CLIMATE ANALYTICS

Climate impacts in northern forests

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ABOUT CLIMATE ANALYTICS

Climate Analytics is a global climate science and policy institute. Our mission is to deliver cutting-edge science, analysis and support to accelerate climate action and keep warming below 1.5°C.

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Summary

Forests, particularly tropical rainforests, are often called ‘the lungs of the Earth’ due to their vital role in our climate system: taking in and storing carbon dioxide and producing oxygen.

To date, far less attention has been paid to their northern cousins: the boreal and temperate forests that stretch across the north of Asia, North America and Europe. But northern forests play just as critical a part in our climate system and for climate mitigation.

Northern forests hold around 54% of the world’s total terrestrial carbon stock and contribute more than one-third to our global terrestrial carbon sink. The boreal biome alone is the second largest terrestrial biome of the world.

High intensity wood harvesting is currently the biggest threat to northern forests. Forests with reduced resilience due to decades of logging activities are now facing further harms aggravated by climate change. These intersecting impacts threaten to turn certain ecosystems from carbon sinks to sources. In contrast, untouched primary forests have been found to be less affected by climate impacts.

Temperatures are rising much faster in northern forest regions than the global average. In some of these regions, the temperature increase has been more than double the global average.

The fingerprints of climate change can already be found across these ecosystems. Reduced snow cover, increases in extreme precipitation and drought, and extreme heat events make it difficult for these complex forest ecosystems to maintain their integrity.

This report provides a review of the current scientific literature on climate impacts in northern forests. It is clear that:

- Northern forests are already being threatened by climate change at 1.2°C of warming. Further warming will only exacerbate climate impacts and pose an existential threat to northern forest biomes.

- Beyond 1.5°C of warming – the limit enshrined in the Paris Agreement – we risk triggering tipping points and regime shifts. These could become widespread around 3.5°C which would irrevocably degrade and even destroy boreal and temperate forests.

- In boreal forests, drought has already led to increased tree mortality in the last two decades. Globally, 30% of tree species are currently at risk of extinction due to different factors. Increased drought impacts from climate change could contribute to the extinction of boreal tree species.

- The frequency and extent of forest fires have been higher in recent years than in any time in the last 10,000 years. More frequent and severe fires are contributing to postfire recovery failure, increased carbon emissions, decreased carbon sink potential and incomplete re-sequestration of carbon in the subsequent growing seasons. Boreal forest fires release 10 to 20 times the carbon emissions per unit of area burned compared to grassland ecosystems.

- Insect outbreaks have been increasing in severity, range, and duration in the past few decades. Warmer climates, longer growing seasons, weakened tree defences following drought or wildfire occurrences support insect development and reduce pest mortality. Acute outbreaks have been recorded across the northern forest regions and have led to large-scale tree mortality events. From bark beetle outbreaks alone, around 14.5 million cubic metres of European forests have been damaged every year from 2000 to 2010. Highly homogenous forests are at higher risks of insect outbreaks and damages, making plantations or managed forests more vulnerable than old-growth forests.

- As temperatures rise, northern forests are expanding northward into new territories, and are experiencing dieback events along their southern-most borders. However, warming impacts are outpacing forest advance, threatening any carbon sequestration potential of the northwards expansion.

- Crossing tipping points within boreal forests will have consequences for the global climate. Both the northward expansion and the southward contraction of forests change the Earth's land surface albedo (how the Earth's surface reflects or absorbs light from the sun) but ultimately the combined effect diminishes the important function of these forests as carbon sinks. This could lead to northern forests becoming a considerable carbon source.

Given the important ecosystem services that northern forests provide and their role as an integral carbon sink in efforts to limit warming to 1.5°C, northern forests warrant urgent and effective forest conservation. Forest clearing from human activities remains the number one threat to these precious ecosystems. With the scale and severity of the climate impacts that these forests are facing today, more needs to be done to adapt our forestry and conservation practices to ensure these forests do not experience irrevocable harm. When developing restorative and regenerative forestry practices, much can be learned from indigenous knowledge.

The forests best-equipped to withstand climate impacts are those with high structural diversity – such as old-growth stands. These old stands also deliver enhanced multifunctionality and provide the most ecosystem services. While trade-offs between ecosystem service provision will have to be made, the conservation of the remaining old-growth forests should be made a priority.

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Northern forest definition and typology

This report looks at northern forests, defined here as boreal and temperate forests of the northern hemisphere. Northern forests are home to a wide array of biomes. These are defined by their environmental conditions and ecosystem structures and distributed according to climatic conditions.[1] The different forest biomes found in the Northern Hemisphere are shown in Figure 1, which include the boreal forest, temperate coniferous forest, temperate broad-leaf and mixed forest, and Mediterranean forest considered here.

Distribution of forest biomes in the Northern Hemisphere

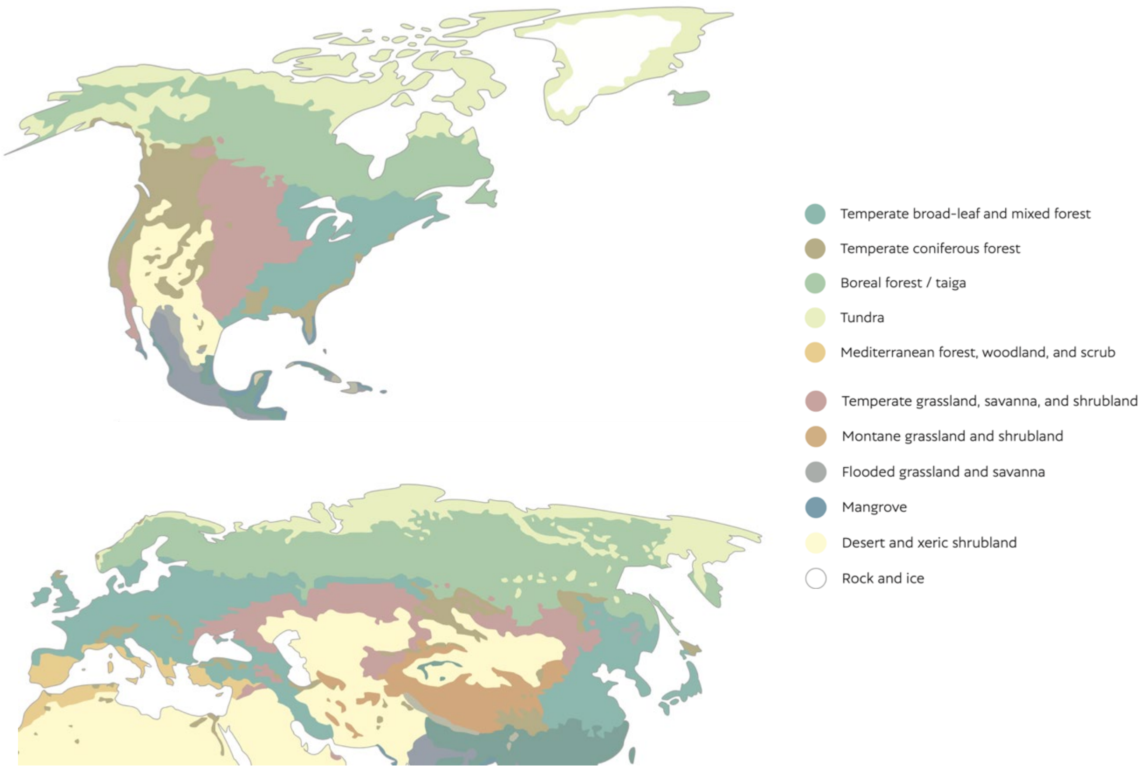

Figure 1: The distribution of forest biomes in the northern hemisphere. The northern forests covered in this report include the boreal forest in dark green, temperate coniferous forests in brown, temperate broad-leaf and mixed forest in turquoise, and Mediterranean forests in orange.[1]

Boreal forests

Boreal forests span from 50° N latitude to just below the Arctic and are defined by average July temperatures of 13°C on the northern border and 18°C on the southern border.[2, 3] Covering 14 million km^2 and accounting for about 25% of forests globally, boreal forests constitute the second largest terrestrial biome in the world.[4,5] Around 24% of the world's tree species exist in boreal forests.[4]

Other characteristics of the boreal forest region are its long, cold winters lasting at least six months with temperature differences between the yearly maximum in summer and minimum in winter reaching up to 56°C.[1] The region receives limited precipitation of 300-900mm per year, mainly in the form of snow.

Boreal forests are largely made up of evergreen conifers such as pine, fir, and spruce. Their distribution varies regionally. For example, in the Russian boreal region, the northern most trees are deciduous needle-leaved larches. Shedding their leaves in winter allows the trees to withstand extreme temperatures down to -70°C.[1] Fennoscandian boreal forests are dominated by Norway spruce and Scots pine, which have also been favoured in forest management. However, the northern tree line is made up of birches.[1,6] In North America, 60% of boreal forests are black spruce forests.[7]

Overall boreal tree diversity is low compared to temperate forest systems, with 14-15 tree species dominating locally.[1] These forests have low net primary production (the remaining energy after respiration that is available for growth and reproduction), of which half is performed by understory vegetation.[8]

Generally, the boreal forest belt consists of a southern part of managed forest and a northern, shrinking part of primary, unmanaged forest, where natural disturbance regimes still prevail.[9]

Temperate forests

Northern hemisphere temperate forests can be broadly grouped into coniferous, temperate broad-leaf and mixed, and Mediterranean forests. They inhabit a wide array of climatic zones and are characterised by the occurrence of seasonal frost.[1] Around 22% of global trees are found in temperate biomes.[4] In the temperate zone, generally very little primary forest remains (see Box below).

