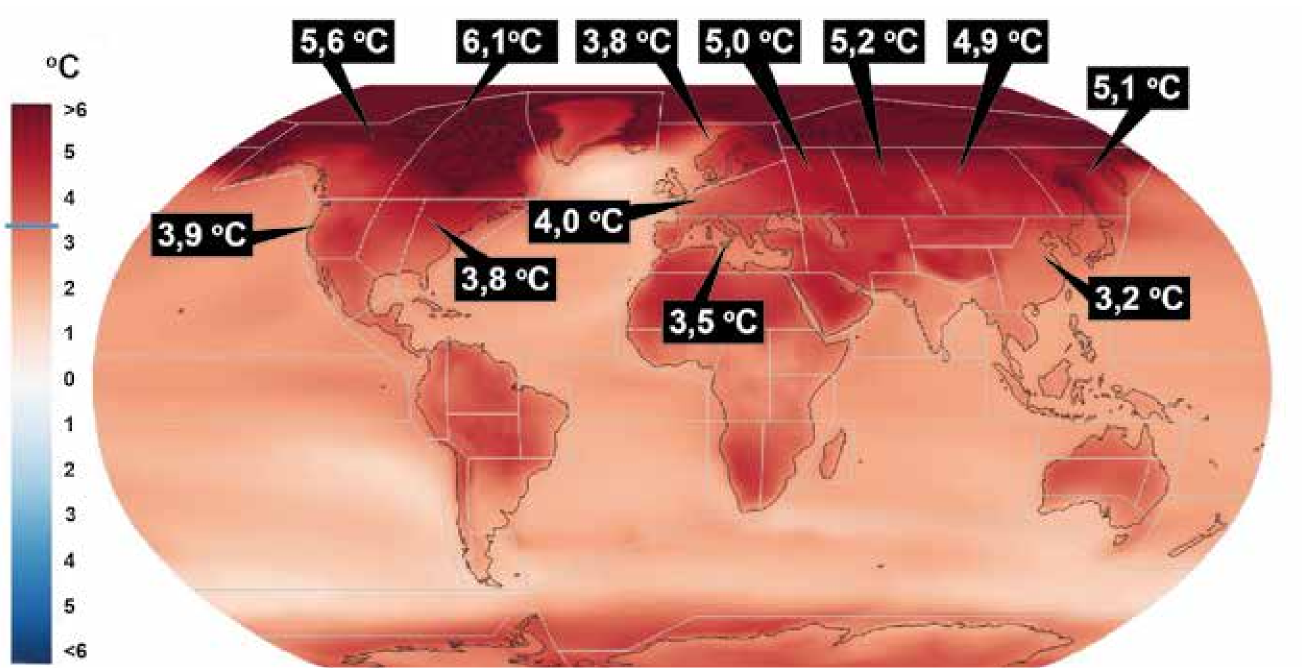


Figure 4. Projected annual mean warming (°C over preindustrial levels by 2100) in the northern forest zone with global warming of 3°C. Data based on 34 global climate models.[26]

comes increasingly as rain instead of snow, accelerating the decline of seasonal snowcover. Water levels during summer and early autumn will decrease and summer droughts are estimated to increase throughout the region.[23]

At 3°C of global warming, precipitation is projected to increase by around 10% over most northern forest zones (with considerable regional variations), except for the Mediterranean area, where a decrease by 15% from pre-industrial levels is expected.[23]

Climate impact on northern forests

Positive growth effects

A longer vegetation period due to warmer climate may increase forest growth, especially at northern latitudes. Rising atmospheric CO_2 concentrations may also have direct positive effects on tree growth, since carbon dioxide and water are the two components utilised by green plants during photosynthesis. Experiments have shown that higher CO_2 concentrations in the air can increase tree growth. In practice it is however difficult to link effects on tree growth to specific environmental factors.

The carbon density (the amount of carbon stored per ha) of northern forests has increased by about 5% over the last three decades, and the same trend has been observed for all forest biomes globally. Increasing tree growth due to CO_2 fertilisation has been suggested as a driver behind this trend.[2] However, there is little direct evidence of CO_2 fertilisation under natural forest conditions.[27] Even if such an effect exists, it is likely to decline in the future as other resources, such as water or nutrients, limit growth.[28] Recent growth decline in some areas has been interpreted as an early sign of such limitations.

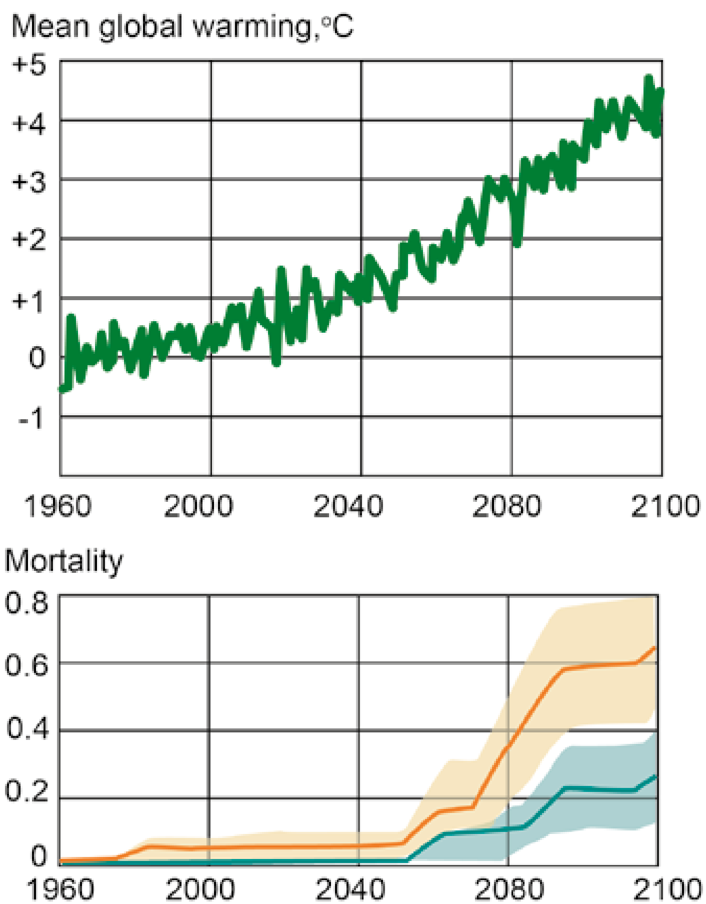


Figure 5. Projected drought-induced tree mortality under a scenario of about 4°C global mean temperature rise by the end of this century (RCP 8.5). Red graph is considered to show a more realistic response of trees to rising temperatures than the blue graph, representing a more static response. After 27.

Disturbances

Disturbances, primarily droughts, wildfires, pest outbreaks and wind throw, are an integral part of ecosystem dynamics in forests all over the world, but have become more frequent and intense in recent decades due to global warming.[23,29] As temperatures continue to increase and drought events become more frequent and intense, these effects are likely to be even more severe and widespread, and so will their impact on the carbon balance of forests and forest soils. Disturbance change is expected to be among the most profound impacts of climate change on forest ecosystems in the coming decades.[29]

Droughts

Droughts affect forests ecosystems and their carbon balance directly as trees die from water deficit, but also indirectly through interactions with other disturbances. Forests become more flammable following drought events, increasing fire risk and intensity. Water stress weakens the vitality of trees, thus making them more susceptible to insect attacks.

Tree mortality is not only triggered by high-intensity drought. Frequent low-intensity dry conditions can also contribute to forest mortality. While short-term impacts can be negligible, it is important to consider cumulative effects as changes in other climatic conditions can lead to abrupt responses due to accumulated stress.[30]

Approximately 43% of Canada's boreal forests have experienced significantly increasing drought-induced tree mortality trends over

YELANTSEVV/ADOBE STOCK

the last 50 years, and these trends have accelerated since 2002. This increase in tree mortality has resulted in biomass carbon losses of approximately 0.46 Gt per year, contributing to the recent shift of Canada's forests from carbon sinks to sources. Under the increased drought conditions predicted for this century, the capacity of Canada's boreal forests to act as a carbon sink will be further reduced.[31]

Forests all over Europe experienced reduced tree vitality and mortality during the 2018–2022 heat and drought events. In Poland, for example, tree cover loss in state forests only amounted to between 20,000 and 60,000 ha annually, while in Germany tree losses were recorded on 500,000 ha (about 5% of the total forest area).[32]

This trend may seem contradictory, since climate change over the northern forest region (except the Mediterranean area) has increased precipitation. However, more rain in parts of the year and in some areas does not counteract drought events elsewhere during other seasons. Mean values do not reflect the more extreme weather events of all kinds that are part of the ongoing climate change.

Forest fires

Both the frequency and extent of fires in northern forests are currently higher than at any time over the last 10,000 years. The main drivers behind this development are warmer and drier conditions in combination with more frequent strong wind events.[23]

> *"The frequency and extent of forest fires are currently higher than at any time over the last 10,000 years"*

The 2017 fire season saw many high-profile fire events in Canada, California, Portugal and Spain. These were followed in 2018 by extreme fire seasons in Greece, England, Sweden and North America. In British Columbia it was the worst fire season on record, and California experienced the largest, most destructive and deadliest (in terms of human lives lost) forest fires on record.[33] During the 2023–2024 fire season notable events in northern forests included record-breaking fire extent and emissions in Canada and the largest recorded wildfire in the European Union (Greece).[34]

In Russia, forest fires affected between 2 and 11 million ha over the years 2001–2019, and there was a significant trend of larger annual areas burnt over this period. The period ended with two years of extreme fire danger in succession, 2018 and 2019, which was a unique phenomenon – consecutive years with high fire impacts have never before been recorded in Russia.[13] In Siberian larch-dominated stands the fire return interval has fallen from 101 years in the 19th century to 65 years in the 20th century.[13,35]

> ***"The Siberian silk moth affected 10 million ha of Russian larch forests in latitudes where this insect had rarely been seen before."***

Natural fires are ignited by lightning, but in populated areas a considerable proportion of forest fires is caused by human activities. In western Siberia, for example, humans are presently responsible for 65% of forest fires.[36]

The extent of wildfires is widely anticipated to continue increasing in the future.[37] In the Mediterranean region a mean global warming of 3°C is expected to increase the annual area burned by over 50%. In Interior Alaska, the predicted increase in lightning may increase the mean potential area burned by around 50% over the next 50 years.[23] In boreal Canada the probability and intensity of wildfire could more than double over large areas by the end of this century under the RCP8.5 scenario of 4.4°C global warming, while another recent analysis modelled a 29–55% increase for north-western Canada and Alaska under the same scenario.[38,39] On the national scale, the annual area burned in Canada is projected to increase by two to four times by 2100.[36]

The RCP8.5 scenario is one of four Representative Concentration Pathway scenarios developed by the IPCC. It is a high-emissions scenario with limited measures to mitigate further warming.

Pests

Insect outbreaks have been increasing in severity, range and duration across the northern forest regions over the past few decades. The main driver behind this development is heat, often accompanied by water stress, which weakens plant resistance.[23] Outbreaks are cyclical and often synchronous over large areas, causing large-scale mortality of host trees in a relatively short period. Although insect outbreaks generally have less severe punctual impacts on forest productivity than fires, they often affect larger areas. In Canada, for example, insects damaged 16.5 million hectares of boreal forest in 2017, whereas 3.4 million ha burned that same year.[19]

In North America, spruce budworm is the main defoliator of spruce and fir forests, affecting large areas and causing extensive timber loss, but massive attacks by other species are also occurring.[19] In 2008 and the following years, British Columbia experienced an unprecedented outbreak of the mountain pine beetle, affecting 37 million ha of boreal forest.[40] In the 1990s a multi-year outbreak of spruce beetle killed 90% of the spruce forest in the Kenai peninsula of Alaska.[41]

Bark beetle outbreaks in North America and Europe have reached unprecedented levels in recent decades.[15] Following the hot and dry summer of 2018, spruce bark beetle killed more than 118 million m^3 of spruce in Europe, which is 8 to 51 times more than the annual figure for the decades 1970–2020. Other severe attacks have followed, with the highest mortality in spruce monocultures in Central Europe, previously outside the species' natural distribution range.[42] In Sweden alone, about 26 million m^3 of spruce was damaged by bark beetles between 2018 and 2021.[43] It should be noted, however, that climate change is not the only driver behind the increasing bark beetle infestations in Europe. High volumes of more or less uniform, even-aged spruce forests and the exposed forest edges created by clear-cut harvesting are also contributing factors.[42]

In 2000–2001, the Siberian silk moth affected an area of more than 10 million ha of Russian larch forests in latitudes where this insect had rarely been observed before. The Siberian silk moth and gypsy moth have also recently reached territories where outbreaks have never been recorded before.[13]

The frequency and severity of insect outbreaks all over the northern forest zone are projected to increase. Warmer climates, most pronounced in the boreal region, will lead to higher winter survival of insects. Longer growing seasons will further support the northward expansion of insects' range limits, while at the same time heat and drought events will decrease the vitality of trees, making them more susceptible to insect attacks.[19]

Wind throw

Like fire and pests, wind throw is a natural disturbance in forests all over the world.[29] In most parts of the northern temperate forests, it is the dominant disturbance agent.

The number of natural disturbances observed in European forests has increased since the 1950s, with wind being the most important factor (46% of total damage), followed by fire (24%) and bark beetle outbreaks (17%). The majority of wind damage was caused by extreme storms, supplemented by chronic damage at particularly high rates during the 1990s and 2000s.[44] In a compilation covering 29 European countries it was estimated that wind damaged 23 million m^3 of timber per year during the first decade of the 21st century.[36]

In Sweden, the Gudrun storm of 2005 caused wind throw of 75 million m^3 close to a total annual harvest of the entire country at the time.[45]

Interactions between natural disturbances

Interactions between natural disturbances are common and well documented, especially in boreal forests. The most frequently reported interaction is the increased flammability induced by drought events, which increases the frequency and severity of fires. Interactions between insect outbreaks and abiotic disturbances are also common and critical to the dynamics of biotic disturbance agents. For example, the large number of dead trees resulting from drought, fire or windfall can trigger a sharp increase in insect populations and amplify the spread and intensity of outbreaks. On the other hand, stands affected by insects increase the amount of flammable fuel and therefore the potential spread and severity of a fire.

In boreal forests, the fire cycle can affect insect outbreak severity, since long fire intervals may increase the abundance of late-successional host trees with reduced vitality, while short fire intervals may increase the abundance of broadleaf stands and thus favour better control by natural enemies. These and other similar interactions are of critical concern, as they may further intensify climate-induced increases in natural disturbances, heightening the risk of exceeding ecological thresholds and tipping points.[19]

Close-up of a bark beetle infested tree. The tree has died and the bark has fallen of, exposing the tracks of the egg-laying female (vertical) and the larvae (horisontal).

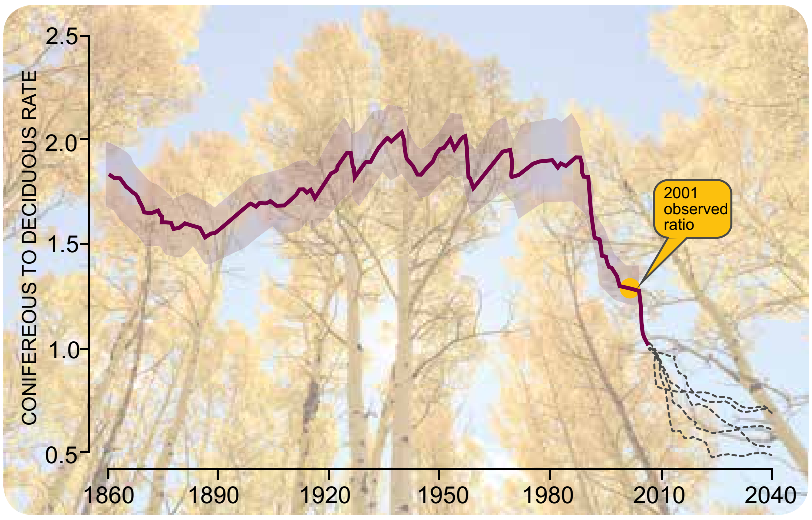


Figure 6. Reconstructed, observed and projected ratios of spruce to deciduous tree species in interior Alaska 1860–2040. The historical and projected ratios are derived from a forest-disturbance model that integrates fire, forest succession, and climate change across landscapes (ALFRESCO). The dotted lines represent projections under climate predictions from five different global circulation models (GCMs). (Simplified after 46.)

Ecosystem transitions

Natural disturbances in northern forests may be large-scale and stand-replacing, but under stable environmental conditions a forest similar to that damaged or destroyed by the disturbance will normally develop, even if it may take a century or more. Under rapidly changing climate conditions, however, warming and disturbances may, separately or in combination, cause fundamental, rapid and irreversible ecosystem shifts, such as transforming forest into open grasslandsor scrubland. Such transitions of ecosystems will not only affect carbon balance and future climate. It will have severe consequences for other vital ecosystem services, jeopardise the survival of indigenous and local communities and pose a great threat to the biodiversity of the ecosystems affected.

"When this transformation phase is completed, around 2040, two-thirds of Interior Alaska's forests – an area the size of Spain – will be deciduous, mostly aspen."