The region's wide range of temperatures and rainfall vary from -30°C in winter to 30°C in summer. Precipitation varies between 750-1300mm per year.[8]

Temperate coniferous forests are found in the mountainous regions of Europe, North America, and China, with smaller sized coniferous forests in Korea and Japan. They cover an area of approximately 2.4 million km^2.[10]

Temperate conifers grow in regions with a minimum of 250mm annual precipitation and while they can withstand freezing conditions, they are not adapted to temperatures below -45°C. These regions include some of the largest trees on Earth, such as the coastal redwood trees that can reach more than 100m in height. The most important tree species in coniferous forests include pines, firs, spruces, hemlocks, larches, cypresses, cedars, and junipers. Pines alone have more than 90 species.[10]

One of the most iconic temperate coniferous forests is the Northeast Pacific coastal temperate rainforest, which spreads over more than 2000km along the North American West Coast, starting in south-central Alaska and into Northern California, through British Columbia. The region is characterised by cool summers, with annual air temperatures averaging from 5.6°C in the north to 11.6°C in the south. High precipitation can surpass 5000m per year and constitutes some of the highest annual precipitation in North America.[11]

These forests consist of large and long-lived conifers, abundant peatlands, and deep soils. The Northeast Pacific temperate rainforest can be divided into four subregions by its climatology. From north to south these are the sub-polar, perhumid (wet climates with permanent high humidity), seasonal, and warm or coastal redwood subregions. Around 92% of the temperate rainforest region is covered by the perhumid and seasonal forests. The perhumid regions experience wetter and cooler climates — with more snow and ice — compared to the southern regions. The seasonal subregion has a warmer, drier climate.[11]

The **temperate broad-leaf and mixed forests** of the Northern Hemisphere can be divided into five ecoregions, Europe, eastern North America, the Pacific Northwest, and east and west Asia.[1]

These forests grow in climates with warm summers and cold winters and experience the majority of precipitation in summer, during their growing season. All ecoregions share a common origin and therefore share many genera of trees such as maples, oaks, beeches, chestnuts, birches, ashes, and elms. Throughout the region beech and maple dominate colder environments, while oaks are increasingly found in warmer and drier ones.[1]

The forests of Central Europe are an example for broad-leaf and mixed temperate forest biomes. The region experiences both its highest temperature and highest precipitation during the summer months. Two highly important species for the area are the European beech trees and the Norwegian spruce. In Germany for example, spruce dominates 47% of all conifer stands and beech grows in 36% of broadleaf stands.[12]

Another temperate deciduous and mixed forest biome is located in northeast Asia. The forests, spanning through China, Russia, Japan, and Korea are characterised by broadleaved species such as oak and Korean pine. The area, in common with boreal and temperate forest has four distinct seasons with seasonal variations in temperature and precipitation. Heavy precipitation can be observed during the summer monsoon and there is low precipitation in winter.[13] These forests can range from coastal areas to mountain ranges of 2000m altitude.[14]

Mediterranean forests are characterised by Mediterranean climates. Mean annual temperature ranges from 6.5-12.7°C, with temperature extremes in summer. The mean annual precipitation is between 355-1160mm and highest precipitation rates are observed in winter. The area is home to both conifer and broadleaf trees with Scots Pine and Holm Oaks as dominant species.[15]

Northern forest management

There are fundamental differences between remaining primary forests and managed forests and their distribution across boreal and temperate zones.

High intensity wood harvesting is currently the biggest threat to northern forests. While this report focuses on the changes driven by climate change and their impacts on northern forests, it is important to note that many of these impacts also occur due to or are exacerbated by industrial logging practices.[16–18] Logging also affects forest resilience — a measure of an ecosystem's ability to adapt to emergent disturbances and covers multiple mechanisms, as well as forest recovery, persistence and reorganisation.[19,20]

Very few primary forests are left. While being sparsely populated, about two-thirds of boreal forests are under some form of management.[9] Overall up to 80% of global forest ecosystems have been altered by anthropogenic interaction.[23] The global cover of intact forest landscapes was estimated at 12.8 million km^2 in 2000. That equals 22% of all forest landscapes. Nearly half of global intact forest landscapes are found in Russia, Canada, and the USA (mainly Alaska) and therefore within the northern forest region.[22]

Terms

Primary forest refers to forests that have been left to develop through natural disturbances and processes. It has never been logged or otherwise altered by human interference. The only exception is presented by indigenous stewardship.[21]

Intact forest landscapes (IFL) are defined as ecosystems that show no remotely detectable sign of human activity and have a minimum area of 500 km^2. These landscapes include primary forests as well as intact ecosystems that are treeless due to climatic, soil, or hydrological conditions, treeless areas after natural disturbance, and areas influenced by low-intensity, historic anthropogenic influence.[22]

Secondary forests have been altered by logging practices or agriculture and grazing activities and gone through recovery processes either naturally or artificially.[21]

When it comes to intact forest landscapes, temperate forests contain the smallest amounts of any northern forest type, with many European countries having none left (see Figure 2). The area of intact forest landscapes globally continues to decline, with boreal forest declining at an increasing rate. While the biggest relative loss of intact forest area occurred in Romania — which lost all its intact forests over 2000-2013 — the absolute loss has been higher in Canada and Russia, which lost 142,000 km^2 (4.7%) and 179,000 km^2 (6.5%) of their intact forests respectively.[22]

Extent of forest ecosystems and intact forest landscapes

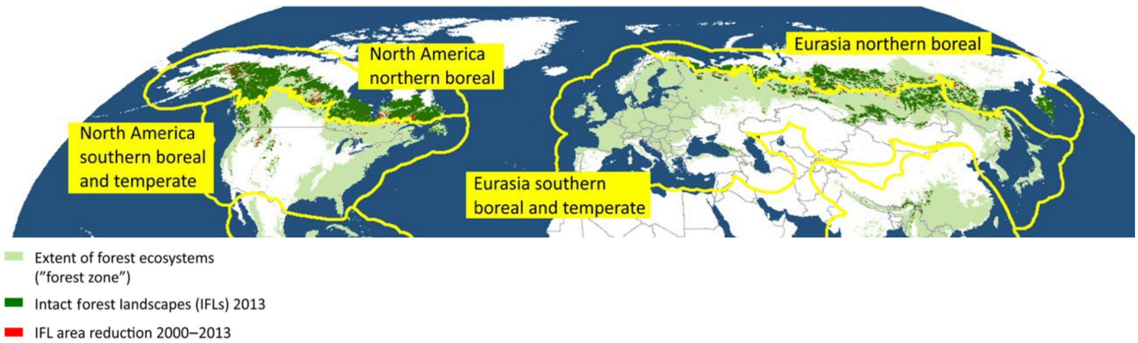

Figure 2: The extent of forest ecosystems and intact forest landscapes of northern forests. The extent of forest ecosystems is shown in light green with intact forest landscape area in 2013 marked in dark green. The reduction of intact forest landscape area for the period 2000-2013 is shown in red.[22]

The shift to high intensity logging practices involving clear-cutting and short rotation cycles has often left forest biomes vulnerable to disturbances by significantly altering the functions and interactions between organisms and the environment. This can affect the proportion and spatial distribution of trees of different age classes and of different forest species, the dynamics of forest species at different heights, availability of deadwood, the quality of soil properties, and site productivity.[18,24]

Most boreal forests have been under intensive management, mainly for timber production. Boreal forests contribute 33% of lumber and 25% of paper products to the global market. The region’s forestry approach has led to simplified forest structures. This increases their vulnerability as homogeneous forest systems are particularly susceptible to the impacts of climate change, pollution, and fragmentation.[9]

Wood harvest has been unsustainably high throughout the boreal forest region over the last decades, in countries including Russia, Canada, Sweden, and Finland. These country-level examples show similarities that are both striking and alarming.

In Russia, for instance, the current forest management model of mainly clearcutting mature forests and leaving the areas for natural regeneration could deplete forest resources.[25]

In boreal Canada, wood harvest has significantly increased compared to 50 years ago. Logging activities have caused the collapse of woodland caribou populations through the decline of primary forests, reductions in age-class distributions, changes in dominant tree species, forest homogenisation, landscape fragmentation, and loss of deadwood availability.[5]

Swedish forest policy has historically focused on wood production and the economic potential of sustainability. While in recent years efforts have been made to include environmental, social, and cultural considerations, weak implementation mechanisms support business as usual.[26]

In both Sweden and Finland, intensive forest management focused on timber production has decreased the forest’s habitat quality and connectivity. Landscapes of young and structurally simplified forests are faced with considerable challenges and vulnerabilities. One of the biggest concerns is posed by biodiversity loss.[5]

In Finland, for example, 816 forest species are currently endangered and 31% of all threatened species have forests as their primary habitat. For most of these species the primary driver of mortality is the change of forest habitat. In Sweden, more than 50% of threatened species are connected to forest habitats, with 43% dependent on forests and 1400 species directly threatened by the clear-cutting of forests.[5]

The role of northern forests in the climate system and the carbon cycle

Northern forests play a significant role in the climate system. Forests store carbon in above- and below ground biomass. *Figure 3* shows biomass distributions across the Northern Hemisphere, a measure for a region's carbon stock representing the balance between carbon accumulation through growth and carbon loss through decay and combustion.[27]

Above and below ground living biomass densities

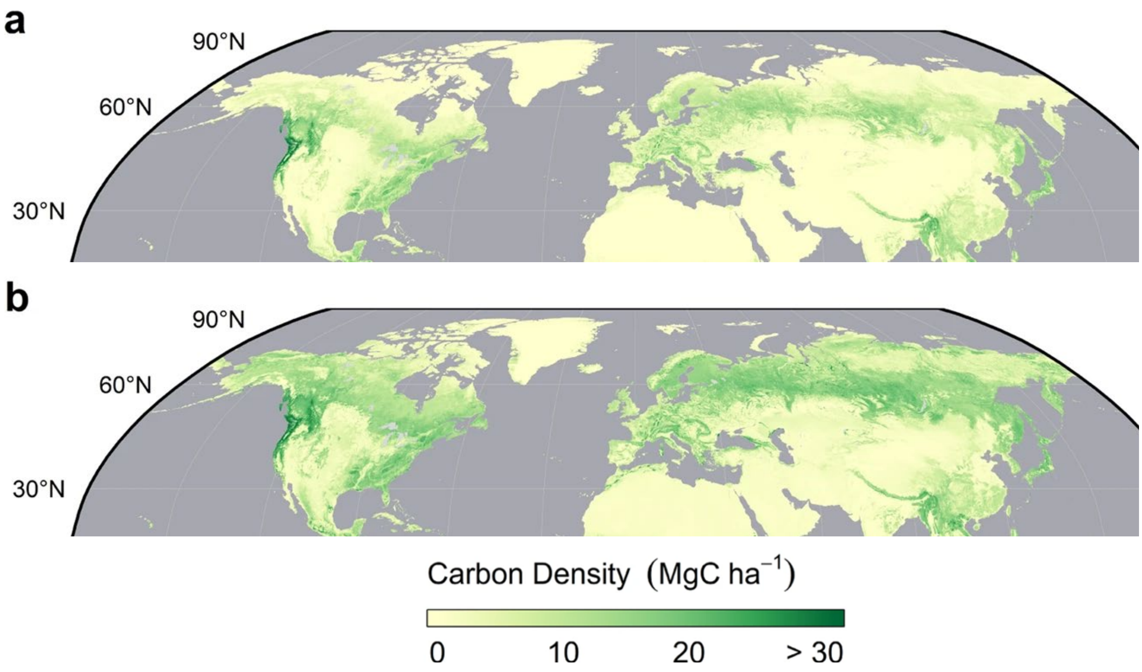

Figure 3: The above ground (panel a) and below ground (panel b) living biomass carbon densities at 5 km spatial resolution in the Northern Hemisphere. Carbon density is depicted in a colour bar ranging from light to dark green and given in units of MgC per hectare which is equivalent to tC per hectare.[27]