Such large-scale shifts are already taking place. Around 1990 a transition from spruce-dominated to deciduous forest began in Interior Alaska, driven by climate change and climate-induced increase in fire frequency. Model studies indicate that when this transformation phase is completed, around 2040, two-thirds of Interior Alaska's forests – an area the size of Spain – will be deciduous, mostly aspen. These forests are far less likely to burn than old-growth coniferous forests. However, decreasing fire frequency will not mean that the forests of Alaska that turned into a carbon source when the transition began, will return to their former state as a carbon sink. On the contrary, the change may lead to positive feedbacks to global warming. One reason for this is higher soil temperatures, speeding up the decomposition of organic matter.[46]

Similar climate-driven, rapid, large-scale ecosystem changes are underway or projected in several parts of the northern forest zone. For example, even under conservative assumptions of warming rate, wildfires could speed the transition of approximately half of the mixed wood and conifer forests of Alberta, Canada, to deciduous forest and grassland by 2100.[47]

Since the mid 1900s, beech has experienced climate-driven growth declines of up to 20% over large parts of Europe, most pronounced in southern parts of its distribution range. While growth increase is projected for mountain regions and the small area of beech forests in Scandinavia, decline is projected to continue by 20–50% (depending on region and climate change scenario) in the bulk of European beech forests by the end this century. Since beech is a key tree species in large parts

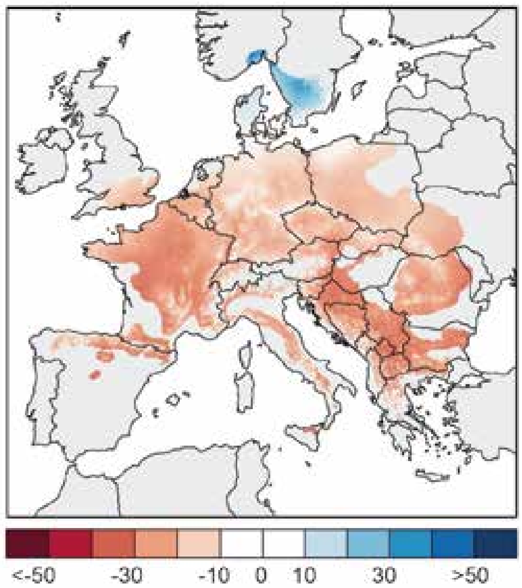


Figure 7. Changes in beech growth patterns in Europe 1955–1985 and 1986–2026 as percent of basal area increment. Red colour indicates decrease, blue colour increase.[48]

of Europe's forests these growth changes indicate serious ecological consequences.[48]

A much debated large-scale transition in the northern forest zone is a climate-driven shift of the boreal biome northward through expansion at its northern boundary and contraction at its southern boundary respectively. Projections of such future range shifts emanate from Ecological Niche Models (ENMs). Such models basically assume that plant species and vegetation types at any given moment will be present in areas with suitable environmental conditions.[49]

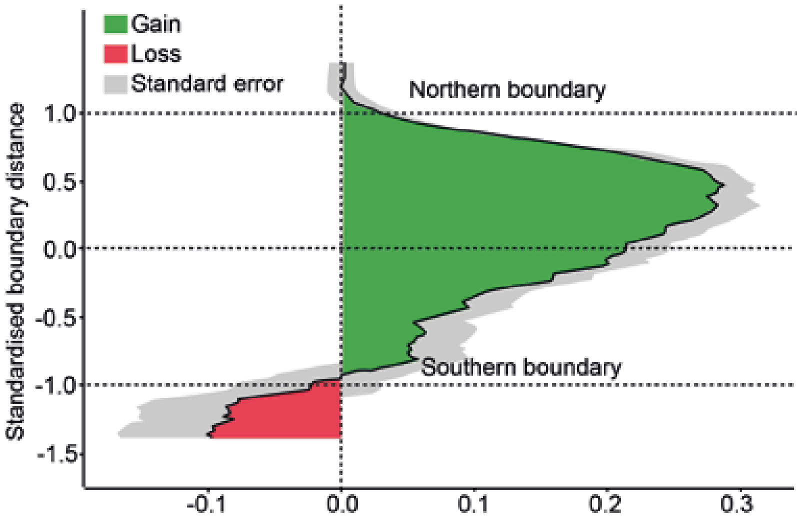


Figure 8. Tree cover changes 2000–2019 (% as running means) across the North American boreal biome, based on data from 13,000 sample plots along 69 south-north transects. The horizontal lines indicate the northern and southern boreal boundary. Standardised boundary positions were calculated for each sample plot based on its relative position within the boreal boundaries (49).

The increased "greening" of the Arctic tundra seen over the last few decades has been interpreted as a sign of ongoing northward shift of the boreal forest biome. However, even if widespread expansion of woody species into Arctic tundra has already been observed, this does not imply that the boreal forest is smoothly migrating northwards at the same pace as temperatures increase. In fact, there is little biome-scale evidence for such a shift.[49] One simple explanation for this is that the poleward advance of forest at the forest-tundra ecotone takes place at rates of 10–100 metres per year due to limitations in tree dispersal ability, while the climate change velocity (i.e. the speed at which a given isotherm moves) in the Arctic is 10 to 100 times faster. This supports the increasingly prevalent view that equilibrium models (such as ENMs) are unrealistic in their predictions of the rate at which terrestrial biomes will shift in response to changing climate.[50]

Unsurprisingly, a satellite based study found no evidence for tree cover expansion in the north from 2000 to 2019 anywhere across North America, while fast losses were noted along the southern biome boundary. Losses were largely related to wildfires and logging, but also happened in the absence of these disturbances in areas with warm temperatures. Some of the losses at the southern margin might be expected to be followed by expansion of temperate forests into the boreal biome, but no such effect was found. Mixed and broadleaf forests generally lost tree cover in a similar way to coniferous forests.[49] Tree cover loss at the southern edge of the boreal forest belt has also been reported from other parts of the northern forest zone.

Several model-based studies indicate that climate-driven replacement of boreal forest by grassland and deciduous forest is expected to continue.[37] With further warming these events may affect very large areas and have implications for carbon storage, regional and global biodiversity and the livelihood of local and indigenous communities

In this context "greening" indicates an increase and "browning" a decline in biological productivity. The terms originate from spectroradiometrical studies of Earth's land surface, based on satellite images.

Boreal forests as a tipping element

Tipping elements are components of the Earth system which may respond in a non-linear way to climate change by transitioning toward substantially different long-term states upon passing key thresholds or "tipping points". In some cases, such changes could cause additional greenhouse gas emissions, leading to further global warming[37] and thus become self-perpetuating. Melting of the Greenland ice sheet and widespread abrupt permafrost thaw are two of about ten such tipping elements identified by Earth system science. Tree cover loss in the boreal forest biome is a third.[51] In fact, boreal forest shifts represent one of the more potentially immediate and significant climate system tipping elements.[37]

The mechanisms behind a tipping point transition of boreal forests are those described above *(p. 18-22)*: dramatic increases in natural disturbance regimes and die-back at the southern boundary, replacing closed canopy forest with grassland, open woodland or (in best-case scenarios) deciduous temperate forests.

It has been projected that boreal regime shifts may start at 1.5°C and become widespread by 3.5°C, but 4.0°C has also been suggested as the tipping point threshold.[51,52,53] As mentioned, however, such changes are taking place on a regional scale already at the present 1.3°C of mean global warming. This should be seen as a strong warning signal, especially since it has been shown that intermediate forest states are rare and potentially unstable in the boreal biome, which suggests that forested areas may transition to systems with sparse tree cover abruptly.[54]

> ***"allowing global warming to push northern forests from an overall carbon sink to a source would likely make it impossible to halt warming at 1.5°C"***

Once a tipping point has been passed and the ecosystem transition is underway, the process will be self-reinforcing and irreversible, at least at any relevant timescale. This stresses the importance of time in climate mitigation: bigger emission reductions later on cannot compensate for insufficient reductions now.[55]

The massive character of the potential transitions will of course have consequences not only for the carbon balance. It will profoundly affect biodiversity, indigenous peoples and the capacity of forests to deliver a range of ecosystem services, including wood products.[54]

Effects on carbon fluxes

As described above, the present level of global warming (around 1.3°C) has already induced dramatic increases in fire and other disturbances in northern forests and forest die-back at the boreal-temperate transition zone.

Emissions from fires in the boreal region increased by 4.8 Mt C per year over the period 2000–2020. This increase in fire emissions poses a widening threat to climate, given that the post-fire vegetation may not be able to sequester all carbon lost at the fire event.[56] The carbon in boreal forest soils has normally accumulated over centuries or even millennia, and if such "old" or legacy carbon is released to the atmosphere, it cannot be fully recovered by the next forest generation, especially not with shorter time intervals between fire events. Fire release of legacy carbon has been shown to take place in black spruce forests in western Canada, especially in young forests and under dry conditions. As boreal wildfires continue to increase in size, frequency and intensity, the area of young forests that experiences legacy carbon combustion will probably increase and have a key role in shifting the carbon balance.[57]

The uncertainty of this estimate is ±4.2 Mt.

One single disturbance event, the large Lothar storm in 1999, reduced the European carbon balance by about 16 Mt C.[58]

An estimate based on an ensemble of climate change scenarios indicates that the projected increase of fire, pest and wind disturbances in the forests of Europe will increase timber losses by close to one million m^3 annually 2021- 2030, which may reduce the carbon storage potential by 0.18 Gt under a business-as usual scenario.[15]

Exceeding the tipping point for boreal forests has been estimated to release an additional 50 Gt of carbon into the atmosphere over a period of 50 years[51], which corresponds to about one-third of the remaining carbon budget for a 50% chance to limit warming to 1.5°C.

The figures are alarming, and might even raise the question whether it is wise to rely on forests as carbon sinks for climate mitigation. However, despite the rapid increase in disturbances driving a negative trend, northern forests are still a major sink of about 0.7 Gt C per year.[2] The reported fire emissions in the boreal forest (see above) represent a decrease of the northern forest sink by less than 1%. The Lothar storm reduced the forest carbon sink in Europe (including European Russia) by 5% and the projected disturbance-induced timber losses in Europe may reduce the forest carbon storage potential by about 7%.[15]

Looking at the effects of disturbances from this perspective by no means implies that they are of minor concern. Northern forests remain a carbon sink of global importance that must be protected. Since every increment of warming above the present level will further increase the impact on forests and their carbon store[56], urgent and imperative action is needed to reduce fossil fuel emissions, in line with the long-term objectives of the Paris Agreement. As shown *(p. 23-24)*, allowing climate change to push northern forests from an overall carbon sink to a source would likely trigger positive feedback loops, making it impossible to halt global warming at 1.5°C, even with zero fossil fuel emissions. ■

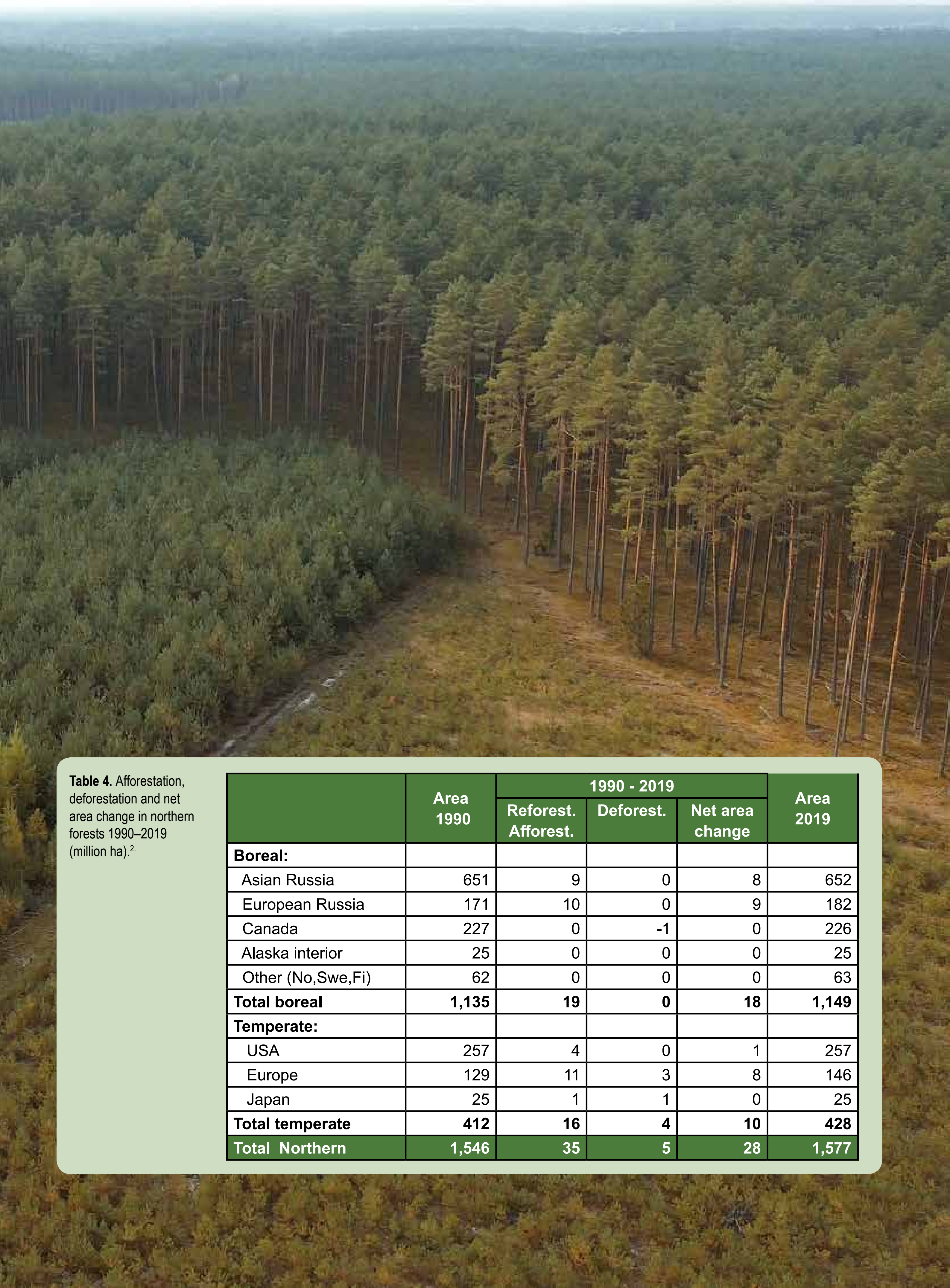


Table 4. Afforestation, deforestation and net area change in northern forests 1990–2019 (million ha).[2]

	Area 1990	1990 - 2019			Area 2019
		Reforest. Afforest.	Deforest.	Net area change	
Boreal:					
Asian Russia	651	9	0	8	652
European Russia	171	10	0	9	182
Canada	227	0	-1	0	226
Alaska interior	25	0	0	0	25
Other (No,Swe,Fi)	62	0	0	0	63
Total boreal	**1,135**	**19**	**0**	**18**	**1,149**
Temperate:					
USA	257	4	0	1	257
Europe	129	11	3	8	146
Japan	25	1	1	0	25
Total temperate	**412**	**16**	**4**	**10**	**428**
Total Northern	**1,546**	**35**	**5**	**28**	**1,577**

3 THE COSTS OF INDUSTRIAL FORESTRY

Deforestation

Globally, deforestation is a major threat to forests, their biodiversity and their climate mitigation capacity. The world loses 0.9–2.3 Gt of carbon every year through deforestation.[59]

As mentioned *(p. 13)*, in a historical perspective deforestation of temperate forest has been extensive, decreasing the overall area to less than half of its original extent. Boreal forests, especially the southern part, have also been cleared for human settlements, infrastructure and agriculture, albeit at a much smaller scale. Over the last three decades however, the picture is different. While the global forest area has declined by 210 million ha (5%) due to a net loss of tropical forests (273 million ha), northern forest have increased by 2%. In total over this time span, deforestation in northern forests has been 4.6 million ha, while reforestation and afforestation has totalled 35.4 million ha (0.3% and 2.2% of total forest area, respectively) *(table 3, facing page)*.[5,2]

Loss of forest area, regardless of scale and even if compensated by reforestation or afforestation, should always be of great concern because of its negative effects on biodiversity, carbon balance and other ecosystem services. The limited extent of deforestation in northern forests is highlighted to underline that constant or increasing forest area cannot be seen as an indicator of overall forest health, and that factors other than deforestation are the major drivers behind the decreasing northern forest carbon sink. There is, for example, no trace in the area statistics of the switch from carbon sinks to sources of boreal forests in Canada and Asian Russia over the period discussed here.