Carbon sink, source, stock and flux[29,30]

Carbon sinks refer to processes, activities or mechanisms that remove carbon from the atmosphere. This includes for example primary production from plant photosynthesis. It is measured in gigatonnes of carbon (GtC) per year. The process of storing carbon is also referred to as carbon sequestration.

Carbon sources describe processes or activities that release carbon into the atmosphere. An example of a carbon source in forests is plant autotrophic respiration which is part of the natural carbon cycle or logging forests. Similar to sinks it is measured in GtC per year.

Stocks are the quantity of carbon found in a carbon pool and are usually quantified in GtC. This includes, for example, carbon stored in living biomass such as trees, in dead wood and litter, or in soil.

Carbon fluxes describe the exchange of carbon from one pool to another. In the case of forest ecosystems, these processes include carbon fixation, allocation and plant metabolism and is measured in GtC per area per year.

The assessment of carbon sinks, sources, stocks and fluxes is highly dependent on the methods used and can therefore vary significantly between studies.

Table 1 shows the carbon stocks in the regions of northern forests. The FAO regions coinciding with our definition of northern forests include Europe, Western and Central Asia, East Asia, and North America.

The northern forest region holds 54% of the world's total carbon stock. Europe (including the entirety of Russia as per the FAO division) as well as North America hold around a quarter of the global carbon stock each. Compared to worldwide stocks, northern forests store larger amounts of carbon in soil.[31]

This storage function is particularly vulnerable to high intensity logging practices, including clear-cutting. Research has shown that logging leads to a long-term decline of soil organic carbon.[32]

Total carbon stock and soil carbon stock in northern forest regions

Region	Total carbon stock [GtC]	Total carbon stock [%]	Carbon in soil [% of total carbon]
Europe, Russia	172.442	26	58
Western and Central Asia	5.358	1	48
East Asia	37.907	6	56
North America	139.951	21	50
World	662.088	100	45

Table 1: Showing total carbon stock in GtC and percent of global carbon stock for the FAO regions coinciding with northern forests. Soil carbon stock is shown as percent of total carbon stock.[31]

The boreal region is home to a significant carbon stock and an extensive soil organic matter pool.[33] Most of the forest's carbon is stored in the region's soils, rather than the above-ground vegetation, with estimates of the proportion of soil carbon ranging from 70-80% to up to 95% of the total boreal carbon stock.[34]

Within the boreal region, the largest carbon stocks are situated in **Russia**, which contains 60% of the boreal forests globally.[3] However, due to inconsistencies in the state forest registry, use of different reporting methods and sparse sampling, the size of these stocks might be significantly underestimated. Using remote sensing in combination with National Forest Inventory data, the carbon stock of living tree biomass alone has been found to be up to 47% higher than reported.[35]

In addition to being a major store of carbon, the northern forest, in particular the boreal forests, is one of the larger contributors to the net terrestrial sink of carbon in forests at the global scale.

This sink plays a significant role in reducing the effects of CO_2 emissions.[36] If it weakens to the point where there is a release of carbon from soils and trees, this would make the task of limiting warming to 1.5°C significantly harder, and could lead to an amplification of global warming (see tipping point section).

Plant carbon dynamics

The incorporation of carbon into plant matter through photosynthesis is referred to as gross primary production. This carbon is rereleased through plant respiration, decomposition, and disturbance. The plant carbon uptake minus respiration is referred to as net primary production. Accounting for decomposition leads to the measure of net ecosystem production. The long-term carbon storage is described by the net biome production and also takes into account disturbance. [37]

Carbon budget of terrestrial ecosystems

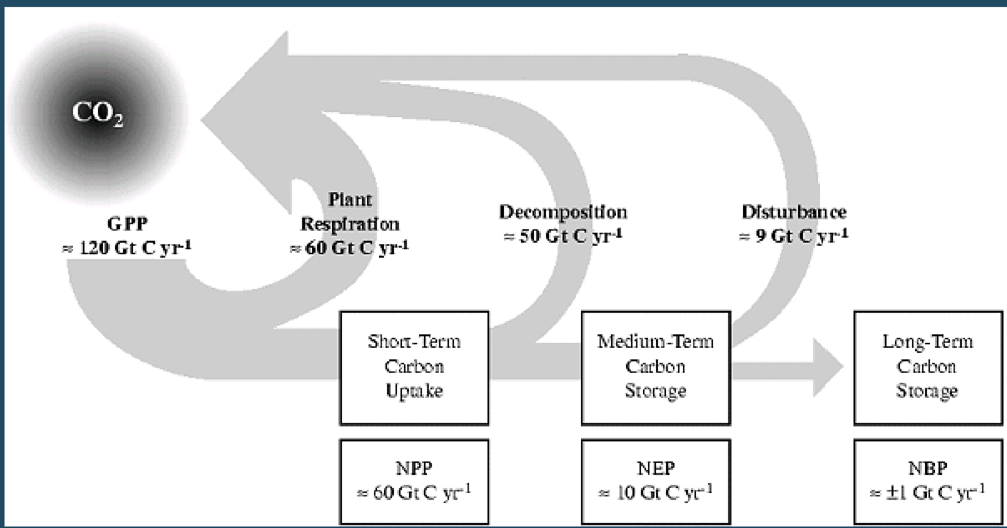

Figure 4: The relationship between gross primary production (GPP), net primary production (NPP), net ecosystem production (NEP), and net biome production (NBP) and how it affects the terrestrial carbon cycle. Decomposition includes heteroptrophic respiration of litter and soils, disturbance includes both natural and anthropogenic sources.[37]

In the high latitudes, plant photosynthesis is thermally limited and only a small portion of photosynthesised carbon can be attributed to aboveground tree growth.[38] Global warming and increasing CO_2 concentrations have already started influencing carbon sink dynamics and have been enhancing carbon uptake in the northern high latitudes.[39] A mixture of CO_2 fertilisation due to elevated atmospheric CO_2 concentration driven by anthropogenic CO_2 emissions and increased growing season temperatures have led to an observed acceleration of carbon uptake during the growing season from May to August at similar rates across the northern high latitudes.[40]

However, the benefit of increased photosynthetic activity due to temperature and CO_2 increases is diminished by the fact that climate change also increases carbon loss from respiration in the late growing season. Respiration rates and respiratory carbon loss are largely controlled by early growing season productivity and expand significantly with tree cover.[40]

The accelerated rates of net carbon release between September and October show a spatial variation with the highest increases observed in areas of high tree cover in the southern boreal biomes.[40] The potential increase of carbon storage due to increased plant photosynthesis is limited.[41,42]

The observed increase in carbon uptake through primary production is further counteracted by higher decomposition rates under warmer conditions. Faster microbial growth, metabolism and respiration, increased enzymatic activity, and priming of soil nutrient pools have led to accelerated carbon releases.[8] On top of these processes, wildfires are also driving increased carbon loss in boreal forests.[43]

Looking into the regional distribution of northern forest carbon sinks, boreal forests alone account for around 30% of the terrestrial carbon sink.[40] The overall boreal forest area constitutes the largest carbon sink in the northern forest region.[28]

For example, a large forest carbon sink is found in **Eastern Europe** (including what is defined as European Russia), making up around 65% of the total European carbon sink. This region includes both boreal forests and temperate deciduous and mixed forests. Between 2010-2019 the region's annual carbon uptake was around 0.45GtC per year which is almost three times higher than the respective uptake by the northern, western, and southern European biomes together. The region's carbon sequestration hotspots are situated in the Southern Ural Mountains and on the border region between Russia, Belarus, and Ukraine. The border region has seen large carbon uptakes due to agricultural land abandonment and resulting forest restoration.[45]

However, over the past decade, rates of carbon sequestration as a result of agricultural land abandonment have declined, while emissions from logging and agricultural expansion have increased. This has led to the decline of the annual net land carbon sink in Eastern Europe. The greatest declines were recorded in the Czech Republic, Ukraine, and Poland.[45]

The declining trend of carbon uptake in Eastern Europe can further be attributed to climate-driven natural disturbances. After a strong heatwave in 2010, the forests of European Russia showed much lower carbon uptake compared to the regional average. The rise in forest fires, more frequent temperature extremes, and days without precipitation have further contributed to this trend.[45]

A study on the Siberian carbon sink has found substantial losses in live biomass and above-ground carbon attributed to fire and drought.[45] This trend has also been seen in other parts of the boreal biome, including Alaska and Canada.[11,47] These impacts are further discussed in the next sections.

As for the temperate northern forests, the **Northeast Pacific** coastal temperate forests store more than 1000 tC per hectare when below and aboveground carbon stores are combined, making it one of the world's most significant carbon storehouses given its area. The size of the forests' aboveground carbon store increases from north to south and is high compared to both tropical and boreal biomes.