Loss of primary and old-growth forests

Only about 1% of the northern temperate broad-leaved forest area is substantially unaltered and can be considered old-growth or natural forest, while about one third of the boreal forests is still largely unaffected by human impact.[4,11] In total, half of the remaining primary forests in the world is in the northern hemisphere.[22] In the northernmost part of the boreal zone there are still large, intact and unfragmented landscape mosaics of primary forests and peatlands, covering hundreds of square kilometres *(figure 2)*.[60]

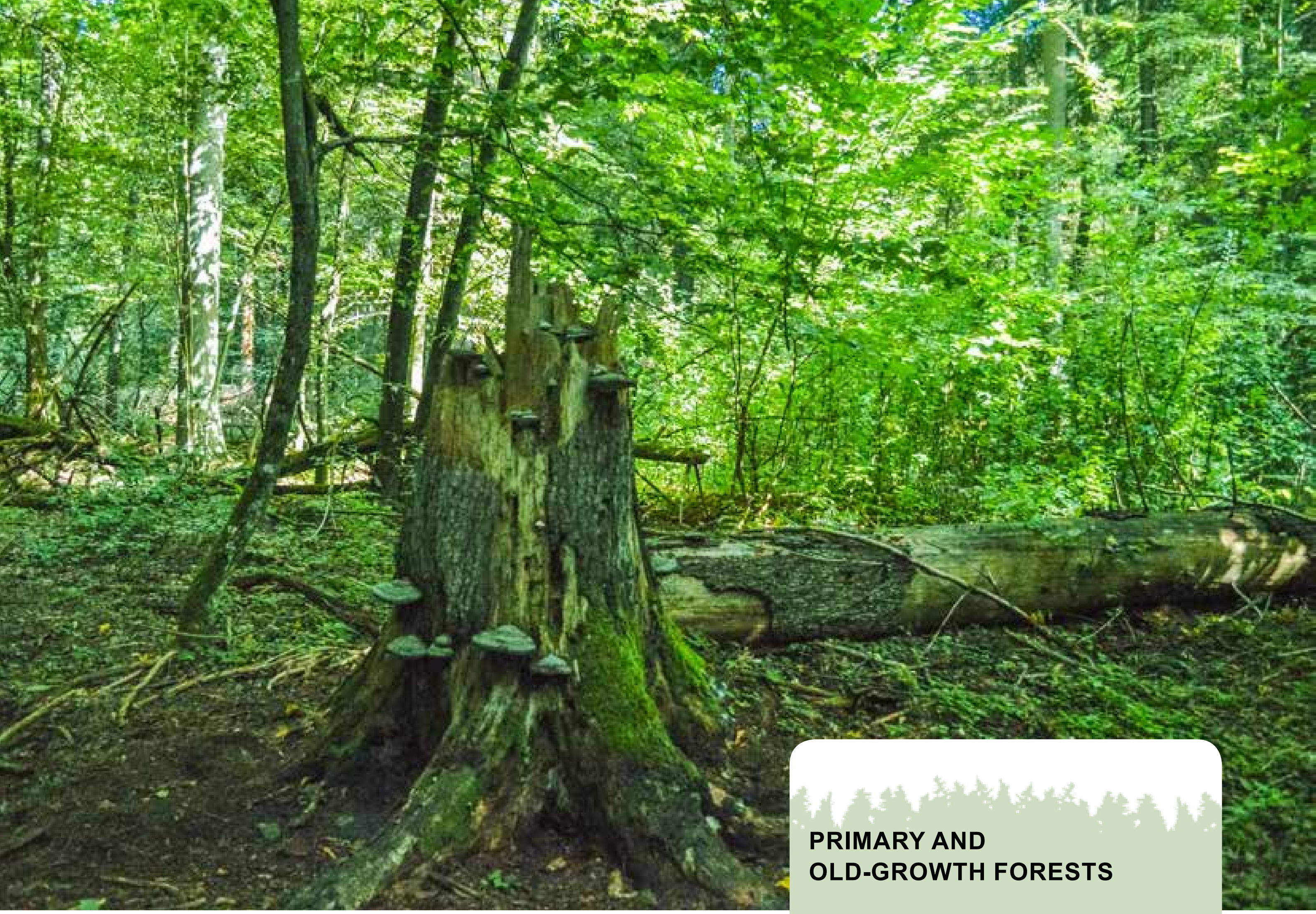
Industrial forestry and other forms of exploitation (i.e. oil extraction and mining) are damaging or destroying old-growth forests at an alarming rate, causing habitat loss and fragmentation. Even the small remaining areas in managed parts of the boreal zone are lost

DEFORESTATION, REFORESTATION AND AFFORESTATION

Deforestation occurs when forests are converted to non-forest uses, such as agriculture or road construction. The conversion is, or is at least intended to be, permanent.

Reforestation is the conversion of previously forested land back to forest, while **afforestation** is the establishment of a forest or a stand of trees in an area where there was no recent tree cover. Reforestation and afforestation can be done by planting trees or allowing a new forest to develop through natural regeneration.

ALEXGO/ADOBE STOCK



The forest of Bialowieza in on the border between Poland and Belarus is one of - if not the only - remaing large tracts of primary forest in temperate Europe.

by clear-cutting followed by rotation forestry management. In Sweden, for example, at least 19% of all clear-cuts since 2003 have occurred in forests that were most likely not previously felled and regenerated by planting or seeding. At the present rate of this conversion, no such forests will remain by 2070.[12]

Largely as a result of clear-cutting, Canada lost 2.3% of its intact forest landscape area between 2000 and 2013, Russia 4.3% and Sweden 0.8%.[60] It should be noted that even if these landscapes are fragmented, parts of their old-growth forests may remain unharmed, at least for some time.

Intact forest landscapes are areas of 500 km^2 or more.

Forest management

Around 75% of the northern forest area is under some form of management. Here, forestry is the principal disturbance agent affecting the ecosystems, albeit to a smaller or larger extent in interaction with natural disturbances. The current and future resilience of these managed ecosystems and their ability to store carbon depend mainly on which management strategies are chosen, and the frequency and severity of natural disturbances.[11]

PRIMARY AND OLD-GROWTH FORESTS

Primary or primeval forests have never been logged and have developed following natural disturbances and natural processes, regardless of their age. Also included as primary, are forests that are used inconsequentially by indigenous peoples and local communities living traditional lifestyles.

Old-growth forests are stands that have developed the structures and species composition normally associated with old primary forest. Old-growth forests may be secondary, e.g. regrown after logging or other disturbances, but have been left to grow undisturbed long enough to develop structures and processes similar to those of primary forests.

Natural forests are composed of indigenous trees and not classified as forest plantations (i.e. not established by planting or/and seeding in the process of afforestation or reforestation).

Other definitions than these occur, and the terms are not used consistently in the scientific literature. In much of Europe, for example, the term primary forest may refer to an area of forest land which has probably been continuously wooded at least throughout historical times. It has not been completely cleared or converted to another land use for any period of time but may have been affected by small-scale human disturbances, even patch felling.[61]

GEORGE COLE/ADOBE STOCK

Rotation forest management with clear-cut harvesting is the predominant management model in northern forests. After planting, seeding or natural regeneration forests are managed to create and maintain even-aged stands of one or a few tree species, often for economic reasons favouring other species than those that would occur naturally. In Central Europe, for example, large areas of originally deciduous forests (dominated by beech, oak or birch) have been converted to conifer plantations. German forests have gone from 90% broadleaf to 80% spruce domination[4] In Sweden, the share of deciduous trees in managed forests is presently less than 10% of the level in similar unmanaged forests in western Russia.[62]

> *“ German forests have gone from 90 percent broadleaf to 80 percent spruce domination”*

The negative consequences of intensive forest management of this type include the simplification of forest structures, the disappearance of old, large trees and a decline of the amount of deadwood. Short harvest rotations with clear-cutting fundamentally alter ecosystem structure compared to conditions produced through natural disturbances.[63] Formerly complex ecosystems characterised by considerable variations in habitat type, including vertical tree structure, tree species composition, age distribution and deadwood dynamics, are transformed into simplified forest habitats.[64]

Managed forests are normally harvested when 50–150 years old. Such forests are generally more productive than old-growth forests in terms of annual biomass increment, but have lower carbon stocks[22], because they lack old and big trees. For example, in temperate mixed-conifer forests of western North America just 1.4% of the trees with the largest stem diameter contained 49% of the forests' complete above-ground biomass. In German oak forests, the largest trees that made up 11% of the stands accounted for 50% of the biomass.[65] Logging trees before they are allowed to reach such levels of maturity will affect carbon storage negatively, regardless of how dense and fast-growing stands rotation forestry is able to create. Forests under rotation forestry have considerably smaller growing stock than extensively managed or old-growth forests.

PETR/ADOBE STOCK

Rotation forest management with clear-cut harvesting is the predominant management model in northern forests.

The clear-cut harvesting method not only causes loss of habitat, but also fragmentation and loss of connectivity. Remaining fragments of habitat in a matrix of simplified forest may lose their ecological functionality, because they are too small and too far apart in relation to the dispersal ability or habitat requirements of related species.

Clear-cutting also has adverse effects on carbon balance through the release of soil carbon. Especially in boreal forests, where soils are usually poor, trees invest a large part of their resources below ground in fine roots and mycorrhiza to secure their supplies. When trees are logged this underground biomass dies and begins to decompose. In the absence of a canopy shelter, the top soil layer is warmed by the sun, which speeds up decomposition. This makes the clear-cut area a carbon source, even if new forest is planted as soon as possible. Selective logging of single trees or in very small patches does not cause this effect.

> ***"Rotation forest management and clear-cut harvesting inevitably cause forest degradation."***

Eventually the carbon sequestration of the new forest will compensate for these emissions (unless legacy carbon stored over a longer time than a rotation period is released). In southern Sweden (boreal temperate transition zone) clear-cuts were found to be carbon sources up to 13 years after logging and reached carbon balance after approximately 30% of the rotation period, which in the studied stands was 60–90 years.[66] In northern Sweden, the total time-span to reach carbon balance has been calculated at 40 years.[67,68]

In the present situation, where the forest sink is essential to reach net-zero greenhouse gas emissions by mid-century this "clear-cut effect" is of utmost importance when developing forest management models for climate mitigation. Increasing clear-cut harvesting today (for whatever purpose) is simply counterproductive in relation to the long-term objectives of the Paris Agreement.

In conclusion, rotation forest management and clear-cut harvesting inevitably cause forest degradation. Even if the degraded northern forest ecosystems have so far been able to deliver a sustained or even increased yield of timber, this has been achieved at the cost of severe negative effects, such as biodiversity losses and reduced potential for other ecosystem services, including carbon storage. In addition, the weakened resilience of degraded forests increases the risks of future ecosystem collapses, especially in times of rapidly changing environmental conditions.

The ultimate driver: increasing wood demand

A common driver behind deforestation, exploitation of old-growth forests and intensified rotation forestry is the ever-growing demand

ECOSYSTEM INTEGRITY AND FOREST DEGRADATION

Ecosystem integrity (or intactness) refers to the completeness and functionality of an ecosystem and its ecological processes, particularly in relation to its natural state. Declines in integrity reduce habitat quality for native species, disrupt ecological processes and functions, and diminish ecosystem resilience and capacity to sustain species and many ecosystem services. Such decline in integrity is also referred to as ecosystem degradation.

While there is no internationally agreed definition of forest degradation, a group of NGOs and scientists have converged around the below:

Forest degradation refers to anthropogenic disturbances resulting in the immediate or long-term loss or deterioration of the ecological integrity of a forest ecosystem, measured at multiple scales, including stand and landscape level, and using a non-industrially impacted naturally regenerating forest as a baseline. These disturbances include impacts to:

- native species abundance and composition.
- forest structure and functioning.
- tree age-class distribution.
- carbon stocks and other ecosystem services.
- adaptive capacity (resilience).

More intact ecosystems support higher biodiversity and reduce extinction risk. Conversely, more degraded ecosystems support lower biodiversity and have higher extinction risk.[124]

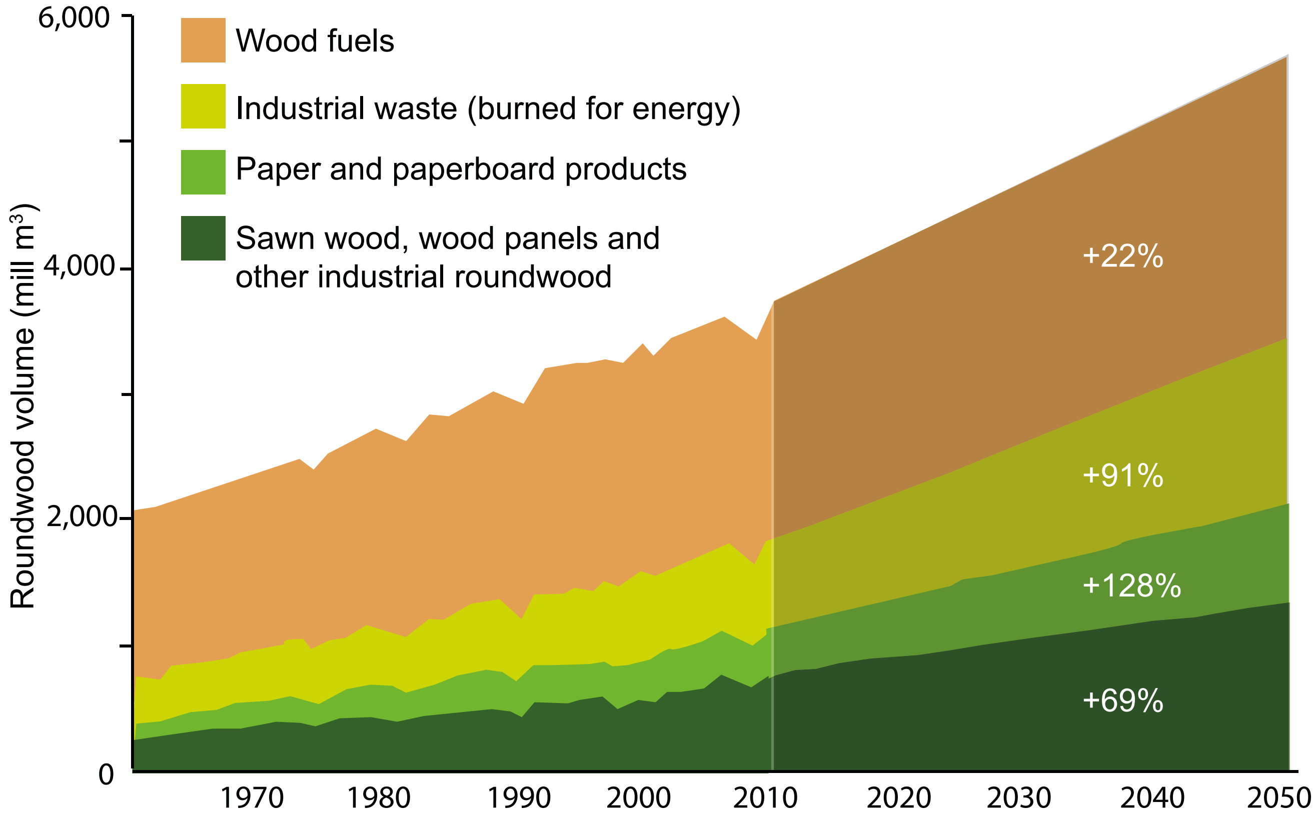


Figure 9. Historical and projected increases in global wood product production (million m^3) 1961–2050. The increase in fuel wood production is mostly in the southern hemisphere (Africa, South America and Southern Asia),[1] but there has also been a considerable increase in Europe. The total growth 2010–2050 is projected to be 54%.[69]

for wood. Both legal and illegal logging contribute to deforestation, especially in tropical areas. While deforestation is also driven by other factors, such as agricultural expansion, industrial wood demand is undoubtedly the single most important driver for intensified and expanding forestry in northern forests. 75% of the global supply of sawn wood and pulpwood comes from northern forest.

The global demand for industrial roundwood (sawn wood and pulp wood) was around 1,500 million m^3 by the turn of the century. It is expected to double by 2050.[69] Other studies project increases in the same range or even higher.[19]

4
A CARBON SINK IN PERIL

This section summarises how the combined impact of global warming and forest management, described in the previous sections, have affected carbon pools and fluxes in northern forests over the last three decades.

The art of carbon accounting

There are different data sources available for actual and projected carbon fluxes from forests and other land ecosystems. One is the national greenhouse gas inventories used by governments to report emissions from the land use sector (LULUCF) to the UNFCCC. Another source is Integrated Assessment Models (IAMs), designed and used to analyse energy technologies, energy use choices, land-use changes and societal trends that cause – or prevent – greenhouse gas emissions. IAMs are used to answer "what if?" questions, such as "what if countries impose a universal price of $100 per tonne of CO_2 emissions by 2030" ? [73]

> *"If countries report some of the natural carbon sink as anthropogenic, warming will continue at perceived net-zero emissions"*

There are significant discrepancies between data from national greenhouse gas inventories and IAMs, attributed to differences in the definition of what counts as *"managed land"* and *"anthropogenic emissions"*.

IAMs only include direct fluxes resulting from human activities, such as harvesting, land-use change, and tree regeneration via afforestation, while national inventories count all emissions and carbon absorption on land as anthropogenic, including indirect carbon fluxes (natural responses to human-caused environmental changes), such as increased plant growth caused by CO_2 fertilisation.

The IAMs only consider land that has undergone extensive human activity as managed. National greenhouse gas inventories consider larger forest and other land areas as *"managed"*. Reporting emissions from unmanaged land is optional. Some countries include unmanaged land in their reporting, others don´t.

The combination of these differences leads to national inventories estimating a much larger carbon sink from forest land than IAMs. Recent scientific assessments reveal the global discrepancy is 4.4–5.5 Gt CO_2 per year (2000-2020). While national reports represent northern forests as a net sink, most IAMs indicate that northern forests acted as a net carbon source in both 2015 and 2020.