Similar to many other parts of the boreal forest zone, the perhumid region (a subregion of the Northeast Pacific coastal temperate forest) has young, poorly drained soils and a large proportion of wetlands, which store large below-ground carbon stocks. The seasonal region of the Northeast Pacific coastal temperate rainforest has well-developed and drained soils, and harbours higher aboveground carbon stocks. Aboveground storage in the southern seasonal forests can reach 685 tC per hectare while belowground storage is largest in tidal forested wetlands where it can reach up to 822 tC per hectare.

Cool temperatures and persistently saturated soils constitute unfavourable conditions for decomposition, leading to the significant accumulation of soil carbon. The region's carbon stores have been stable over several decades, largely due to the historic scarcity of large disturbances. Its stability is threatened by projected increases in disturbances due to climate change.[11]

In the **Mediterranean** part of northern forests, the Mediterranean forests are heavily utilised, with only few intact ecosystems remaining. Carbon sequestration analysis in Italy has quantified the yearly sequestration of the Mediterranean shrublands at 22 tC per hectare. The analysis further showed that large shrubs sequestered the highest amount of carbon according to their volume and leaf area indices.[48]

Observed and projected climate change in northern forests

The increase of land surface air temperature has been considerably higher than the global mean surface temperature rise. Land surfaces have warmed 1.65°C (1.36-1.90°C) by 2013-2022 compared to 1850-1900 while global mean surface temperature reached 1.15°C of warming.[49] This trend is more pronounced in the northern high latitudes with large regional differences in physical climate change (see Figure 5).

Here we describe some of the key past and projected changes for Europe, North America, and Asia from climate change, focussing on changes in temperature and precipitation.

Observed mean temperature trends

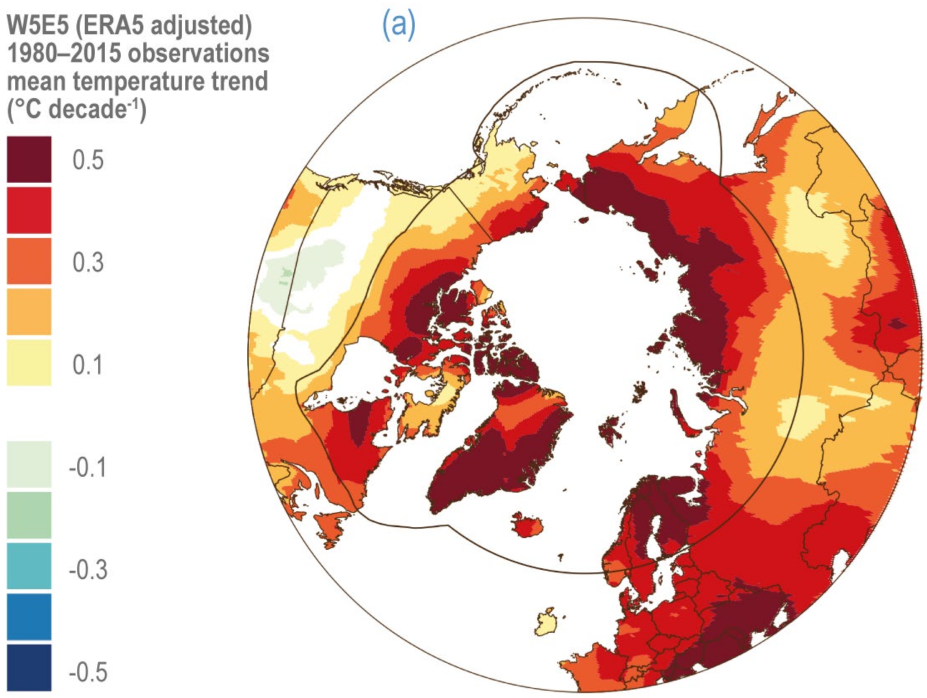

Figure 5: The observed mean temperature trend between 1980-2015. Trends are shown as decadal warming in °C per decade. It clearly shows the arctic amplification with highest decadal warming rates in the high latitudes.[50]

Due to the above average warming of land masses and high latitudes, northern forest regions are warming much faster than the global average and will experience amplified warming in the future (see Figure 6).

Figure 6 shows the projected temperature trends at global warming levels of 1.5°C (Paris Agreement compatible), 2°C, 3°C (what current policies are steering towards), and 4°C. [51]

At 1.5°C of global warming, the annual mean surface temperature across northern forests reaches around 2°C and the Arctic is projected to warm by 3°C. At 4°C global warming, the Arctic is even projected to experience a 2.4-fold temperature increase, which would translate into a staggering increase of 9.6°C in annual mean surface temperature relative to pre-industrial times. On average, the entire region is projected to experience around 6°C of warming under a very high emissions scenario leading to around 4°C of global warming. In line with the average temperature increase, the magnitude and frequency of heat extremes are projected to increase as well.[52]

The average temperature will further affect regional water cycles. Precipitation, evapotranspiration, and river discharge are projected to intensify across the northern hemisphere and especially in the high latitudes. Snow cover, an important factor for arctic biodiversity, will decrease under all scenarios. Seasonal snow cover is projected to decrease by 8% with every degree of warming.[34] The decrease across the Arctic for example can be limited to a 5-10% decrease in snow cover duration (compared to 1986–2005) under a low emissions scenario keeping warming to below 2°C. Under a very high emissions scenario of up to 4°C global warming, snow cover duration will decline by 15-25% until 2100.[53]

Projected mean temperature trends

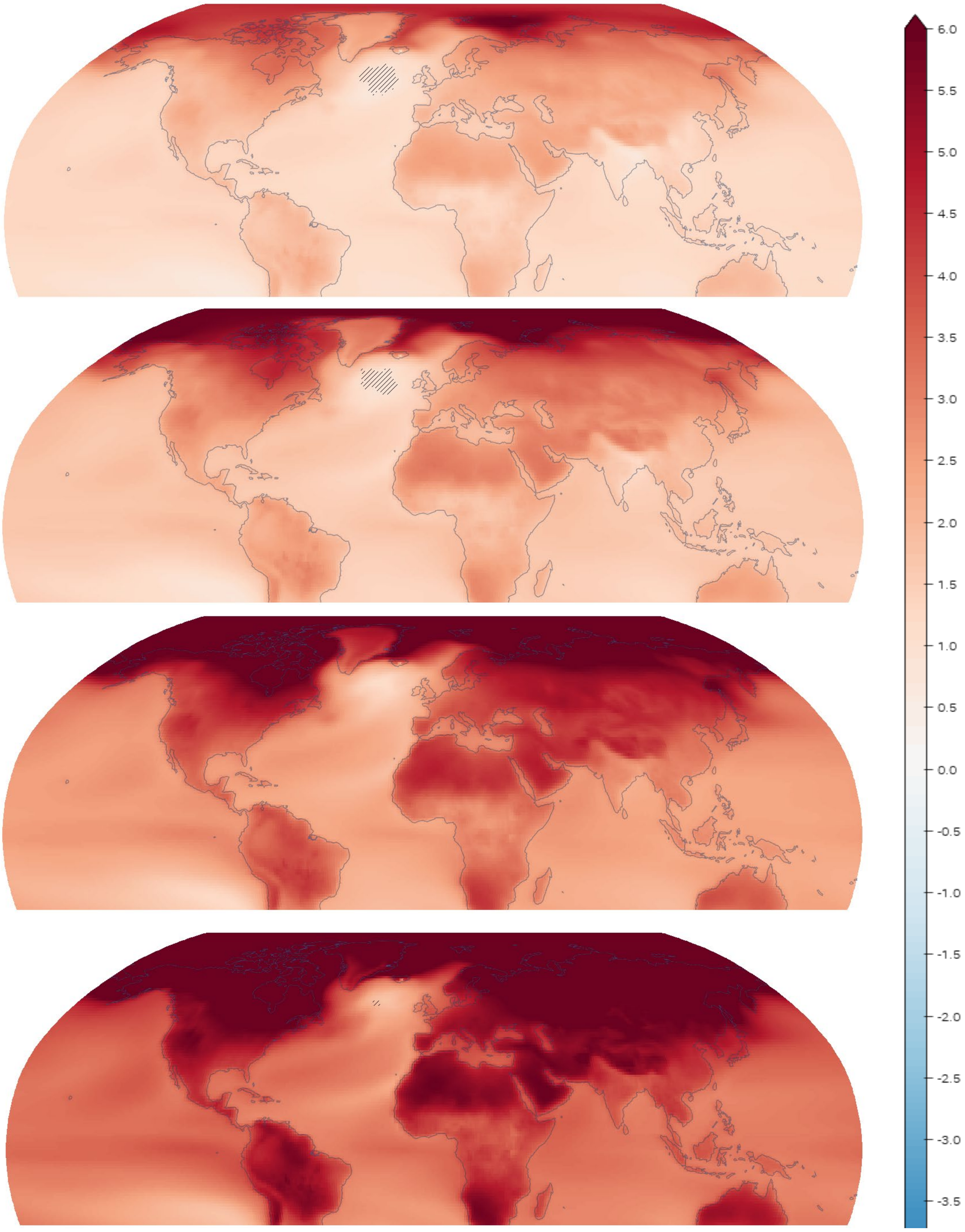

Figure 6: Regional distribution of projected warming in °C at (from top to bottom) 1.5°C, 2°C, 3°C, and 4°C of global warming using SSP5-8.5 relative to the reference period 1850-1900.[54]

Europe

Emerging climate change in Europe since 1950 includes increasing mean and maximum temperatures, frequency of warm days and nights, and heatwaves. Temperature increases have reached rates of up to 1°C per decade between 1980-2015 in some higher latitudes and mountain regions. In all European regions, temperatures have consistently increased by 0.04 - 0.05 °C per year.[55]

Precipitation has been increasing over most parts of Europe and precipitation extremes have increased over Northern and Eastern Europe. Lake and river ice has decreased in Northern, Western-central and Mediterranean Europe.