These discrepancies have significant policy implications. While milestones towards the Paris Agreement's temperature goal (such as reaching net-zero CO_2 emissions) are generally set using IAMs, countries report emissions and removals from the LULUCF sector using national inventory systems. If countries report reaching net zero by counting some of the natural carbon sink as anthropogenic, warming will continue at perceived "net-zero" emissions, as the accounting system masks what the carbon cycle really sees.[74]

◀ LULUCF = Land Use Land Use Change and Forestry

Facing page: Carbon sequestration in progress. The foliage of a beech tree absorbing carbon dioxide and solar energy.

MSLOKADOBE STOCK

In this report, the main source for data on forest carbon stocks and sinks is a scientific article, independent of national greenhouse gas inventories and IAMs, published by Pan et al in Nature 2024.[2] It is based on data from ground-based measurements by the global forest community, combined with area estimates from remote sensing in national forest inventories and other types of land surveys. All forest carbon pools and fluxes on all forest land are included, regardless of whether they are anthropogenic or not. Thus the carbon sinks/sources reported are considerably larger than in national inventories as well as in IAMs. For example, while the annual forest carbon sink from northern forests was about 0.6 Gt between 2010 and 2019 according cording to national inventories, Pan et al. estimated the sink as almost 1 Gt.

The importance of these differences must be judged in the light of the uncertainties about all figures on carbon fluxes in nature. Pan et al. estimate the uncertainties of their data on the global forest sink to around 0.4 Gt, while other estimates of terrestrial sinks have uncertainties in the range of 0.5–1.8 Gt.[2]

> *"While the global forest sink increased between 1990 and 2020, the northern forest sink declined by 23 percent"*

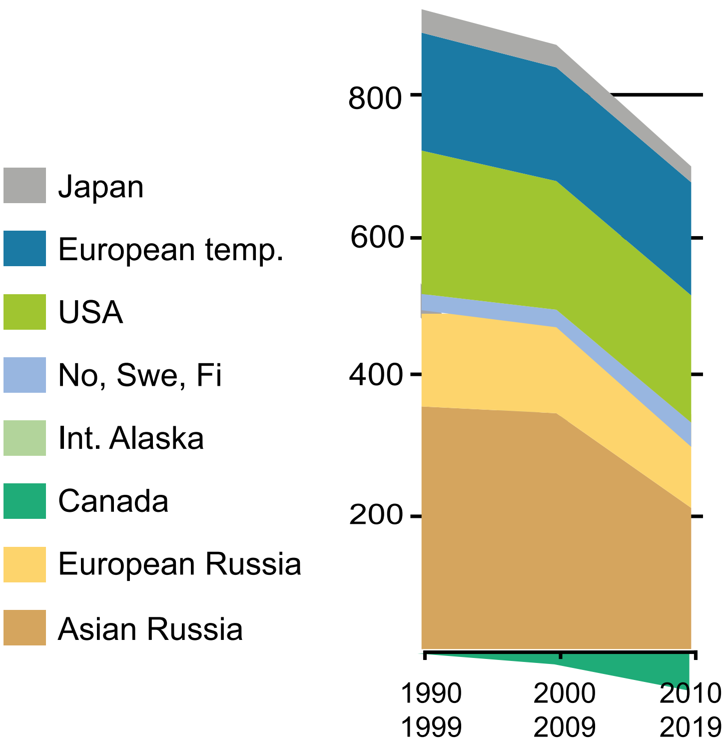


Figure 10. The northern forest carbon sink 1990 - 2019 as mean values per decade (Mt carbon). (Data from 2.)

A declining carbon sink

While the global net forest carbon sink increased between 1990 and 2020, the northern forest sink declined by 23% over the same period, as a result of negative trends in boreal and temperate forests alike. This includes the carbon stored in harvested wood products (HWP), which has remained almost stable at around 10% of the total sink.[2]

Unless this trend is reversed, northern forests may shift from an overall net carbon sink to a carbon source as early as 2060.

Boreal forests

Although the boreal forest area has been stable since 1990, its carbon sink has decreased by 36%. This development was strongly affected by increased wildfires, insect outbreaks and logging in Asian Russia, reducing the sink in this area by 42%, with the greatest reduction occurring in the late 2010s. Living biomass in this region switched from being a large carbon sink (145 Mt) in the 1990s to being a source of 20 Mt/year in the 2010s.[2]

The forest carbon sink of European Russia has been relatively stable since 1990. A small increase in the 2000s was probably driven by forest expansion on abandoned agricultural land, while the subsequent decrease in the 2020s was probably the result of increased harvesting and disturbances.[2]

In Canada, managed forests were approximately carbon neutral in the 1990s, but turned into sources over the next two decades. In the 2010s, living biomass, deadwood and litter pools all became carbon sources and the soil sink was reduced by 35%, reflecting increased impacts of disturbances, warming and droughts.

Through intensified rotation forestry the forestry sector in the Nordic countries (Norway, Sweden and Finland) has been able to increase harvest levels and net annual incre-

	1990-1999	2000-2009	2010-2019
Boreal:			
Asian Russia	347	338	202
European Russia	133	143	134
Canada	0	-20	-48
Interior Alaska	5	1	1
Other (No, Swe,Fi)	23	25	35
Subtotal boreal	**508**	**486**	**324**
Temperate:			
USA	205	184	182
Europe	169	163	162
Japan	34	32	23
Subtotal temperate	**407**	**379**	**367**
Total northern	**916**	**865**	**691**

Table 4. Annual carbon sink in northern forests (Mt C), average per decade.[2]

ment simultaneously over several decades, thereby also increasing the biomass carbon pool. The forest carbon sink has increased by 52% between 1990 and 2020 as a result of management strategies, longer growing seasons and possibly CO_2 fertilisation.[2] Over the last few years, however, net increment rates have been stable or even decreased in each of the countries, whereas harvest level has continued to increase.[70]

Presently in Sweden, the gap between annual growth and harvest plus natural losses is just about 5 million m^3, the smallest margin in 50 years.[71] This is the main reason why net carbon uptake in Swedish forests has decreased by about 30% over the last four years alone (2020–2024).[72] The forest carbon sink is presently smaller than at any time since official reporting began in 1990.

An interesting observation from North America is that while warming has caused a contraction of overall boreal forest area, interior boreal forests have become denser, which means that biomass – and thus carbon stock – has increased.[49] To what extent this might compensate for carbon losses caused by the southern contraction remains to be seen.

Temperate forest

The carbon sink in the forests of the US has decreased by 11% by 2020 compared to the 1990s, as a result of increased natural disturbances and summer droughts during the 2000s. The sink did not recover fully during the 2010s, but the rate of decline was reduced.[2]

In Europe, the temperate forest sink declined by 4% from the 2000s to the 2020s, due to increased disturbances[2] and management changes. Many countries in eastern Europe have recently intensified forest management and harvesting, which results in decreasing areas of old forests with large carbon stocks.[70]

The overall decrease in the northern temperate forest sink between 1990 and 2020 was 9% *(table 4)*.

5 CLIMATE, BIODIVERSITY AND RESILIENCE

This section summarises how the combined impact of global warming and forest management, described in the previous sections, has affected the biodiversity and resilience of northern forests.

Biodiversity under threat

Because of the inertia of forest ecosystems to environmental change, much of the cumulative ecological effects of the large-scale alteration of northern forest structures remain to be seen. Delays in ecological responses are in part due to long successional sequences and long-lasting legacies from the more natural forest stages of the past (such as slowly decaying pools of fallen deadwood), and delayed population responses to habitat degradation and loss, a phenomenon known as extinction debt.[63]

In Finland and Sweden, around 90% of forests have been exploited for timber production by means of rotation forestry and clear-cutting[19] - more than in any other part of the boreal zone. Very little old-growth forests remain. Thus, it is reasonable to assume that the effects on forest biodiversity seen in these countries reflect what can also be expected in other parts of the boreal forests, unless management practices and intensity changes.

A couple of examples can give a picture of the structural changes resulting from forest management in this area. In Sweden, the share of deciduous trees has decreased (by volume) to less than a tenth of the level found in similar unmanaged forests in European Russia.[62] The volume of dead wood has increased lately, but at an average of 5%[75] of growing stock it is still far below levels in unmanaged forests of similar types (typically 20–30%, although with considerable variations between regions and forest types).

Clear-cutting has caused extensive habitat loss, as well as fragmentation of the forest landscape, which negatively affects a large number

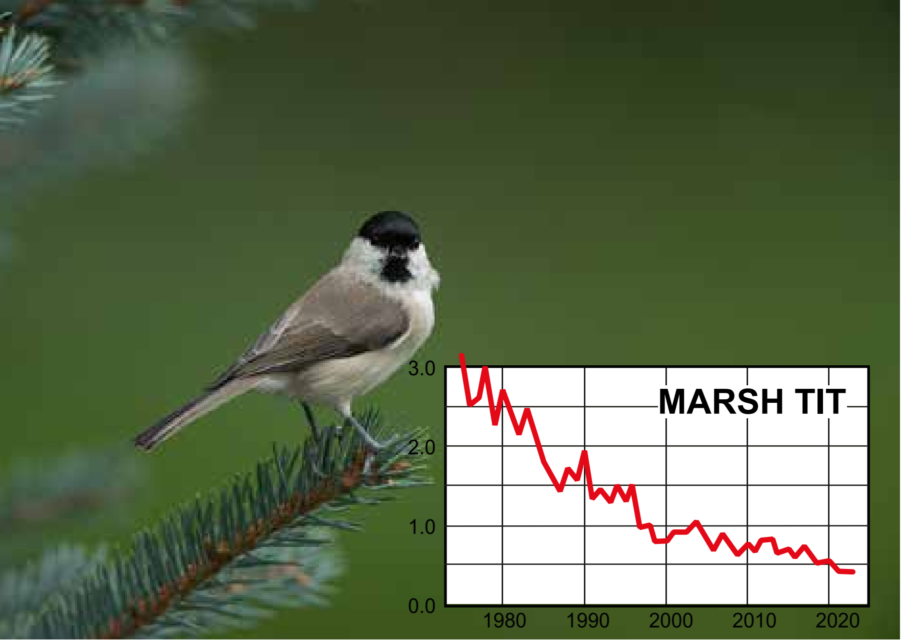
BIODIVERSITY IS A CLIMATE ISSUE

Climate change and the rapid decline of biodiversity are two major threats to human well-being and planetary health. They are intertwined in many ways and cannot be addressed separately. Biodiversity is an integral part of ecosystems, and healthy ecosystems are a prerequisite for an enduring land carbon sink, which is why safeguarding biodiversity is fundamental to climate-resilient development.[80] Correspondingly, global warming affects biodiversity by causing rapid changes in environmental conditions and ecosystem structures and distribution, which is why biodiversity losses can only be stopped if global warming is halted.

A striking illustration of the links between climate mitigation and biodiversity is the relationship between ecosystem productivity and tree species diversity. A study based on data from 777,126 sample plots, mostly in the northern forest zone, containing more than 30 million trees of 8,737 species has shown that the more diverse a forest stand is in terms of the number of tree species present, the higher is its productivity. This in turn means that continuing biodiversity loss would result in accelerating decline in forest growth worldwide, and thus in a decline in the forest carbon sink. Forest management that converts monocultures to mixed-species stands has often seen substantial positive effects on productivity.[81]

Facing page: Bearded lichen, *Usnea longissima*, grows in old-growth spruce forests and is extremely sensitive to disturbances. It is one of 2,000 redlisted forest-dwelling species in Sweden.

ROGER OLSSON



WOLFGANG KRUCK/ADOBE STOCK

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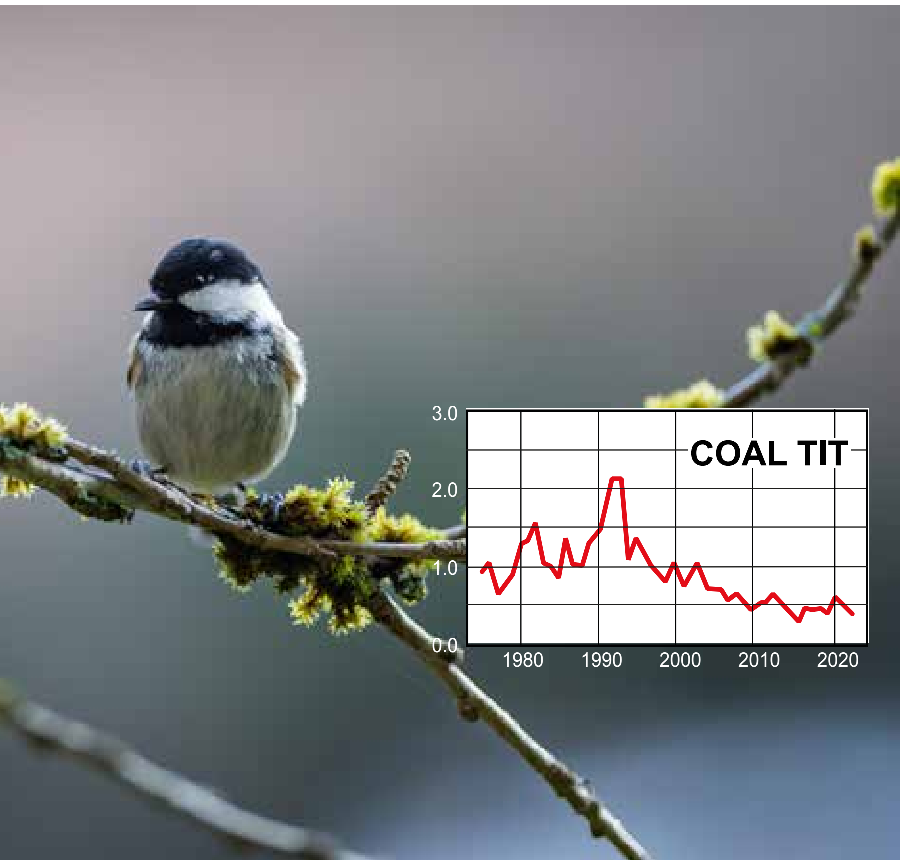


MARK ANDREU/ADOBE STOCK

of species. In highly fragmented landscapes, remaining patches of old-growth forests often lose their functionality as habitats because they are too small or too far apart. In the southern boreal region of Sweden, about 8% of productive forest land is protected as reserves or voluntary set-asides, but due to fragmentation and lack of connectivity, only 2% is estimated to be functional for relevant groups of species.[76]

As a result of this and other structural changes, 2,000 forest-dwelling species are red-listed in Sweden, and 1,400 of them are very negatively affected by forestry. Clear-cutting is a major cause of threats to Sweden's red-listed species, second only to overgrowth of meadows and abandoned grazing lands.[77] In Finland, 32% of red-listed species (2,113 species) are forest-dwelling.[64]

Since 1979 the Swedish forest legislation includes measures to mitigate the effects of forestry on biodiversity, such as retention of dead wood and old trees, and discourage the logging of small areas of importance for wildlife. These regulations have been strengthened over time, and forest managers have been targeted in extensive information campaigns to improve their implementation. Over the same period of time, the share of formally protected forests has increased from 3% to 9% of the total forest area. In addition, around 70% of the Swedish forest area has been certified under one (or both) of the major certification schemes FSC and PEFC. There are still no detectable signs of this having released the pressure on forest biodiversity.

The number of red-listed species is not the only indicator of deteriorating ecosystem health. Populations of several common non-migrant forest-dwelling birds, such as the willow tit, have declined dramatically over the last 50 years. Since common species may be of greater importance for ecosystem health than rare ones, this is a matter of concern even if there is no imminent extinction risk.