Annual mean temperature rise over Europe will be larger than the global average. The largest winter warming will be observed in Northern and Eastern Europe, while the Mediterranean region will experience the largest summer warming. Climate change will lead to an increase in hot days and a decrease in cold days. Both ice glacier volume and snow cover will be substantially reduced. Global warming of more than 2°C would also lead to widespread increases in precipitation extremes.[56]

Mediterranean Europe has already warmed by 1.5°C compared to pre-industrial levels. This has led to increases in intensity, number and length of high-temperature extremes and more frequent and intense droughts, particularly in summer. These extremes are further projected to increase. Precipitation is predicted to decline by 4-22% and rainfall extremes will likely increase in the northern Mediterranean. Mediterranean tropical cyclones are projected to decrease in frequency while simultaneously increasing in intensity.[57]

North America

Over North America, mean annual temperatures have been, and are projected to continue, increasing. In near-Arctic latitudes of North America this warming has been specifically pronounced at rates of around 0.5°C per decade (see also Figure 4).[55] This is accompanied by decreasing snowpack and snow extent over Canada and the western US. Lake ice in Canada, south of the Arctic region, and glaciers over all of North America have similarly declined. Annual precipitation has also decreased across western North America.

Projections predict continued increase in intense heatwaves, humidity-inclusive heat stress, diminished snowpack, extreme precipitation, and more intense storms.[58] In the Northeast Pacific coastal temperate rainforest, the climate crisis is changing the hydroclimatology.[11] Temperature increases are leading to glacier recession which could eventually result in a decline of glacial runoff. Cold season precipitation is increasingly characterised by rain instead of snow, accelerating the decline of seasonal snow-cover. Water levels during summer and early autumn will decrease and summer droughts are estimated to increase throughout the region.[11]

Asia

East Asia has seen increasing annual mean temperatures since the 1950s, with warming trends in most areas surpassing 0.1°C per decade. The strongest warming of 0.3-0.4°C per decade has been observed in northern China. These temperature trends are projected to continue to increase under all scenarios.

For precipitation, both increases and decreases have been observed with significant regional differences. Observed increases over north-west China and South Korea are projected to continue due to the estimated strengthening of summer monsoon circulation.

In North Asia, annual mean temperature has increased by up to 1.2°C per decade in 1976-2014 and is projected to further increase at rates higher than the global average. Annual precipitation has similarly increased by 5-15mm per decade over the region and is projected to continue this trend. Kamchatka and the Chukchi peninsula constitute exceptions where precipitation has decreased by up to 20mm per decade. Over Siberia, snow cover duration has decreased.[59]

Climate impacts in northern forests

As climate change intensifies, its impacts on forests, including northern forests, are becoming ever more apparent. This underscores the importance of limiting global warming in line with the Paris Agreement and increasing forest resilience. It further highlights the urgent need for northern forest conservation due to their crucial role in the Earth and climate system (see also last chapter). Climate change in northern forests is primarily leading to habitat and biodiversity loss, droughts, fires, pests, and vegetation shifts. None of these impacts occur in isolation and most can further exacerbate each other, amplifying the risks.

This manifests as forests becoming more flammable following drought events, increasing the frequency and severity of fires. Similarly, stands affected by insect pests develop more flammable fuel, again increasing the potential of forest fires. After large mortality events induced by drought, fire, or windfall, forests will have a larger ratio of dead trees, which can likewise lead to the spread and intensity of insect outbreaks.[5]

The record-breaking 2023 wildfire season in Canada demonstrates how these disturbances can interact. One fire in northern Quebec alone spread over an area of more than 1.2 million hectares making it one of the ten biggest fires in Canada since 1950.

These fire extremes followed unusually hot and dry conditions in May-June of 2023. In addition to the heat and low humidity, the fire season was worsened by low precipitation, a combination that is also known to affect the resilience of boreal forests. Climate change made the cumulative severity of Québec's 2023 fire season to the end of July around 50% more intense. The occurrence of a similarly severe fire season has become seven-times more likely. [60,61]

These interactions also negatively affect the stability of soil carbon stocks. Summer droughts in combination with subsequent increased fire prevalence could push forest ecosystems from carbon sinks to sources. Increases in disturbances caused by climate change heighten the risk of forests surpassing ecological thresholds and tipping points.[5]

Habitat and biodiversity loss

Changes in climatic conditions across the northern forest region has already led to habitat and biodiversity loss. With every degree of warming, these losses will worsen (see Figure *7, 8*).

Compared to today's levels, 1.5°C of global warming would result in very high habitat losses for eastern Russia, (particularly the Siberian boreal forests) and high habitat losses for large parts of North America (including boreal forest areas and the North West Pacific temperate rainforest).

At 2°C of global warming, we will start to see some of our northern forests experience up to 50% of biodiversity loss compared to under 25% at 1.5°C of global warming (Figure 8).

At 3°C of global warming (which current projections indicate is likely under current policies)[51], almost all of the northern forest area will be at risk of very high habitat losses and more than 50% of biodiversity loss.

Present and projected habitat losses

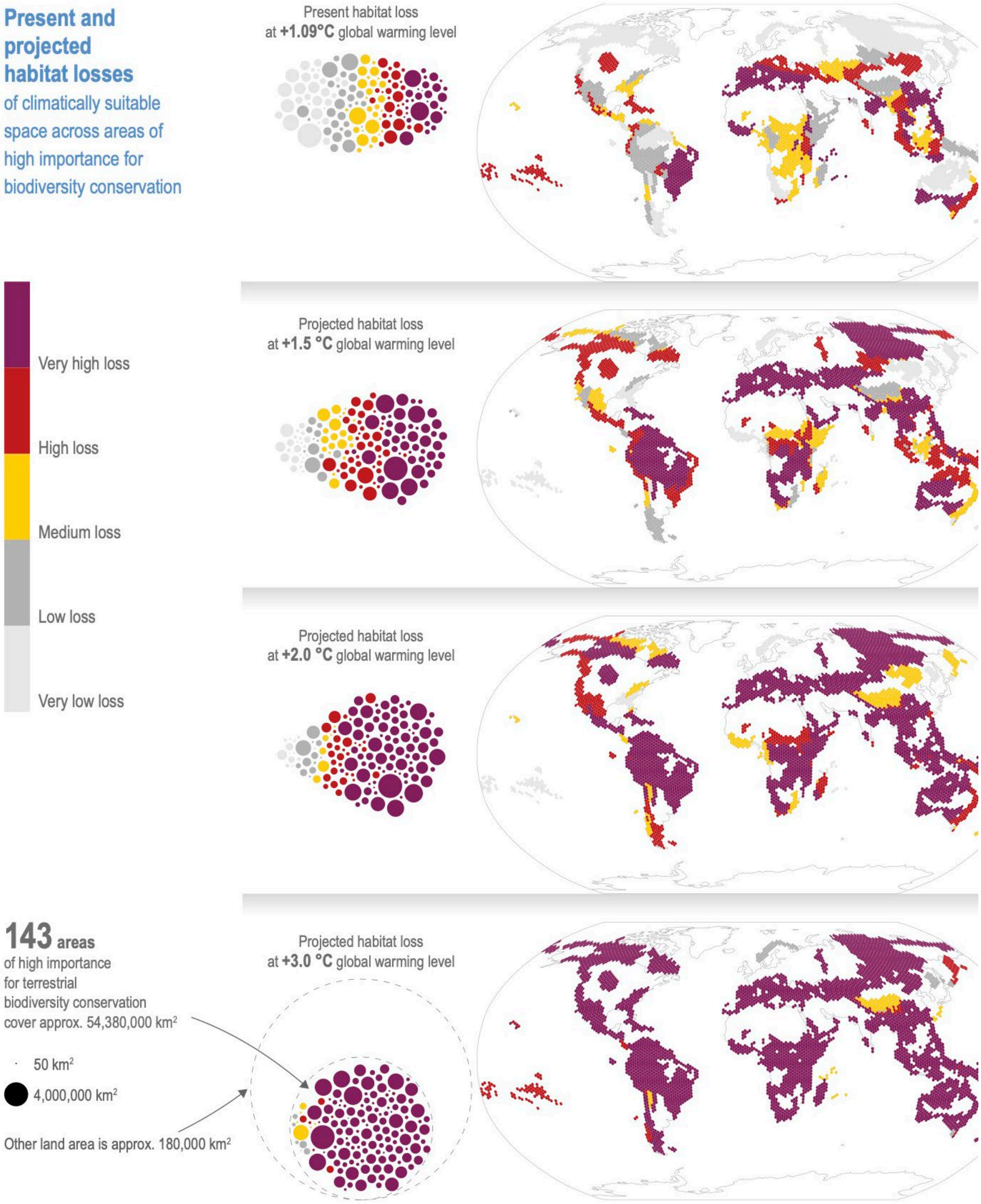

Figure 7: Present and projected habitat losses of climatically suitable area shown for 1.09°C, 1.5°C, 2°C, and 3°C of global warming. Five categories of loss are distinguished: very low loss 0-20%, low loss 20-40%, medium loss 40-60%, high loss 60-80%, very high loss 80-100%. Circle clusters show losses in the five categories of 143 areas of high importance for biodiversity conservation. The individual circles are scaled to size.[54]

Projected loss of terrestrial and freshwater biodiversity

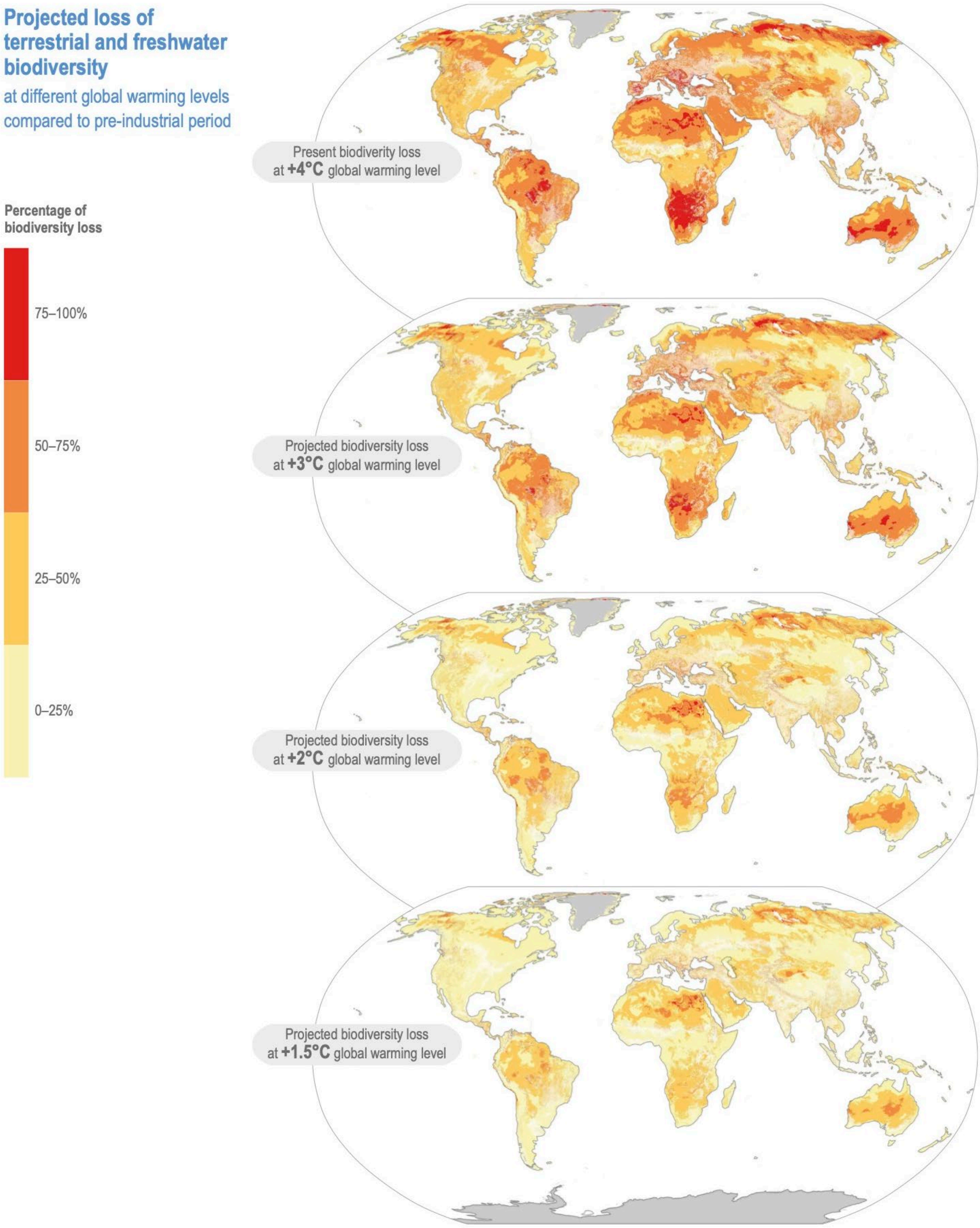

Figure 8: Projected loss of terrestrial and freshwater biodiversity shown for 1.5°C, 2°C, 3°C, and 4°C of global warming. Indicating the proportion of species whose current habitat will become unsuitable due to climate change in intervals of 25%.[54]

Drought

Many northern forest regions have already experienced droughts. In boreal forests this has led to increased tree mortality in several regions over the last two decades and drought-induced mortality is projected to increase further with increased warming.

The sensitivity of forests to drought events depends on the intensity and frequency of droughts, and the tolerance of tree species. Droughts can result in forest mortality and decreasing forest structural complexity. Between 1.5°C and 3°C of warming, risks from droughts increase simultaneously with water stress, heat related events, and habitat degradation.[62]

Tree mortality is not only triggered by high-intensity drought. Frequent low-intensity dry conditions can also incite 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.[63]

Globally, 30% of tree species are currently at risk of extinction — mainly due to habitat loss, exploitation for products, and invasive pests and diseases. Climate change also has a measurable impact.[64] The observed increase in drought in combination with warming might contribute to the extinction of boreal tree species.[8] We are already seeing the effects in western Canada, where forests dominated by drought-intolerant aspen have experienced diebacks equivalent to postfire mortality levels.[5]

Remaining forests will see a decrease in net primary production, soil carbon content and microbial biomass. This threatens the function of forests as carbon sinks, which is particularly concerning.

Soil health is also at serious risk. Despite the overall intensification of regional water cycles, boreal soils risk being exposed to further drying due to snow and permafrost decline. The decline of snow cover will accelerate the extinction rates of vascular plants, including conifers, ferns, moss and lichen by up to 32% for Arctic alpine species, and 12% for boreal species by 2050 for all warming rates.[50]

Many specialised bacteria are sensitive to droughts, and persistent water limitations will lead to changes in microbial communities. In turn, this leads to the decline of ecosystem processes, such as nitrification. The decomposition of forest organic matter will decrease, due to a reduction of microbial abundance and enzyme activity, as well as changes in fungi composition in deadwood systems. This will lead to an increase in carbon storage, but will be outweighed by the drought-induced decrease in net primary production.[8]

Case study on the impacts of drought in Europe

After the 2018-19 drought in Germany, there was high forest mortality in Norwegian spruce and European beech trees.

Water availability and drought conditions during the growing season strongly controlled the growth of both beech and spruce trees, and a correlation was observed between beech growth and drought conditions in the year prior. Moreover, drought-growth correlations are stronger for dying trees compared to healthy ones, suggesting an increase in drought sensitivity over time, and more pronounced differences in growth during wet and dry years in tree stands with high mortality rates.

Another observed trend was the heightened drought sensitivity of younger trees as their root systems are not yet adapted to changes in water availability.

Spruce trees close their stomata to avoid drying out under drought conditions. This likely leads to carbon starvation and subsequent weakened defence capacity against, for example, insect or pathogen attacks. Spruce bark beetle outbreaks were observed in drought-stricken forests in 2018 and 2019.

Beech trees on the other hand, maintain high transpiration rates under drought conditions which leads to risks of hydraulic failure and can result in mortality.

A key driver of beech mortality is estimated to be the soil properties, as beech growth is strongly dependent on soil moisture content. Clay soils for example have high water storage capacities but are also more resistant to water uptake. Therefore, recurring drought conditions would lead to water depletion and slow recovery in clay soils.[12]

These findings agree with a similar study examining the impact of the 2018 drought in Sweden. It found that soil moisture was a key determinant for drought response. The study also looked at the drought implications for different forest types. Untouched primary forests were found to be less affected compared to secondary forests leading to the conclusion that forestry may exacerbate the impacts of droughts.[65]

Case study on the impacts of drought in Korea

An extreme drought was recorded in Korean temperate forests in Spring 2017 following a period of marked precipitation reductions starting from August 2016. The responses of oak and pine tree dominated stands showed significant differences. The soil moisture in the Korean pine stand was markedly lower and during the drought period the soil moisture difference between the two stands diverged further. The study suggests that evergreen forest species consume greater amounts of water from fall to spring and during their longer growing season, leading to the substantial difference in soil moisture between stands.

Differences in water stress between the oak and pine tree species can also be explained by root water uptake depth. Korean pines have shallow root-systems concentrated in the upper 30cm of soil. These upper soil layers are especially vulnerable to drought conditions as increased soil evapotranspiration will mainly happen there. Drought conditions further led to increased respiration rates and reductions of net ecosystem productivity in both stands, highlighting the connection between natural disturbances and the functionality of the forest carbon sink. In the pine stand, this resulted in a temporary switch to a carbon source. Both stands recovered net ecosystem productivity in subsequent years, with the Korean pine stands recovering faster. But legacies from the drought are still being observed, including increased carbon emissions from respiration.[13]

Forest fires

Forest fires are a natural occurrence and can contribute to the age and species diversity in forests.[66] Historically around 1% of boreal forests are burned through natural processes annually. But changes in temperature and the hydrological cycle is leading to increased wildfire risk. Like droughts, forest fires have been increasing in frequency and severity across northern forests due to climate change.[67–69]

In recent years both the frequency and extent of forest fires have been higher in recent years than in any time in the last 10,000 years.[50]

The likelihood and intensity of fires is further increased by water stress which in turn is amplified by global warming. High levels of plant water stress are driven by decreased precipitation, high temperatures, and low moisture content.[68] On the other hand, higher spatial heterogeneity and high slopes have been shown to reduce fire spread, increasing the forest fire resistance.[70]

In Europe, a study looking at fire vulnerability between 1979-2018 found that fire vulnerability was particularly high in the Iberian Peninsula, Italy, Southern France and parts of Belarus and Ukraine due to increased water stress. Other identified regions of high fire vulnerability are Sweden, Finland, European Russia, the southern Iberian Peninsula, and Turkey.[70]

In North America, the fire season has lengthened, and the number of fires observed has increased over the last four decades. The predicted increase in lightning will have a flow-on effect of increasing the mean potential area burned by 2050-2074 up to 29-35% in the Northwest Territories and 46-55% in interior Alaska.[71]

Damages from fires will increase with warming (see Figure 9). At around 1.5°C of warming the risk of damage increases from moderate to high. An example of this is that the area burned per fire season in the Mediterranean region is expected to increase by over 50%. At 3°C of warming, over 100 million people would be additionally exposed to wildfire damage.[62]

Risk of wildfire damage per degree warming

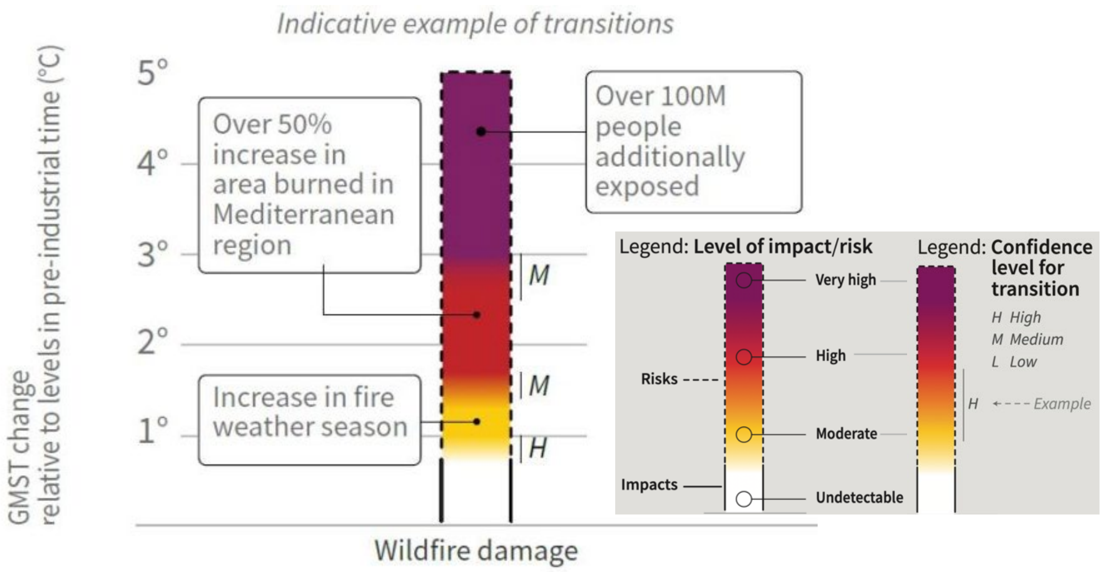

Figure 9: "Burning embers" showing the risk of wildfire damage in relation to global mean surface temperature change. The colour bar represents level of impact/risk while the confidence level for transition is given with the letter H for high and M for medium. Text boxes explain example impacts for the different levels of impact.[62]