The case of the caribou widens the perspective to the entire boreal zone. The caribou in North America and wild reindeer in Eurasia have both experienced large distribution con-

Figure 11: Summer population trends of three species of non-migrating forest-dwelling birds in Sweden 1974–2024. Trends are shown as an index in relation to the base year 1998 (with an index of 1).[79]

SCOTT/ADOBE STOCK

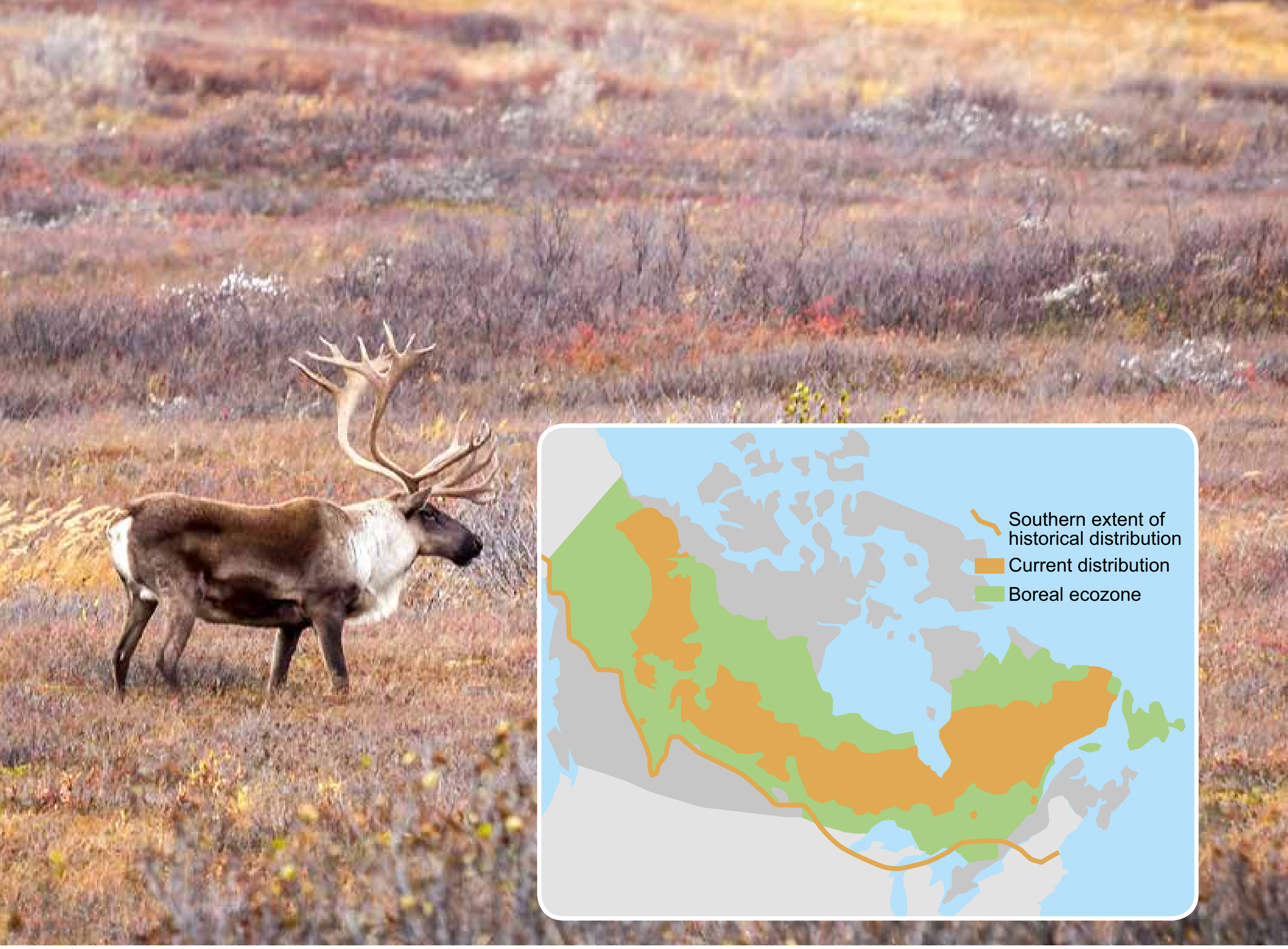


Figure 12. Historical (red line) and present (orange) distribution of caribou in North America. Boreal forest area shown in green.[78]

tractions over a long period of time *(figure 12)* as result of human-induced disturbances. In Ontario, the northwards contraction of caribou range by 34 km per decade over the period 1880–1990 has been explained by the northward expansion of timber harvesting, but climate change may also be a contributing factor, and is expected to drive further contraction of the caribou distribution range in the future. Triggered by a rapid expansion of grasslands and contraction of mixed and coniferous forests in the province of Alberta, the distribution of the woodland caribou is projected to decrease 29–52% by 2080 under various climate scenarios.[78]

"In Alberta, the distribution of the woodland caribou is projected to decrease 29–52 percent by 2080"

Effects on resilience

Resilience is the capacity of an ecosystem to return to its former state following a perturbation, including maintaining its essential characteristics in terms of species composition, structures, ecosystem functions, and process rates. The resilience of a forest ecosystem to changing environmental conditions is determined by its biological and ecological resources, in particular the diversity of species, the genetic variability within species and the regional pool of species and ecosystems. Resilience can be seen as a function of ecosystem integrity or intactness. Loss of integrity also means loss of resilience. Resilience is also influenced by the size of forest ecosystems (the larger and less fragmented, the better), and by the condition and character of the surrounding landscape.[82]

The predominant management model in northern forests affects ecosystem integrity and resilience negatively in a number of different ways. It creates even-aged stands dominated by one or two tree species, and with less structural diversity than natural forests, vertically (stratification) as well as horizontally ("patchiness"). The proportion of ecologically important elements such as old trees and deadwood is low compared to natural conditions. This, in turn, causes habitat loss which negatively affects biodiversity. Regeneration by planting impacts genetic diversity, since varieties other than those locally present – or even alien species – selected for high volume production are generally used.

In addition to further climate-induced increases in disturbances and the ongoing exploitation of remaining old-growth forests, the ecosystem degradation by intensified forestry and unsustainable management practices threatens to accelerate biodiversity loss and carbon pool depletion of northern forests in the near future.[11]

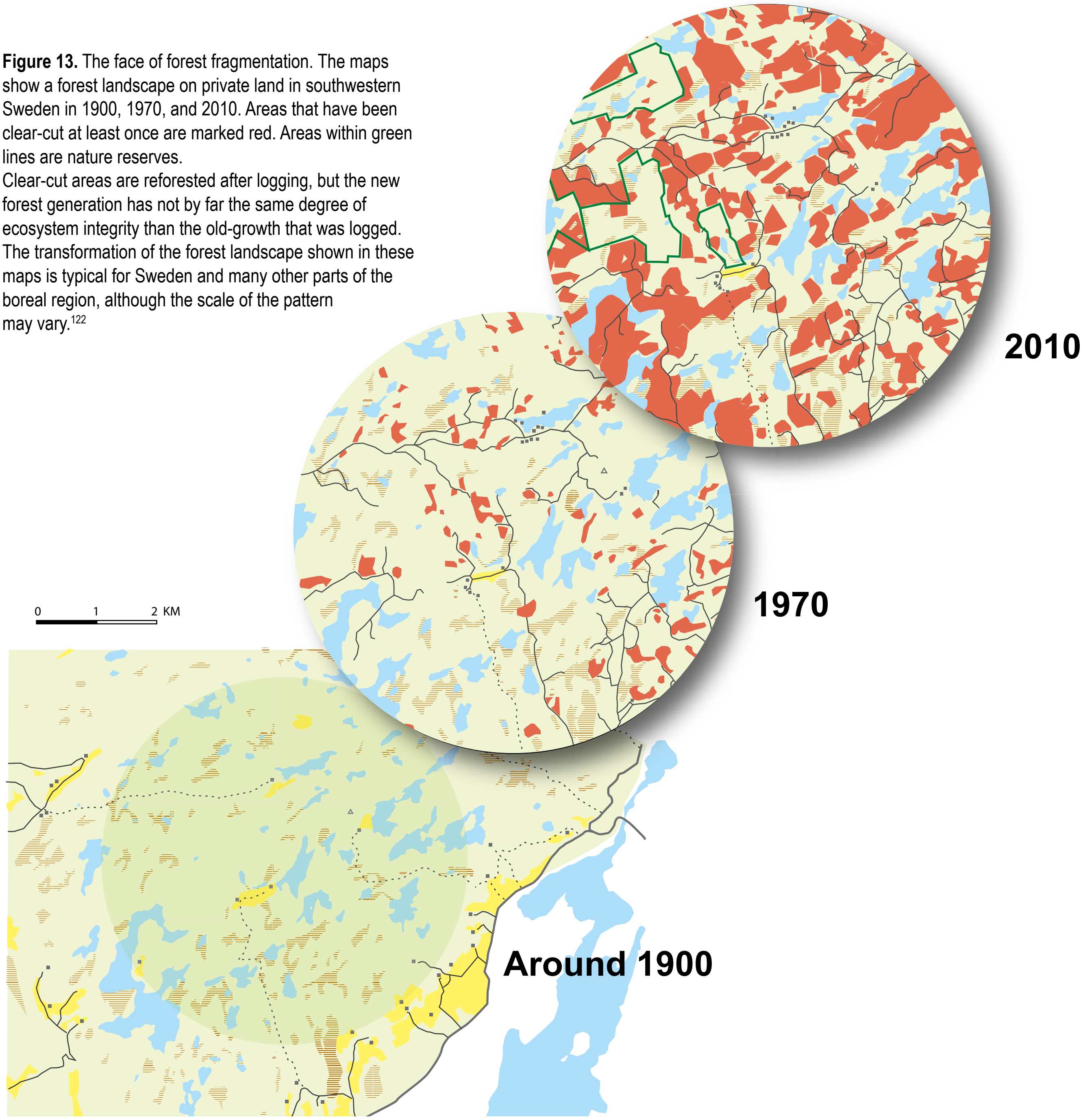


Figure 13. The face of forest fragmentation. The maps show a forest landscape on private land in southwestern Sweden in 1900, 1970, and 2010. Areas that have been clear-cut at least once are marked red. Areas within green lines are nature reserves.
Clear-cut areas are reforested after logging, but the new forest generation has not by far the same degree of ecosystem integrity than the old-growth that was logged. The transformation of the forest landscape shown in these maps is typical for Sweden and many other parts of the boreal region, although the scale of the pattern may vary.[122]

6 STRENGTHENING THE NORTHERN FOREST SINK

The need for carbon sinks

Bringing greenhouse gas emissions as close to zero as possible is imperative in order to limit global warming to 1.5ºC. In addition, negative emissions, i.e. the uptake of atmospheric carbon, will be needed to compensate for greenhouse gas emissions that cannot be avoided, even under scenarios of truly sustainable development.

SSP scenarios used to analyse different pathways of climate mitigation measures generally rely rather heavily on negative emissions in land ecosystems. Four different 1.5ºC-aligned scenarios assume between 209 and 377 Gt of cumulative negative carbon emissions from 2005 to 2100, i.e. a carbon sink of 2.2 - 3.9 Gt per year *(figure 14)*.[84] Other estimates suggest 6 Gt per year as a maximum.[83]

SSPs (Shared Socio-economic Pathways) are climate change scenarios of projected socio-economic global changes up to 2100 defined by the IPCC. They are used to derive greenhouse gas emissions scenarios with different climate policies.

"Under suitable management and if global warming can be limited, the northern forest sink has a great potential to contribute to climate mitigation"

Technical solutions for removing carbon from the atmosphere (such as direct air capture, DAC) are under development, but their potential and safety remains to be demonstrated. The world's forests, on the other hand, have been a carbon sink for millennia and remain so to this day. Globally, forests account for 91% of total land ecosystem carbon sequestration, out of which around 20% – 0.7 Gt annually – by northern forests.[2] As shown, this carbon sink is under threat and may be lost unless appropriate action is taken. Under suitable management and given that global warming can be limited to 1.5ºC, however, it has a great potential to contribute to climate mitigation far more powerfully than today.

The potential

The land sector has historically lost hundreds of gigatonnes of carbon through changes in land use. It has been estimated that under present climate conditions 226 Gt of this former carbon pool could be restored, out of which 87 Gt through reforestation of previously forested areas, and 139 Gt in existing forests under appropriate management and conservation.[59] Close to 40% of the potential of existing forests are in the three major northern forest countries of Canada, Russia and USA. In addition, the potential carbon gain in the forests of Europe has been estimated at 12.7 Gt,[85] meaning that almost half (49%) of the global forest carbon removal potential is in the northern forests.

These figures show the maximum potential stock that can be maintained by natural processes within an ecosystem in a resilient and self-sustaining manner (also referred to as carbon carrying capacity, CCC). There are of course socioeconomic and other constraints on how much of this potential can be utilised. Under any kind of timber-producing forestry the growing stock will be smaller than maximum, simply because part of the growth is harvested.

Basically three groups of measures can increase the carbon removal capacity of northern forests. First and foremost, and in line with the objectives of the Kunming-Montreal Global Biodiversity Framework, a greater share of northern forests should be protected and restored. Next, shifting clear-cut forest management to ecologically sound forest management models would substantially increase the removal capacity of northern forests. And finally, investing in reforestation and afforestation, if done in a socially and environmentally acceptable way, can provide additional benefits to increase forests' removal capacities.

Protecting remaining old-growth forests

Remaining primary and old-growth northern forests are insufficiently protected and are presently being lost at an alarming rate (*see p. 27*). Overall, less than 10% of northern forest area is effectively protected. The remaining, shrinking tracts of primary forests in the northern boreal zone cannot compensate for the lack of old-growth forests in other part of the region. Further losses will increase the need for future ecosystem restoration.

Primary and old-growth forests are the last remnants of the natural forest ecosystems of pre-historic times. They have a higher degree of ecosystem integrity – intactness – than forests affected by the currently prevailing management models. Since they are more diverse and complex in composition and structure than managed forests they are more resilient to environmental changes. They are also hotspots for northern forest biodiversity. They provide and, if left undisturbed, will continue to provide carbon sequestration and other precious ecosystem services.

Contrary to a common perception, old forests are not carbon neutral, nor will they die and start to decompose if left by themselves. Old-growth forests usually continue to accumulate carbon until they are at least 800 years old, even if growth and carbon sequestration

KATO08/ADOBE STOCK

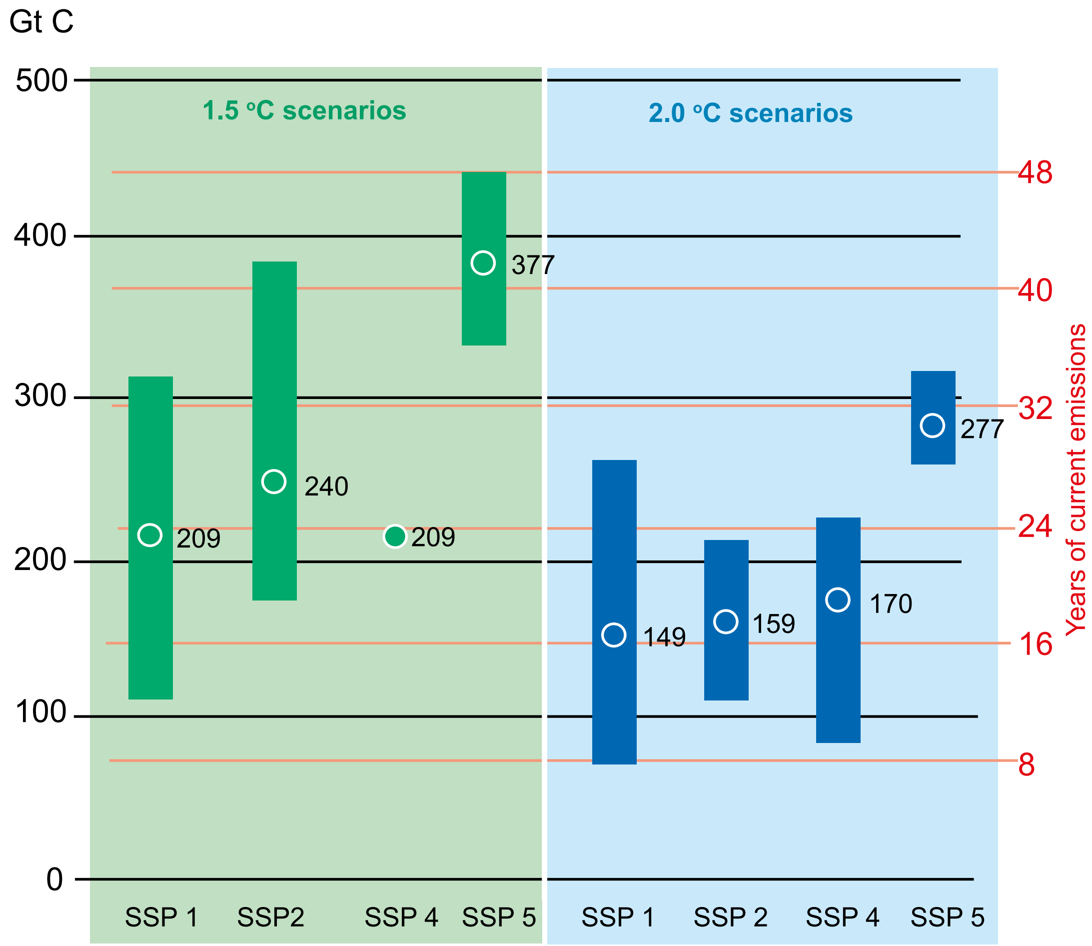


Figure 14. Average (circles), smallest and largest (bars) cumulative negative emissions between 2005 and 2100 by four SSPs for 1.5°C (green) and 2.0°C scenarios (blue). Values shown in Gt C on left hand axis and relative to years of current emissions on right hand axis.SSP1 is a "sustainability scenario", while SSP 5 allows a high degree of fossil-fuelled development. After 84, redrawn and recalculated from CO_2 to carbon.

Spring in the Krakov old-growth oak forest in Dolenjska, Slovenia.