In addition to the changing climate, shifting vegetation due to warming will further influence fire risks in boreal regions.[8,50,72]

Fires are also sources of carbon emissions. The last two decades have already shown a significant increase in fire emissions in boreal Eurasia. Boreal forest fires have caused 10 to 20-fold the carbon emissions per unit of area burned compared to other ecosystems like grasslands. This climate-fire feedback loop consists of more frequent and severe fires and postfire recovery failure due to climate warming. This leads to increased carbon emissions, decreased carbon sink potential, and incomplete resequestration of carbon in subsequent growing seasons.[72]

The 2021 fire season was an exceptional example with a record amount of carbon emissions from boreal fires (see Figure 10).[72] However, the 2023 fire season appears to have produced even higher emissions, with Canada alone estimated to have emitted around 0.41 GtC from wildfires – more than the entire boreal zone in 2021.[74]

Emission anomalies from boreal fires in 2021

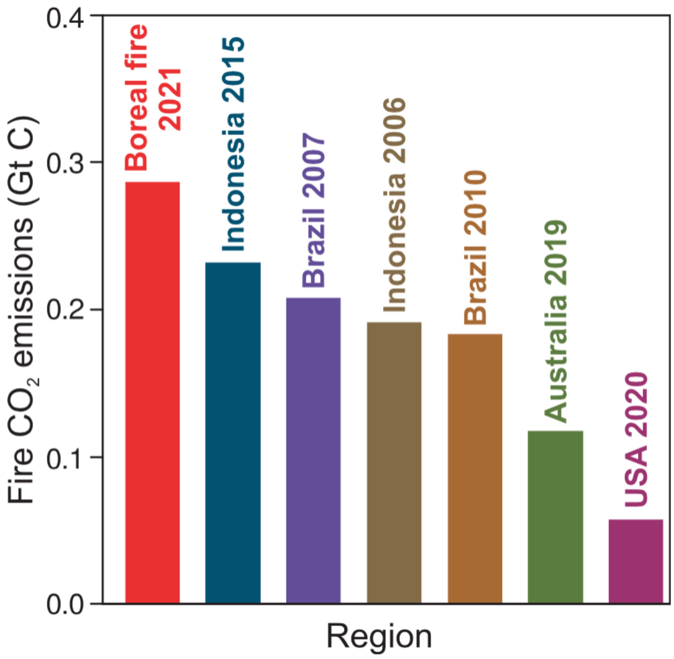

Figure 10: The emissions anomalies of the boreal forest fires in 2021 compared to other large extreme fire events in different regions and years. Emission anomalies of fires are calculated with respect to the 2000-2020 average.[72]

Fires also play a role for soil carbon. Boreal forest soils constitute a major part of the boreal forest carbon stock. Carbon has accumulated over natural fire events by soil portions escaping combustion underneath the burned layer, termed "legacy carbon".[7]

However, with more layers burning because of increased fires, this “legacy carbon” is now threatened. For example, past wildfires in the Northwest Territories of Canada suggest that legacy carbon emissions from increasing fire frequency in boreal forests can take up to a century to be re-sequestered and could turn these forests from a sink to a source of carbon.[7]

Predicting how much carbon will be released from boreal forest soils is complicated by uncertainties surrounding the impacts of fires on permafrost .[71] Fires will lead to permafrost thaw, exposing previously frozen organic matter to microbial decomposition.[8]

Overall, increasing wildfire occurrence causes a reduction of carbon stocks, threatening forests’ role as carbon sinks. It can further lead to changes in soil and permafrost regimes, compositions of dominant species, and even to postfire regeneration failures.[71]

Pests and pathogens

Insect pests and pathogens in northern forests are projected to increase, with rising temperatures being the main driver.[75] Pest outbreaks lead to lower forest productivity by affecting tree growth and reproduction, as well as leading to large-scale tree mortality. This in turn affects forests’ carbon uptake and threatens important carbon sinks.

Insect pests

Insects harm trees by feeding on them: defoliators feed on leaves or needles and bark beetles feed on the phloem or cambium parts of the trees. The impacts of outbreaks on tree growth, seed production, tree regeneration, and successional processes significantly affects forests’ productivity and dynamics.[76]

Insect outbreaks generally affect large geographic areas and occur in cycles which are highly linked to temperature.[77, 78] Heat, which is often accompanied by water stress, weakens plant resistance while simultaneously supporting insect development and reduced pest mortality rates.[5] Highly homogenous forests are at higher risks of insect outbreaks and damages.[70]

Insect outbreaks have been increasing in severity, range, and duration in the past few decades. Acute outbreaks have been recorded across the northern forest regions and have led to large-scale tree mortality events. Compared to the past few million years, the modern rate of plant insect damage appears unprecedented, despite decreasing insect populations.[79]

Across the boreal zone, the frequency and severity of insect outbreaks is projected to increase with warming. Warmer climates in the region will lead to higher winter survival of insects. Longer growing seasons in boreal forests will further support the northward expansion of insects' range limits.[5,8] In south-central Alaska, the spruce beetle has infested 0.5 million hectares of forest since 2016. Previously, the spruce beetle was not present in Alaskan forests due to cold restraints.[71]

In Europe, insect outbreaks and damages have increased over the last four decades. With increased mean regional temperatures of 0.5°C compared to 1970-1990, European forests have steadily become more vulnerable to insect outbreaks and damages (see Figure 11).

Since reaching that temperature threshold around the year 2000, bark beetle outbreaks have risen in many European regions. Between 2000-2010 bark beetle infestations have led to 14.5 million cubic meters of damage per year.[80] The damages from beetle outbreaks have since increased all over Europe. In East Central Sweden alone an estimated 8 million cubic meters of trees have been killed by spruce bark beetles in 2020.[78] In southern Sweden, a further 26 million cubic metres of spruce forest have been killed by this beetle between 2018 and 2021.[81]

Increased vulnerability to insect outbreaks

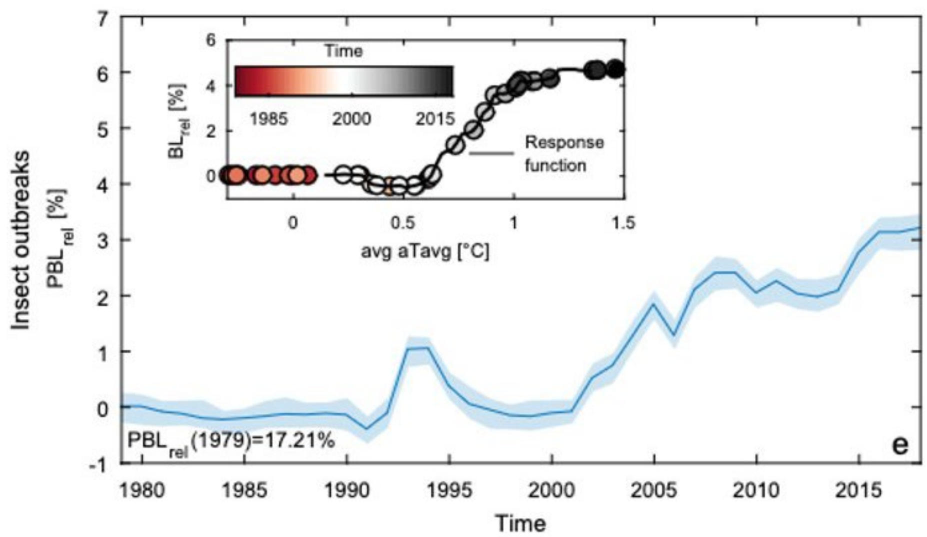

Figure 11: Insect outbreaks over time and the response function of insect pests to temperature anomalies in Europe. PBL and BL describe the potential biomass loss and biomass loss respectively and are measures for vulnerability.[70]

Pathogens

Pathogens can attack all parts of a tree (including foliage, stem, and roots) causing structural problems and reductions in photosynthetic activity, water and nutrient uptake. Diseases induced by pathogen infestations reduce growth and productivity. In conjunction with other disturbances, pathogen outbreaks can lead to forest decline and mortality.

Pathogen life cycles respond mainly to temperature but also precipitation and humidity. However, their sensitivity to precipitation regimes and humidity makes pathogen outbreaks harder to predict. Pathogen activity is likely increase in circumboreal forests under all warming levels.[5]

Ecosystem migration

Climate change is driving many forests species to migrate northwards. An overall greening of the tundra has been observed with the expansion of shrub vegetation, and subarctic and boreal species. This trend has been observed from satellite images between 1985-2019 and shows the beginning of a northward shift of the boreal biome with rising temperatures.

The establishment of trees in higher latitudes is supported by increased southerly winds, and nutrient availability driven by warming. This leads to better growth, reproduction, and dispersal. But, at the same time, extinction rates of vascular plants, moss, and lichen are being accelerated.[50, 82]

In North American boreal forests, a shift towards higher ratios of deciduous tree cover has been observed and a replacement by grasslands and deciduous forest both along the southern edge and within the interior regions is projected. On the northern edge, boreal forests are expanding, driven by increasing temperatures.[71]

It is clear that previous limitations to seedling colonisation in tundra regions are being overcome. The fastest migration rates have been recorded for the mountain birch, a deciduous-broadleaf tree that has been expanding across Fennoscandia. However, even the most rapid tree migrations are advancing slower than the accelerating rate of warming, so there is not a balance between forest expansion and sequestration, and losses from warming.[82]

Case study on white spruce northwards migration in Alaska

A study looking at the expansion of the white spruce range along an Arctic basin in Alaska geolocated 6758 white spruce trees across an area of $1000km^2$ in the Arctic tundra region. They found that nearly all individuals had been established less than a century ago and were rapidly growing.