> ***"Old-growth forests usually continue to accumulate carbon until they are at least 800 years old"***

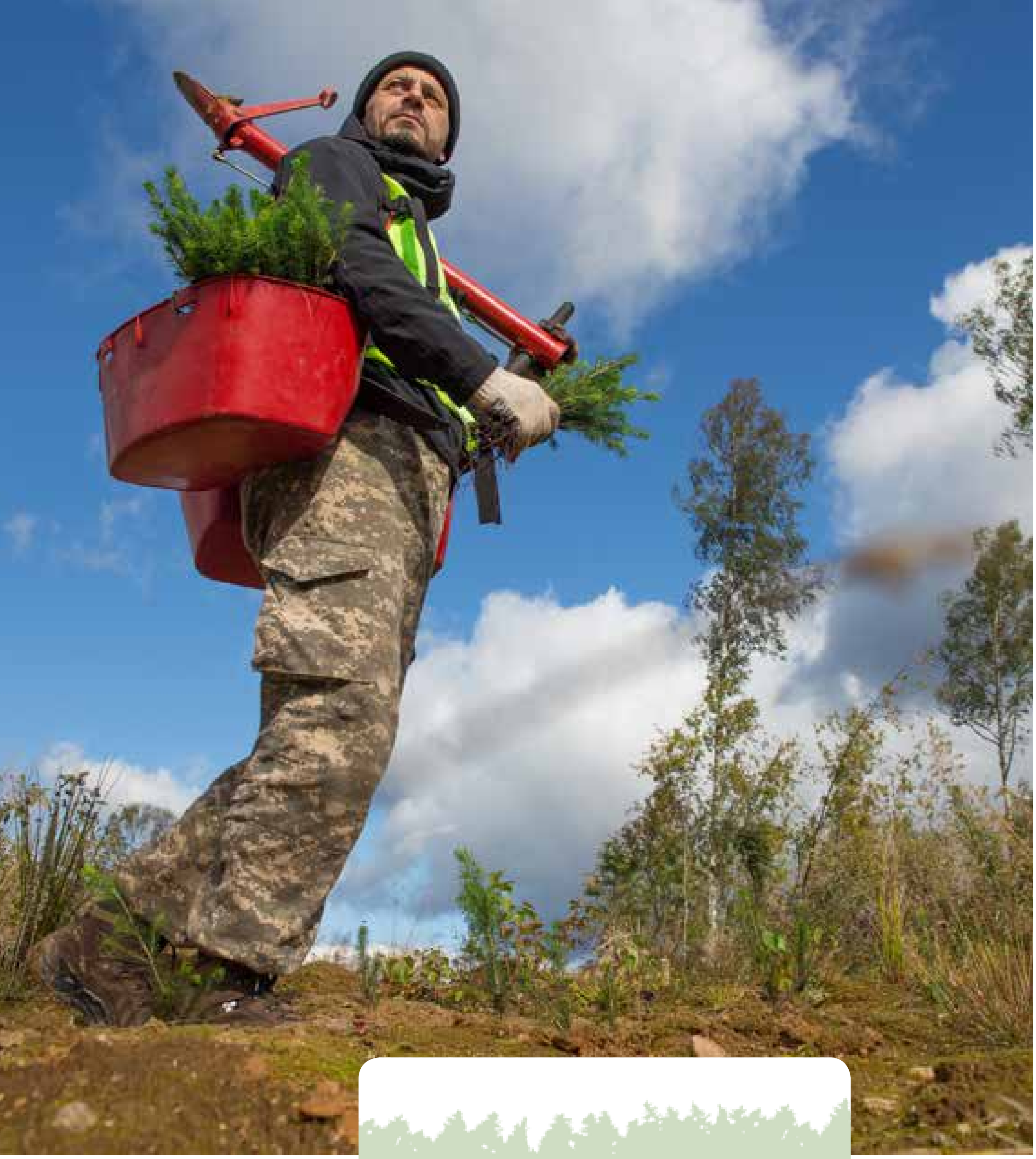
normally diminishes with age. The remaining northern old-growth forests (comprising 15% of the global forest area and about one-third of northern forests) are estimated to provide at least 10% of the global ecosystem carbon sink.[22] A more recent study has reported about a 30% lower estimate for the old-growth carbon sink, but the overall conclusion that even forests of old age remain considerable sinks has not been challenged.[115,116]

Continued exploitation of these forests for timber production will unconditionally cause degradation of ecosystems, loss of resilience and biodiversity, and negatively affect carbon sequestration.[22] There is a considerable risk that soil carbon, accumulated over centuries or even millennia, will be released, in which case it cannot be recovered by ecosystem sequestration over at least the next forest generation. The temperate coniferous forests of north-western North America and the forest and peatland landscapes of eastern Canada and western Siberia are two areas with large pools of such irrecoverable soil carbon, containing 5 Gt and 12 Gt respectively,[86] but probably most old-growth forest soils contain such "old" carbon to some extent.

Reforestation and afforestation

At the global scale, deforestation is a major threat to forests and their ecosystem services, including climate mitigation. For example, the carbon sink of intact tropical forests decreased from 1.28 Gt carbon per year in the 1990s to 0.88 Gt in the 2010s, mainly due to deforestation. During the same period the sink of tropical regrowth forest increased from 1.27 to 1.64 Gt per year, keeping the tropical forest sink largely intact, despite an overall area decrease.[2]

The picture for northern forests is different. As shown *(p. 27)* the overall forest area has been increasing a little since 1990, and the underlying processes of deforestation and reforestation are rather insignificant (in the magnitude of 1% of total forest area). It is therefore a bit surprising that ending deforestation is frequently pointed out as an import-



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Planting new forest.

> *“The amount of land designated for land-based carbon removals is unrealistically optimistic and impossible to implement”*

ant, or even the most important, measure to safeguard and enhance the carbon sink, even in northern forests.

One explanation for this may be that integrated assessment models (IAMs) rely heavily on reforestation/afforestation as land carbon sinks and tend to overlook the potential of managed forests, even for northern forests. For three studied IAM scenarios aligned with the 1.5ºC target, expansion of the forest carbon sink is primarily achieved through ending deforestation and reforestation/afforestation, while the effects of management measures in existing forests are projected to be zero or very limited. According to these scenarios, between 100 and 180 million hectares of pastures and cropland in the northern forest zone are projected to be reforested until 2050.[74] (For comparison, the total area of agricultural land in the European Union is about 170 million hectares.)

MESSAGE-GLOBIOM, REMIND MAgPIE and WITCH

Climate mitigation policies in northern forest countries also rely on reforestation and afforestation as much or even more than the models. According to their nationallly determined commitments (NDCs) under the Paris Agreement, northern forest countries will increase their forest area by 162 million hectares through reforestation and afforestation by mid-century in order to meet their climate goals.[74] The pledge of Russia is by far the largest in terms of area, followed by the USA and Canada.[87] Globally, NDCs include reforestation and afforestation of close to 1 billon hectares, which is equivalent to around two-thirds of global arable land.[88]

Obviously, the amount of land designated for land-based carbon removals in IPCC models and NDCs is unrealistically optimistic and impossible to implement without complex trade-offs for food security, biodiversity and human livelihood. A recent analysis modelling the social and ecological risks of such expansion potentially reduces the amount of land available by up to 79% compared to IPCC estimates.[88]

A simple explanation to the over-reliance on reforestation and afforestation is that it offers an appealing form of carbon removal to governments and industry. Unlike forest protection and management adaptations they don’t imply harvest reductions and immediate, large-scale changes to the industry and energy sectors, and until land is to be allocated for the new forests the land-use conflicts may conveniently be overlooked.

Deforestation is never justifiable and reforestation/afforestation may undoubtedly be a useful tool in the northern forest zone, even if the potential is far smaller than projected in models and NDCs. Regardless of this however, it is safe to claim that extensive reforestation/afforestation programmes come with a higher risk of problematic land-use conflicts and less immediate effects on forests carbon sinks than management measures on existing forest land.

Improving forest management

Intensified forestry for fossil substitution – an option?

There are two opposed views on how forests should best be used to counteract climate change and contribute to meeting established climate policy objectives. One advocates more intensive forestry with increased timber harvesting, while the other argues that it is better to reduce harvesting and change management models in order to allow today's forests to continue to grow and sequester carbon. There are studies that support both views, depending on the time and space boundaries of the system analysed and what assumptions are made about substitution effects – in other words how the biomass that is removed from the forest affects the carbon balance.

Increased wood use could help mitigate climate change if the carbon sequestered in harvested wood products and the fossil fuels avoided by substituting fuels and materials with wood exceed the debit in forest carbon stock caused by harvesting.[89] Studies supporting this strategy always depend on positive substitution effects, but vary a lot as regarding the time perspective and how the system studied is defined, which has a great impact on the outcome. Many studies show positive effects over 100 years or more, which is of limited interest in a situation where a target to reach net-zero emissions must be met within the next 25 years.

The substitution effect is positive if one unit of carbon in harvested wood eliminates the release of more than one unit of carbon released from fossil fuel combustion. Substitution factors below 1.0 indicate that the climate effect is negative. In the scientific literature there has been a trend of decreasing estimates of substitution factors over time, from a value greater than 2 around 2010 to between 0.4 and 0.8 in recent studies.[55,90]

One reason for the limited substitution effect is that most of the wood harvested ends up in short-lived products (such as paper or biofuels), which means that the carbon will be released to the atmosphere within a few years. Globally, about 40% of the roundwood harvested is used in more long-lived wood products (HWP – harvested wood products). However, only 44% of HWP carbon remains stored over longer periods than 25 years.[91,89] This means that of a tonne of carbon removed from the forest today, 830 kg will beback in the atmosphere by 2050 – and most of it even before 2030.

> ***" Of a tonne of carbon removed from the forest today, 830 kg will be returned to the atmosphere by 2050 and most of it even before 2030"***

It is noteworthy that while the removal of carbon from the world's forests in the form of industrial roundwood increased from about 240 Mt in 1990 to 360 Mt in 2010 (a 50% increase),[69] the carbon sink in HWP increased only by about 1%.[2]

Advocating intensified forestry because of its assumed material substitution effects is also problematic because current calculations of the climate benefits essentially ignore the existence of climate policy. For example, the EU emissions trading system will force among others the steel and cement industries of the member states to phase out greenhouse gas emissions by 2040, with or without substitution. Ignoring such policy measures will incorrectly show that increased use of biofuels, for example, will reduce greenhouse gas emissions.[92]

To give a true picture of the climate effects of increased harvests, wood cannot – as commonly done in life cycle analyses – be treated as "carbon neutral", by not accounting for carbon that was present in vegetation and emitted as a result of harvesting, as waste or at end of use. Such approaches give the impression of low, zero or even negative greenhouse gas emissions from wood harvests because, in different ways, the carbon losses from new harvests are offset with carbon sequestration from the growth of broad forest areas. This is inappropriate, because the climate consequence of new harvests cannot logically be altered by forest growth that would have occurred anyway.[69]

Even if the short-term climate effect of increased harvesting is obviously negative, a long-term positive effect would be possible if harvesting improves forest growth and forest structure to a degree where the carbon stock eventually becomes bigger than before the harvest. However, a review of 45 studies did not find any such long-term positive effect. On the contrary, increasing harvests reduced the carbon stock in temperate and boreal forests over 100 years by about 1.6 times the amount of carbon removed in harvested wood.[89]

"The present carbon cost of global wood harvesting is about 0.8 Gt per year"

The present carbon cost of global wood harvesting is about 0.8 Gt per year, and the projected increase in demand and supply will increase these emissions by 0.2 Gt annually. Substitution effects are estimated at 0.24 Gt/year, which not by far makes the harvest "carbon neutral" *(figure 15)*. The estimate of the net carbon source is probably conservative, since it does not include effects on soil carbon.[69]

To summarise, it has become increasingly clear that the substitution effect of present forestry and forest products cannot compensate for the negative climate effects of harvesting these products.[55,93]

Forest management for climate mitigation

The threat of climate change poses two challenges to the management of forest ecosystems:

- forests must be managed in a way that allows them to adapt to a changing cli-

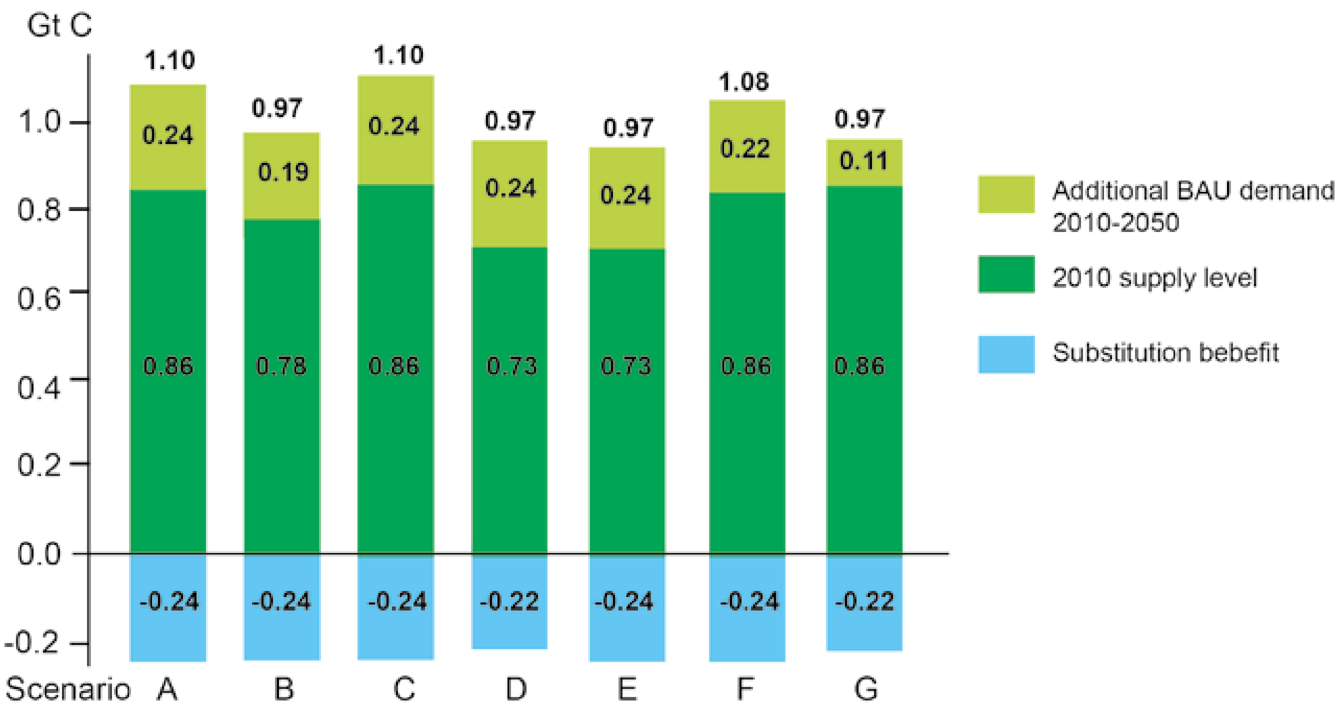

Figure 15. Estimated annual average carbon costs (Gt C) of global wood harvesting 2010–2050 under different scenarios of future wood supply. Carbon costs are time-discounted to changes in carbon storage for 40 years (2010–2050) after each year's harvest. This accounts for forest regrowth and other changes in carbon storage pools over time but discounts these changes (at 4% account rate) back to the year of harvest. They therefore represent harvest-year equivalent emissions, i.e. the value of net changes in carbon each year if all occurred in the year of harvest. Dark green is emissions at 2010 wood supply levels, light green emissions from projected additional business-as-usual demand until 2050. Blue bars show estimated substitution effects. Substitution benefits do not mean that wood use has climate benefits overall because they do not account for lost carbon storage, i.e. biogenic emissions. Substitution benefits do not alter absolute emissions from wood harvest.
Scenarios A–F assume the same future consumption, while scenario G assumes 50% less increase in wood fuel demand. Scenarios: A) Secondary forest harvest and regrowth, B) Secondary harvest and conversion, C) Secondary forest mixed harvest, D) New tropical plantations, E) Higher plantation productivity, F) Higher harvest efficiency, G) 50% reduced wood fuel demand 2010–2050. After (69), values recalculated from CO_2-equivalents to carbon.

"An old tree left to die in the forest is a more durable carbon pool than the same tree harvested, processed and marketed"

mate, i.e. the resilience in degraded ecosystems must be restored, and

- the carbon sequestration and storage capacity of ecosystems must be preserved and improved in order to meet set climate targets and avoid runaway continued warming.

Utilising part of the carbon carrying capacity in existing forests for climate mitigation is in principle simple: allow forests to grow, sequestering carbon in tree biomass. Since the growing stock in managed northern forest is generally far below levels in unmanaged forests the potential of this strategy is huge. The main obstacle for implementing it is the overarching and long-standing forest policy paradigm in industrialised countries, entirely focused on increased yield of raw material for the forest industry. In line with this paradigm, countries choose to set unrealistic targets for reforestation and afforestation, while ignoring the mitigation potential of management changes in existing forests, as do the assessment models developed by the IPCC to analyse pathways to reach climate targets.

Between 1960 and 2010, production and consumption of wood products (including wood fuels) increased by 76% globally. About half of the total harvest was industrial roundwood (for sawn products and paper). The increase in this sector was 44%. The projected increase by 2050 is another 90%. At that time an additional 1,600 million m^3 of roundwood will be removed from the world's forests for industrial purposes every year, which is estimated to increase the carbon cost of global wood harvesting by about 0.2 Gt per year.[69]

To some extent this loss of carbon storage potential can be reduced by improved management models, but by and large it is a direct function of harvest volume. Most of the carbon in a harvested tree will be released into the atmosphere within a decade or two, while a tree left to grow will continue to sequester carbon for at least a century, and often far longer. In fact, it has been shown that an old tree left to die and decompose in the forest is a more durable carbon pool than the same tree harvested, processed and marketed, given the present product mix.[94]

KARIN ÅSTRÖM

Forest under ecosystem management in Lübeck: heterogeneous, multi-layered, uneven-aged and with a natural tree species composition.

Extended rotation periods

It is widely recognised that extending the rotation period in rotation forestry (which equates to increasing the stand volume) has greater positive effects on the forest carbon balance in the short term than any other possible change in forest management.[95] Needless to say, the positive climate mitigation effects will only remain as long as the stand volume is maintained at the higher level.

Ultimately, forests may gradually reach an equilibrium state in which the decomposition of dead wood releases as much carbon dioxide as the growing forest sequesters. Normally however, forests remain sinks far beyond usual harvesting age. Managed forests in Norway, Finland and Sweden have been shown to remain carbon sinks, at levels of more than half of the most productive younger forests, even at a stand age of 150–200 years.[96,68] The carbon sink of temperate beech forests in Europe has been shown not to decline in older stages in comparison to younger stages.[97,65]

A recent Finnish model study showed that a management regime with drastically reduced harvesting levels sequestered far more carbon (by a factor of 2 to 3.5) than a business-as-usual alternative (including substitution effects), even over a time span of 300 years.[94]

However, extending rotation periods by 20–30 years, which might be feasible within the framework of rotation forestry focused on

KARIN ÅSTRÖM

FOREST ECOSYSTEM MANAGEMENT IN LÜBECK AND GOTHENBURG

The cities of Lübeck in northern Germany and Gothenburg in southwestern Sweden are two forerunners in forest ecosystem management. The forests are managed with sustainable, commercial timber production as an overarching objective, albeit with considerations to their importance as recreation areas.

The forest holdings of Lübeck, about 4,000 ha, have been under ecosystem management since 1994. Presently the growing stock is around 430 m^3 per ha, compared to the German average of 329 m^3. The forest managers estimate that the increase can continue to 600 m^3 per ha within the framework of active and profitable forestry.[109] If the growth rate remains the same until this level is reached, the forest will have stored another 34 tonnes of carbon per hectare by 2075.

The city of Gothenburg, Sweden, switched from rotation forestry to forest ecosystem management on 4,700 ha of its forest holdings in 2009. Since then, the growing stock has on average increased from 130 to 170 m^3 per ha, while the net economic revenue from forestry has increased. Climate change and other factors make forecasts difficult, but according to the forest managers 300 m^3 by 2050 is a reasonable target.[110] The average growing stock in Swedish forests is around 150 m^3 per ha.

timber production, is unlikely to improve ecosystem complexity and resilience more than marginally, unless accompanied by other management changes.

Continuous cover forest management

Continuous cover forestry (CCF) is characterised by selective harvesting and natural regeneration, resulting in uneven-aged structures and frequently also in greater tree species diversity than rotation forestry and regeneration by planting or seeding.[98] The adverse effects of clear-cutting on biodiversity and carbon storage are avoided.

> ***"Management with reduced harvesting sequestered far more carbon than a business-as-usual alternative, even over 300 years."***

Ecological theory and empirical studies both support the conclusion that continuous cover forestry methods have less negative impact on biodiversity than clear-cutting.[99] Heterogeneity, an umbrella term for habitat complexity that includes the quantity and quality of various resources and biological niches, is positively correlated with biodiversity.[100] In boreal forests in Sweden it has been shown that this correlation is stronger than that between biodiversity and any other single factor.[101]

In most cases the risk of damage (insect and fungal attacks, grazing damage, frost, drought and wind) is smaller in uneven-aged forests than in even-aged, which means that the resilience is higher.[102]

Shifting to CCF has also been shown to be more effective for carbon sequestration than increasing harvesting rates.[103] A modelling study comparing the climate benefits of different forest management systems over a 100-year period in Finland found that a CCF strategy had the most positive carbon balance and the largest carbon stock, on average 24% higher than rotation forestry and other alternatives.[104]

Continuous cover forestry encompasses a variety of management methods with main-

Forest ecosystem management in progress in the forests of Lübeck, northern Germany. To the left a restored beech forest, to the right a remnant of the abandoned rotation forestry, a spruce plantation.

taining a continuous tree cover as the common denominator. Forest ecosystem management (FEM) is one of them, and probably the most promising solution for achieving sustainable forest management under climate change.[19]

Ecosystem-based forestry, ecoforestry and close-to-nature forestry are other names for the same concept, defined as a management approach that aims to maintain healthy and resilient ecosystems by reducing the gaps between natural and managed landscapes to ensure, in the long term, the maintenance of multiple ecosystem functions.[105]

An overarching principle of forest ecosystem management is that forestry should minimise its impacts on the ecosystem. Harvesting is carried out selectively or in very small gaps (since most disturbances in boreal and temperate forests are small). Tree composition, tree diversity, age distribution and structural diversity should as far as possible emulate natural conditions at every specific site. Forests are regenerated naturally. Thinning and other measures that aim to alter tree species composition or forest structure are exceptions. The higher degree of naturalness in forests managed under FEM principles increases resilience.

Shifting from rotation forestry to ecosystem management is in fact a form of ecosystem restoration, conducted within the framework of timber-producing forestry. According to the IPCC, large-scale ecosystem restoration is imperative to limit global warming to 1.5°C.[80]

"Shifting to ecosystem management is in fact a form of ecosystem restoration"

Several studies show that from a short- or medium-term perspective, closer-to-nature forestry benefits the carbon balance and carbon stock of the forest compared with rotation forest management and clear-cut logging.[106] A main reason for this is that ecosystem-based forestry is based on significantly larger stand volumes, simply because the growing stock in natural northern forest ecosystems is much bigger than in forests under rotation forest management. In addition, selective logging avoids the adverse impact of clear-cutting on the carbon balance.

Forest ecosystem management is a relatively new term, but the principles have been

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practised in Europe since the end of the 19th century. These methods have been vigorously questioned, but have proved their ability to manage sustainable timber-producing forests so that they remain healthy, well-stocked and diverse. However, the areas involved are small. In Switzerland and Slovenia, such methods are, at most, used in 10 percent of the forest area, while in Sweden 1–5% is managed using systems other than clear-cutting forestry.[107] In Germany, the municipality of Lübeck has been using ecological forestry on its forest holdings since 1994, and several other German cities have followed suit,[108] as has the city of Gothenburg in Sweden *(see box)*.

Time to say goodbye...

Shifting from rotation forestry to ecosystem management is a process that in most cases will take decades, depending on the initial state of the ecosystem. The transition process includes allowing the growing stock – and thus the carbon sink – to increase. The development of forests in Gothenburg and Lübeck indicates the potential climate benefits from such a shift. Upscaled to the entire European forest area, the same increase in growing stock as in Gothenburg would sequester about 85 Mt of carbon annually until 2050 and beyond, which corresponds to about 10% of the total greenhouse gas emissions of the European Union. The same development over the entire managed northern forest area would increase the annual carbon sink by about 0.8 Gt, which corresponds to about 20% of the present global carbon sink.

In conclusion, forest ecosystem management is a promising solution for achieving sustainable forest management within a context of climate change, addressing the biodiversity crisis and restoring forest resilience while at the same time utilising a far bigger share of the carbon carrying capacity of northern forests than present management models.

7 THE RIGHT PATH - POLICY RECOMMENDATIONS

Forests can and must play a vital role in mitigating climate change and protecting biodiversity. This is recognised in a number of recent international agreements:

- **The 2015 Paris climate Agreement,** in which governments committed to "take action to conserve and enhance sinks and reservoirs of greenhouse gases, including forests".
- **The 2022 Kunming-Montreal Global Biodiversity Framework** in which governments "call to ensure and enable that by 2030 at least 30 percent of terrestrial and inland water areas, and of marine and coastal areas, especially areas of particular importance for biodiversity and ecosystem functions and services, are effectively conserved and managed".
- **The 2023 Decision of the UN Framework on Climate Change** (UNFCCC) on the Outcome of the first global stocktake "emphasised the importance" of "enhanced efforts towards halting and reversing deforestation and forest degradation by 2030".

Northern forest countries are far from being on track to fulfil their commitments under these agreements. The carbon sink is shrinking and measures to protect and enhance it are grossly inadequate. Two-thirds of the northern forest area is more or less degraded by unsustainable forest management, and additional areas are continuously exploited and degraded. Less than 10% of the northern forest area is under efficient protection.

> ***"Unless the present trend is reversed, the northern forest may turn into an overall source of carbon by 2060."***

Furthermore, the northern forest carbon sink is decreasing rapidly. The drivers of this development are climate-induced increases in natural disturbances, intensified timber harvesting and exploitation of remaining old-growth forests, possibly in combination with decreasing growth effects of warmer climate and CO_2 fertilisation.

Unless the present trend is reversed, northern forests may turn into an overall source of carbon by 2060. To minimise the risk of this happening, greenhouse gas emissions must be reduced rapidly, while at the same time ecosystem resilience must be enhanced through forest protection and ecosystem restoration.

Increasing rotation forest management as a climate mitigation strategy by means of fossil fuel substitution is not a viable strategy. In any relevant time perspective, increased – or even maintained – timber harvest levels will worsen the climate crisis and its negative impact on biodiversity and ecosystem integrity. Thus, the overarching and long-standing forest policy paradigm in industrialised countries, which focuses on increasing the yield of raw materials for the forest industry, should be abandoned. The potential of existing forests as carbon sinks should be given much higher priority in national forest policies.

Increasing the volume of growing biomass through decreased harvest and prolonged rotation periods is the simplest and quickest way to increase the northern forest car-

ROGER OLSSON

bon sink. Doing this within the framework of rotation forest management and clear-cut harvesting will however have limited positive effects on ecosystem resilience and biodiversity. A transition to Forest Ecosystem Management (FEM), on the other hand, will increase growing biomass during the transition period. Such a transition, if applied to the two-thirds of northern forests currently managed, has the potential to increase the carbon sink by 0.8 Gt carbon per year, while at the same time gradually improving ecosystem resilience and reducing the pressure on biodiversity.

Actions at the international level include:

1. Supporting synergies

Both the CBD (UN Convention on Biodiversity) and the UNFCCC leadership should increase synergies in the planning and implementation of national climate, biodiversity and land restoration plans, and strengthen the coherence among NBSAPs (National Biodiversity Strategy and Action Plans), NDCs (Nationally Determined Contributions or climate pledges) and NAPs (National Adaptations Plans).

2. Improving monitoring

The annual dialogues on the outcomes of the UNFCCC's First Global Stocktake should ensure monitoring of and reporting on the implementation of its forest commitments (paragraph 33), and include these commitments in further debates on the integration of the Global Stocktake outcomes into future NDCs.

3. Increasing attention

The role of forests in climate mitigation should remain central in the future agenda of the UNFCCC's Mitigation Work Programme in order to highlight the need for greater global action to protect and restore forests during the rest of this decade.

4. Strengthening implementation

The UNFCCC should establish a multidisciplinary ad-hoc Technical Expert Group with a mandate to advise and support governments in implementing Article 5 of the Paris Agreement, which deals with ecosystems and in particular forests, by operationalising the concept of ecosystem integrity.

5. Enforcing accountability

A forest accountability framework should be set up under the UNFCCC, establishing clear metrics, guidelines and indicators for all drivers of deforestation and forest degradation, for developed and developing countries, and supported by annual, country-led reporting on rates of deforestation and forest degradation.

6. Establishing a dialogue

The UNFCCC should establish a Forests and Climate Change Dialogue, which could operate in a similar way to the Oceans and Climate Change Dialogue, aiming to provide a forum for discussing actions needed to conserve and enhance sinks and reservoirs of greenhouse gases in the world's forests, as well as monitoring progress on action to halt and reverse deforestation and forest degradation.

Actions at the national level include:

1. Mapping, monitoring and accounting

Governments must analyse and map the state of their forests, assess and address the drivers of forest degradation and deforestation and set up a carbon accounting framework that reflects environmental integrity. Furthermore governments must track and address imported deforestation and forest degradation (including of northern forests) associated with products or activities that a country consumes or from which it benefits. To ensure all of the above, adequate capacities need to be established.

2. Setting and enforcing ambitious targets

Governments must set ambitious targets for forest protection and for forest carbon removals, in combination with ambitious greenhouse gas emission reduction targets and fossil fuels

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phase-out dates. Forest carbon removal targets should be set as tons of carbon removed and not as percentages of future projected baselines. These targets should be integrated in NDCs and long-term net-zero plans, and implementation should be ensured by setting up the right framework of policies, actions and measures. Furthermore, governments must develop plans, policies and measures to implement the promise made to halt and reverse deforestation and forest degradation by 2030.

3. Developing a coherent policy framework

Governments must set up a coherent approach to ensure the implementation of all emission reductions as well as removal targets, thereby limiting the negative impact of (energy) transition measures on the state of the forests. Furthermore, governments must provide synergies to ensure implementation of climate, biodiversity and sustainable development objectives, while recognising the value of high-integrity, standing forests. This includes assessing and accounting for the long-term value of forest protection within economic forecasts and budgets. Furthermore, governments must strengthen the rights to land and informed consent of indigenous peoples and local communities.

4. Increasing forest protection

Governments must ensure full protection, conservation and restoration of all their primary and old-growth forests and must establish the necessary framework to protect and restore at least 30% of their forests, in line with the objectives of the Global Biodiversity Framework.

To be functional, this objective must be met on a regional scale. A representative, interconnected network of protected, near-natural ecosystems – a green infrastructure – must be planned and implemented all over the northern forest region.

5. Transitioning to sustainable forest management

Governments must transition current forest management practices to ecosystem management approaches based on partial harvesting

"To give northern forests a chance to contribute maximally to climate change mitigation, governments must reduce unsustainable consumption of forest products"

rather than clear-cutting, in order to maintain healthy and resilient ecosystems by reducing the gaps between natural and managed landscapes to ensure, in the long term, the maintenance of multiple ecosystem functions.

6. Expanding afforestation and reforestation

In addition to increasing forest protection and shifting to sustainable forest management practices, governments must increase afforestation and reforestation efforts, if and when they are based on a framework of ecological principles, which include: encouraging natural regeneration wherever feasible; promoting the concept of green infrastructure across entire landscapes and individual sites; restoring, maintaining and enhancing ecosystems and their multiple ecological, social and economic functions within landscapes; avoiding adverse impacts on natural ecosystems while enhancing their conservation and recovery; and producing positive and tangible benefits in terms of mitigation and adaptation to climate impacts.

7. Strengthening adaptation

Governments must anticipate and prepare for the multifaceted consequences of climate change on northern forests. Shifting to sustainable forest management practices will substantially contribute to this.

8. Forest certification

Governments must support the development of new or existing forest certification schemes that address the role of forests in mitigating climate change and strengthen the protection of biodiversity and provision of ecosystem services other than timber production.

9. Reduce consumption

To give northern forests a chance to contribute maximally to climate change mitigation, governments must tackle and reduce unsustainable consumption of forest products and in particular paper and wood.

10. Limit bioenergy use

Governments must stop rewarding the unsustainable levels of bio-energy consumption, among other things by falsely claiming bio-energy is carbon neutral.

They must instead support the shift towards wiser uses of bio-energy, end all incentives for burning trees and crops, implement the cascading principle so that burning biomass for energy is a last resort, and ensure that scarce biomass resources are used only in sectors with no other options.

REFERENCES

1. **FAO 2025***:* FAO stat. [Online] *www.fao.org/faostat/en/*#home.
2. **Pan, Y et al 2024:** The enduring world carbon sink. Nature. Vol 631:563-569.
3. **Cheng, K et al 2024:** Carbon storage through China´s planted forest expansion. Nature communications. 2024, Vol. 15, p. 4106.
4. **de Gouvenain, RC & Silander, J 2017:** Temperate Forests. Reference Modules in Life Sciences. Elsevier.
5. **FAO 2020:** Global forest resources assessment. [Online] *https://fra-data.fao.org/assessments/fra/2020/.*
6. **IBFRA 2024:** About Boreal Forests. International Boreal Forest Research Association. [Online] *https://www.ibfra.org/about-boreal-forests/.*
7. **Gauthier, S et al. 2023:** Ecosystem Management of the Boreal Forest in the Era of Global change. In Girona M M et al [ed.]: Boreal forests in the Face of Climate Change, chap 1, pp. 3-49. Springer.
8. **Kneeshaw, D 2018:** Is management or conservation of old-growth possible in North American boreal forests. In A M & Keeton, W S Barton [ed.] : Ecology and recovery of eastern old-growth forest, pp. 139-157. Island Press,
9. **Berglund, H & Kuuluvainen, T 2021:** Representative boreal forest habitats in northern Europe, and a revised model for ecosystem management and biodiversity conservation. Ambio, vol. 50, pp. 1002-1017.
10. **Skogsstyrelsen 2015:** Lägsta ålder för slutavverkning. Skogsstyrelsen, rapport nr 1869 (In Swedish).
11. **Gauthier, S et al. 2015:** Boreal foreat health and global change. Science, vol. 349, pp. 819-822.
12. **Ahlström, A et al. 2022:** Widespread Unquantified Conversion of Old Boreal Forest to Plantations. Earth´s Future, p. e2022EF003221.
13. **Leskinen, P et al 2020:** Russian forests and Climate Change. EFI, European Forest Institute.
14. **Sommerfeld, A et al. 2018:** Patterns and drivers of recent disturbances across the temperate forest biome. Nature communications, vol. 9:4355.
15. **Seidl, R et al. 2014:** Increasing forest disturbances in Europe and their impact on carbon storage. Nature Climate Change, vol. 4 (9), pp. 806-810.
16. **Rohr, J. 2014:** Indigenous peple in the Russian federation. IWGA, report 18.
17. **Government of Canada 2025:** Learn about Indigenous peoples and communities. [Online] *www.canada.ca/en/services/indigenous-peoples/about-indigenous-peoples-and-communities.html.*
18. **Samiskt informationscentrum, Sametinget 2025:** Samer.se. [Online] *www.samer.se/1106*. (In Swedish.)
19. **Girona, M M et al 2023:** Management of the boreal forest under climate change. In Girona M M et al [ed.]: In Boreal forests in the face of climate change, pp. 773-837. Springer.
20. **Bradshaw, C J A & Warkentin, I G. 2015:** Global estimates of boreal forest carbon stock and flux. Global and planetary change, vol. 128, pp. 24-30.
21. **Pappas, C et al. 2023:** A circumpolar perspective on the contribution of trees to the boreal forest balance. In Girona M M et al [ed.]: Boreal forests in the face of global change, pp. 271-294. Springer.
22. **Luyssaert, S et al. 2008:** Old-growth forests as global carbon sinks. Nature, vol. 455, pp. 213-215.
23. **Climate Analytics 2024:** Climate impacts in northern forests. Report.
24. **WMO 2024:** State of the climate 2024. Update for COP 26. World Meteorological Organisation.
25. **Climate Action Tracker 2024:** Warming Projections. Global Update
26. **IPCC 2025:** IPCC WG I Interactive Atlas: Regional Information. [Online] *https://interactive-atlas.ipcc.ch/regional-information.*
27. **Brodibb, T J et al 2020:** Hanging by a thread? Forests and droughts. Science, vol. 368, pp. 261-266.
28. **Walker, A et al. 2021:** Integrating the evidence for a terrestrial carbon sink caused by increasing atmospheric CO2. New Phytologist, vol. 229, pp. 2413-2445.
29. **Seidl, R et al. 2017:** Forest disturbance under climate change. Nature Climate Change, vol. 7, pp. 395-401.
30. **Sanchez-Pinillos, M et al. 2022:** Sequential droughts: A silent trigger of boreal forest mortality. Global change biology, vol. 28, pp. 542-556.
31. **Liu, Q et al. 2023:** Drought-induced tree mortality and corresponding decrease in the carbon sink capacity of Canada´s boreal forest from 1970 to 2020. Global Change Biology, vol. 29, pp. 2274-22.
32. **Knutzen, F et al. 2025:** Impacts of damage to European forests from the 2018-2022 heat events. Natural Hazards and Earth System Sciences, vol. 25, pp. 77-117.
33. **Coogan, S C P et al. 2019:** Scientists´ warning on wildfire - a Canadian perspective. Canadian Journal of Forest Research, vol. 49, pp. 1015-1023.
34. **Jones, M W et al. 2024:** State of Wildfires 2023-2024. Earth System Science Data, vol. 16, pp. 3601-3685.
35. **Kharuk, V I et al. 2008:** Wildfire dynamics in the larch dominance zone. Geophysical research letters, vol. 35 (1), p. L01402.
36. **Shorokova, E et al. 2023:** Natural Disturbances from the Perspective of Ecosystem.Based Management. In Girona M M et al [ed.]: Boreal Forest in the Face of Global Change, pp. 88-121. Springer.
37. **Wang, S et al. 2023:** Mechanisms and impacts of earth system tipping elements. Reviews of Geophysics, e2021EG000757.
38. **Wotton, B M. 2017:** Potential climate change impacts on fire intensity and key wildfire supression thresholds in Canada. Environmental Research Letters, vol. 12(9), p. 095003.
39. **Veraverbeke, S et al. 2017:** Lightning a major driver of recent large fire years in North American boreal forests. Nature Climate Change, Vol. 7(7), pp. 529-534.
40. **Kurz, W A et al. 2008:** Mountain pine beetle and forest carbon feedback to climate change. Nature, vol. 452:7190, pp. 987-990.
41. **Olsson, R 2009:** Boreal Forest and Climate Change. AirClim, report.
42. Forzieri, G et al. 2021: Emergent vulnerability to climate-driven disturbances in European forests. Nature communications, vol. 12:1081.
43. **Wulff, S & Roberge, C. 2022:** Inventering av barkborreangrepp i Götaland och Svealand SLU, Inst. för skoglig resurshushållning, report. (In Swedish.)
44. **Patacca, M et al. 2023:** Significant increase in forest disturbances since 1950. EFI, European Forest Institute,. Policy Brief 4.

45. Skogsstyrelsen 2025: 20 år efter stormen Gudrun. [Online] *https://www.skogsstyrelsen.se/nyhetslista/20-ar-efter-stormen-gudrun/.(In* Swedih.)

46. Mann, D H et al. 2012: Alaska´s Boreal Forest Now Crossing a Major Ecological Threshold? Arcrtic, Antarctic and Alpine Research, vol. 44, pp. 319-331.

47. Stralberg, D et al. 2018: Wildfire-mediated vegetation change in boreal forests of Alberta, Canada. Ecosphere. Vol. 9(3), p. e02156.

48. Martinez del Castillo, E et al. 2022: Climate-change-driven growth decline of European beech forests. Communications biology, vol. 5, p. 163.

49. Rothbarth, R et al. 2022: Northern expansion is not compensating for southern declines in North American boreal forest. Nature communications, vol. 14, p. 3373.

50. Rees, W G et al. 2020: Is subarctic forest advance able to keep pace with climate change? Global change biology, vol. 26, pp. 3965-3977.

51. Armstrong McKay, D I et al. 2022: Exceeding 1.5ºC global warming could trigger multiple climate tipping points. Science, vol. 377 p. eabn7950.

52. Gerten, D et al. 2013: Asynchronous exposure to global warming: freshwater resources and terrestrial ecosystems. Environmental Research Letters, vol. 8 030432.

53. Koven, C D et al. 2013: Boreal carbon loss due to poleward shift in low carbon ecosystems. Nature Geoscience., Vol. 6, pp. 452-456.

54. Scheffer, M et al. 2012: Threshold for boreal biome transitions. PNAS Biological sciences. 2012, pp. 21384-21389.

55. Rummukanien, M. 2024: Skogens klimatnytta 2.0. Syntes nr 8. Centrum för miljö- och klimatvetenskap, Lunds universitet. (In Swedih.)

56. Zheng, B et al. 2023: Record-high CO2 emissions from boreal forest fires in 2021. Science, vol. 379, pp. 912-917.

57. Walker, X J et al. 2019: Increasing wildfires threaten historic carbon sink of boreal forest soils. Nature, vol. 572, pp. 520-523.

58. Lindroth, A et al. 2009: Storms can cause Europe-wide reduction in forest carbon sink. Global change biology, vol. 15:2, pp. 346-355.

59. Moe, L et al. 2023: Integrated global assessment of the natural forest carbon potential. Nature, vol. 624, pp. 92-101.

60. Potapov, P et al. 2017: The last frontiers of wilderness: tracking loss of intact forest landscapes from 2000 to 2013. Science advances, vol. 3, p. e1600821.

61. CBD 2025: Definitions. [Online] *https://www.cbd.int/forest/definitions.shtml.*

62. Olsson, R & Stighäll, K 2013: Vitryggens skogar. Rapport. Naturskyddsföreningen, 2013. (In Swedish.)

63. Kuuluvainen, T & Nummi, P. 2023: Strategies for the ecological restoration of the boreal forest facing climate change. In Girona M M et al [ed.]: Boreal forests in the face of global change, pp. 433-466. Springer.

64. Hjältén, J et al. 2023: Ecological restoration of the boreal forest in Fennoscandia. In Girona M M et al [ed.]: Boreal Forests in the face of global change, pp. 467- 489. Springer.

65. Hauck, M et al. 2023: The significance of large old trees and tree cavities for forest carbon estimates. Forest ecology and management, vol. 546, p. 121319.

66. Grelle, A et al. 2023: From source to sink - recovery of the carbon balance in young forests. Agricultural Forest Meteorology, vol. 330, p. 109290.

67. Lindroth, A. 2023: Clarifying the carbon balance recovery time after clear-cutting. Global Change Biology, vol 29, p. 4178-4179.

68. Peichl, M et al. 2023: Landscape-variability of the carbon balance across managed boreal forests. Global Change Biology, vol. 29, pp. 1119-1132.

69. Peng, L et al. 2023: The carbon costs of global wood harvests. Nature, vol. 620, pp. 110-115.

70. Korosuo, A et al. 2023: The role of forests in the EU climate policy: are we on the right track? Carbon balance and managemernt. 2023, vol. 15, p. 15.

71. Naturvårdsverket 2025: Tillväxt och avverkningar i skogen. [Online] *https://www.naturvardsverket.se/data-och-statistik/skog/skog-tillvaxt-och-avverkningar/.(*In Swedish.)

72. Naturvårdsverket 2025: Nettoutsläpp och nettoupptag av växthusgaser från markanvändning (LULUCF). [Online] *https://www.naturvardsverket.se/data-och-statistik/klimat/vaxthusgaser-nettoutslapp-och-nettoupptag-fran-markanvandning/*. (In Swedish.)

74. Climate Analytics 2024: The role of northern forest in limiting warming to 1.5ºC. Report.

75. Fridman, J & Walheim, M 1997: Död ved i Sverige. Fakta skog nr 12. SLU. (In Swedish.)

76. Angelstam, P 2018: Från skydd av skog till ny infrastruktur - om funktionalitet och procenträkning i det svenska skogslandskapet. Rapport 2018:31. Länsstyrelsen i Örebro län. (In Swedish.)

77. Eide, W (ed) et al. 2020: Tillstånd och trender för arter och deras livsmiljöer - rödlistade arter i Sverige. Artdatabanken rapporterar 24. SLU. (In Swedish.)

78. D´Orangeville, L 2023: Current symptoms of climate change in boreal forest trees and wildlife. In Girona M M et al [ed.]: Boreal Forest in the face of climate cange, pp. 747-771. Springer.

79. Green, M et al. 2024: Övervakning av fåglarnas populationsutveckling. Årsrapport för 2023. Lunds Universitet. (In Swedish.)

80. Pörtner, H-O et al. 2022: Climate Change 2022: Impacts, Adaptation and Vulnerability ; summary for policymakers. IPCC.

81. Liang, J et al. 2016: Positive biodiversity-productivity relationship predominant in global forests. Science, vol. 354:6309, p. 196.

82. Thompson, I et al. 2009: Forest resilience, biodiversity and climate change. Secretariat of the Convention on Biological Diversity. Technical series no. 43.

83. Fuss, S et al. 2018: Negative emissions - part 2: potentials and side effects. Environmental Research Letters, vol. 13, 063002.

84. Evans, S & Hausfather, Z : Q& A: How integrated asssessment models are used to study climate change. [Online] h*ttps://www.carbonbrief.org/qa-how-integrated-assessment-models-are-used-to-study-climate-change/.*

85. Keith, H et al. 2024: Carbon carrying capacity in primary forests shows potential for mitigation achieving the European Green Deal 2030 target. Communications Earth & Environment, vol. 5, p. 256.

86. Noon, M L et al. 2022: Mapping the irrecoverable carbon in Earth´s ecosystems. Nature Sustainability, vol. 5, pp. 37-46.

87. Allen, M et al. 2023: The Land Gap Report Briefing Note. 2023 Update. Climate Resource.

88. Zero Carbon Analaytics 2024: Net-zero progress overblown by inconsistencies in carbon land accounting. [Online] h*ttps://zerocarbon-analytics.org/archives/science/net-zero-progress-overblown-by-inconsistencies-in-land-carbon-accounting.*

89. Soimakallio, S et al. 2022: Closing an open balance: the impact of increased tree harvest on forest carbon. GCB Bioenergy, vol. 14, pp. 989-1000.

90. **Hurmekoski, E et al. 2021**: Substitution impacts of wood use at the market level: a systematic review. Environmental Research letters, vol. 16, p. 123004.

91. **Lauri, P et al. 2017:** Impact of the 2°C target on global woody biomass use. Forest policy and economics, vol. 83, pp. 121-130.

92. **Konjunkturinstitutet 2021:** Miljö, ekonomi och politik: Skogen, klimatet och politiken. Report. The Swedish Institute of Economic Research. (In Swedish.)

93. **European Union 2021:** New EU forest strategy for 2030. European Commission, communication 572.

94. **Pukkala, T. 2018:** Carbon forestry is surprising. Forest Ecosystems, p. 5:11.

95. **Lundblad, M et al. 2009:** Flöden av växthusgaser från skog och annan markanvändning. Slutrapport av regeringsuppdrag JO 2008/3958. (In Swedish.)

96. **Stokland, J N et al. 2021:** Volume increment and carbon dynamics in boreal forests when extending the rotation length towards biologically old stands. Forest ecology and management, vol. 488, p. 119017.

97. **Glatthorn, J et al. 2018:** Biomass stock and productivity of primeval and production beech forests. Ecosystems, vol. 21, pp. 704-722.

98. **Pukkala, T & von Gadow, K (eds) 2012:** Continuous Cover Forestry. Springer.

99. **Felton, A 2017:** Effekter på biodiversiteten av hyggesfritt skogsbruk. [ed.] M et al Hannerz. Hyggesfritt skogsbruk. En kunskapssammanställning från Sverige och Finland. Future Forests rapportserie. (In Swedish.)

100. **Stein, A et al. 2014:** Environmental heterogenity as a universal driver of species richness across taxa, biomes and spatial scales. Ecology Letters, Vol. 17 (7), pp. 866-880.

101. **Hekkala, A et al. 2023:** Habitat heterogenity is a good predictor of boreal forest biodiversity. Ecological indicators, Vol. 148, 110069.

102. **Nevalainen, S 2017:** Comparision of damage risks in even- and uneven-aged forests in Finland. Silva Fennica, vol. 51, p. 1741.

103. **Martin, M et al. 2023:** Embracing the complexity and richness of boreal oldgrowth forests. In Girona M M et al [ed.]: Boreal forests in the face of global change. pp. 191-218. Springer.

104. **Diaz-Yánez, O et al. 2019:** Multifunctional comparision of different management strategies in boreal forests. Forestry.

105. **Gauthier, S et al. 2009:** Ecosystem management in the boreal forest, Presses de l´Université de Quebec.

106. **Pukkala, T. 2016:** Which type of forest management provides most ecosystem services?, Forest Ecosystems, vol. 3, pp. 1-16.

107. **Axelsson, R et al. 2007:** Nartural forest and cultural woodland with continuous tree cover in Sweden: how much remains and how is it managed? Scandinavian Journal of Forest Research, vol. 22, pp. 545-558.

108. **Fähser, L 2003:** Naturnahe Waldnützung im Stadtwald Lübeck. Jahrbuch für Ökologie.

109. **Sturm, K. 2024:** Personal communication.

110. **de Mapeau, X 2024:** Personal communication.

111. **Pan, Y et al. 2011:** A large and persistent carbon sink in the world´s forests., Science, vol. 333, pp. 988-993.

112. **Ciais, P et al. 2008:** Carbon accumulation in European forests., Nature Geoscience, vol. 1, pp. 425-428.

113. **World Conservation Society 2019:** Ecosystem integrity in the post-2020 Global Diversity Framework.

114. **Svensson, J et al. 2023:** Boreal forest landscape restoration in the face of extensive Forest fragmentation and loss. In Girona M M et al [ed.]: Boreal forests in the face of global change, pp. 491-510. Springer.

115. **Gundersen, P 2021:** Old-growth forest sink overestimated. Nature, vol. 591, pp. E21-E23.

116. **Luyssaert, S et al. 2021**: Reply to: Old-growth forest carbon sink overestimated. Nature, 2021, pp. E24-E25.

117. **Naaburs, G J et al. 2013:** First signs of carbon sink saturation in European forest biomass. Nature climate change, vol. 3.

118. **Burton, C A et al. 2024**: Fire weakens land carbon sinks before 1.5°C. Nature Geoscience, vol. 17, pp. 1108-1114.

119. **Fan, L et al. 2023:** Siberian carbon sink reduced by forest disturbances. Nature Geoscience, vol. 16, pp. 56-62.

120. **Lenton, T M et al. 2019:** Climate tipping points - too risky to bet against. Nature, vol. 575, pp. 592-595.

121. **Reich, P B et al. 2022**: Even modest climate change may lead to major transitions in boreal forests. Nature, vol. 608, pp. 540-545.

122. **Olsson, R 2014: T**ilbaka till Klevsjöloft. In Mossa, massa, människa. Naturskyddsföreningen. (In Swedish.)

123. **IIASA 2021,** modified after Kraxner et al., 2017, Ogle et al., 2018 and NFIS Canada.)

124. **Della Sala, D A et al. 2025:** Measuring forest degradation via ecological-integrity indicators at multiple spatial scales. Biological Conservation, vol. 302, 110939.

It is widely assumed that forests in industrialised countries in the northern hemisphere – Annex 1 countries under the UN Climate Convention – are not under threat, or at least face less of a threat than tropical forests. But this is a misconception.

Instead of protecting and enhancing the huge climate mitigation potential of northern forests, current climate and forest policies are massively reducing their ecosystem integrity, biodiversity and carbon storage capacity. The main causes are climate-induced increases in natural disturbances, unsustainable forest management, insufficient forest protection and exploitation of the last remaining tracts of old-growth forests.

Unless present trends are reversed, northern forests may become an overall carbon source as early as 2060, at which point the huge volume of carbon stored biomass and soils over centuries will gradually return to the atmosphere, leading to further warming in a self-reinforcing loop. Passing this critical tipping point would make it extremely difficult, if at all possible, to keep global warming below 1.5ºC.

As shown in this AirClim report, there is still a window of opportunity to stop this from happening. Urgent measures include protection and restoration of forest ecosystems and a large-scale transition from rotation forestry and clear-cutting to ecosystem-based management models.

AirClim