Trees in new environments grew more rapidly than individuals at established treelines. Juveniles have continuously moved north and upwards and could be found up to 42km from the established treeline. Juvenile survival and adult growth are improved by the trends of rapid warming, increased snowfall, and improved nutrient availability in the region.

This migration northwards can be explained by changing climatic conditions such as increased open water in the Arctic Ocean during the autumn and winter, higher wind conditions and increased snow cover. Studies have shown that between 1979 and 2019 the Chukchi sea had a larger extent of open water in October, and winter precipitation over the adjacent land region increased.

Winter precipitation is a proxy for snow cover depth. Both snow cover and wind conditions promote the colonisation of tundra by boreal conifers. Wind is important for the transportation of seeds to new areas, while snow cover protects juveniles and allows for thermal insulation, cultivating soil microbes during winter. The furthest colonisation from the established treeline was observed in regions with the highest winter precipitation.

Soil microbe activity is enhanced by the rising soil temperatures both during winter and lengthened growing seasons. Heightened microbe activity in turn leads to higher nutrient availability. Snowmelt also contributes to improved moisture availability during the growing season.[82] All of which has facilitated the white spruce to expand its range northwards.

The speed of forest advance proceeds at rates one to two orders of magnitude lower than the speed of warming, though there can be significant differences among regions. Forest advance is limited by a variety of biotic and abiotic factors that need to be taken into account when making model assumptions about future poleward migration and carbon sequestration.[83]

The potential of increased carbon storage created by the forest expansion into unforested tundra areas is therefore limited.[8]

The potential of tundra greening is further limited by finer-scale landscape processes. Areas of higher elevations have shown lower rates and probabilities of greening. This suggests a limitation of the effects of regional warming on tundra productivity due to colder temperatures, dry soils, and lower snowpack on hilltops. Soils at higher elevation also tend to be characterised by exposed bedrock and unconsolidated sediments which have reduced amounts of nutrients and less pronounced moisture storage.[83]

While the boreal biome is migrating northwards, its ecology is also changing due to biotic pests, temperate species migration, and invasive species. The migration is led by animals and pathogens that drift from temperate to boreal forests at much faster rates than plants. Globally, invasions of alien species have been increasing, driven by climate change and the international transport of people and goods.[5]

For instance, white-tailed deer have been observed to migrate north of their historical range where they were able to proliferate due to a lack in natural predators. By selective grazing they transform native balsam fir dominated forest into spruce-dominated forests and parklands. Throughout the boreal biome, invasions by exotic species including defoliator insects, earthworms, slugs, and pathogens have been increasingly observed and may lead to major ecological changes.[24]

Apart from the northward migration and ecosystem changes, the boreal biome is contracting at its southern borders. The decline of southern boreal forests is being accelerated by timber harvest and wildfires and occurring faster than the northwards expansion.[84]

The processes of northward migration and southward contraction of boreal forests could potentially also be subject to sudden changes (see next section).

Northern forests and tipping points

With continued climate change, northern forests might not only undergo gradual changes but might also be subject to rapid and/or irreversible changes once critical thresholds are reached, also referred to as “tipping points”.

The Intergovernmental Panel on Climate Change defines a tipping point as “a critical threshold beyond which a system reorganises, often abruptly and /or irreversibly”.[86] Armstrong McKay et al. further add the self-perpetuating impacts on parts of the climate system after the passing of a threshold to their definition of tipping points.[87]

Ecosystem shifts within boreal forests have been identified as a potential tipping point for the climate. Both the northward expansion and the southward contraction could change land surface albedo (how the Earth’s surface reflects the sun). This shift would also diminish an important carbon sink, potentially turning these forests into a considerable carbon source. This could lead to significant, continental scale Earth system impacts.[71, 87]

On the southern edge of boreal forests, the risk of acute vegetation mortality and subsequent replacement by open deciduous forest or grassland ecosystems is driven by a mixture of: increasing temperatures, changes in moisture and precipitation patterns, concurrent novel fire regimes and soil conditions, as well as the increased vulnerability to pest outbreaks.

The interaction between natural disturbances could lead to self-perpetuating feedback loops causing synchronised forest dieback on a scale of hundreds of kilometres and a transition to grasslands or prairie states. Paleoclimatic studies suggest that boreal biome extent has shifted within the past 10,000 years due to temperature changes, and highlighting the possibility it can happen again.[71]

This shift is starting to occur in parts of the boreal region and the current rate of transition suggests that a complete shift could happen by the middle of the century if current warming trends continue.[71]

Intermediate states of tree cover after forest mortality events are potentially unstable and could result in more abrupt transitions into systems of sparse tree cover than projected.[71] Modelling studies have shown that these regime shifts will start at 1.5°C global warming and could become widespread if warming exceeded 3.5°C. Figure 12 shows the tipping threshold of boreal forests dieback on their southern edge, which has been estimated at 4°C with a wide uncertainty range of 1.4-5°C. Scientists therefore cannot rule out risk at much lower levels of warming, reinforcing the need to limit warming to 1.5°C.[87]

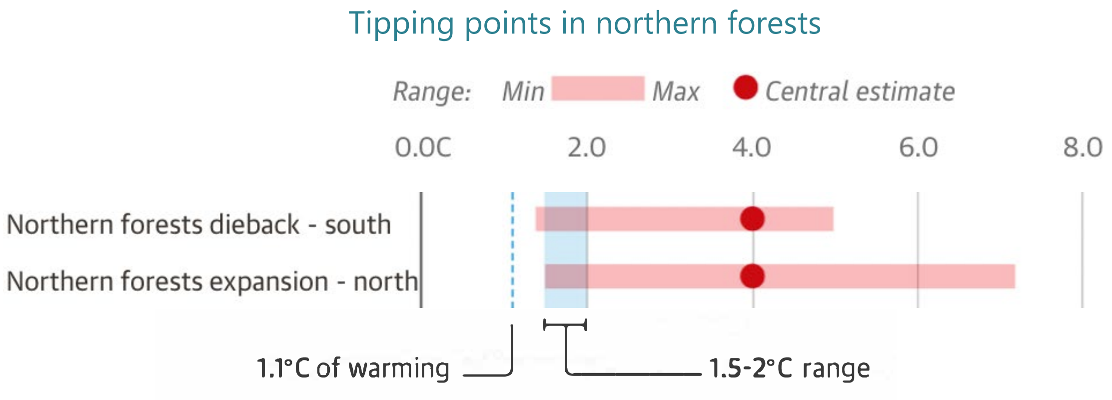

Figure 12: Tipping point estimates based on Armstrong McKay et al., 2022.[88] The central estimate is shown as a red dot with uncertainty ranges depicted in a pink bar. The dashed blue line shows the current level of warming while a blue bar shows the 1.5-2°C range.

If tipping points are crossed, partial dieback of boreal forests at their southern edge over around 100 years could lead to emissions of 52GtC; northern expansion over similar timescales could lead to partial uptake of 6GtC.[89] As forest dieback increases surface albedo, southern boreal dieback could contribute to decreasing global mean surface temperatures of around 0.18°C. It is unclear whether increased emissions or albedo from forest dieback would dominate the climate feedback which ranges regionally from -0.5°C to +2°C.[87]

On the northern margins, an expansion of the boreal forest risks decreasing land surface albedo, leading to enhanced global warming. Regime shifts are projected to become widespread by 3.5°C warming, with the tipping point estimated between 1.5-7.2°C and the central estimate at 4°C, indicating large uncertainties. The biome shift would happen over around 100 years and lead to an uptake of around 6GtC.

Decreased albedo and increased evapotranspiration caused by the forest expansion into previously barren land would lead to a positive climate feedback of an added +0.14°C per degree warming. Regionally this mean surface temperature increase would reach 0.5-1°C.[87]

The estimates for reaching tipping points of the boreal biome vary widely and are strongly dependent on warming scenarios. Vegetation models remain constrained in being able to accurately project complex ecosystem dynamics and changes in biomass carbon. But major vegetation shifts have been predicted in a growing number of publications and point to a serious possibility of transitions beginning this century.[71]

The inclusion of several drivers as well as noise within models further lowers the estimated temperature at which the tipping point would occur.[91] This points to the likelihood that the tipping points for the boreal forest are the lower end of the temperature range identified.

For example, multiple lines of evidence indicate an emerging regional tipping point[92–94] in the southern Siberian forests that could lead to the rapid replacement of forest ecosystems with non-forest systems. This would result in significant negative consequences for carbon stocks.[92] Field studies in the southern boreal forest provide another line of evidence that even low levels of warming could trigger quite adverse changes, including regeneration failure of currently dominant boreal forest species.[93]

In addition, present models do not consider plant thermal tolerance limits. When these limits are included, tipping points may occur at lower global warming levels than otherwise estimated, which would threaten the boreal biome's ability to assimilate and sequester carbon. This has the potential to trigger an abrupt ecological tipping point.[94]

Other ecosystem tipping points need further investigation. Soil dynamics and the soil carbon storage for example are still insufficiently understood.[95] The current debate around tipping points tends to focus solely on temperature thresholds. A study looking into alternative thresholds identified a potential tipping point for the extinction of vascular plants, moss, and lichen if the snow cover duration decreases by 20-30%.[96]

The urgent need for northern forest conservation in the context of the Paris Agreement

Some of the main challenges forests will face under climate change have been described in the previous section. They include:

- biodiversity loss
- reduction of undisturbed old-growth forests
- reduced tree growth
- increased disturbance regimes including drought, wildfires, and pests
- ecosystem shifts (such as those triggered by invasive species)
- reduced carbon sequestration
- possible loss of carbon stocks
- habitat fragmentation.

These observed and projected challenges highlight the importance of limiting warming to 1.5°C in line with the Paris Agreement to minimise impacts and risks to northern forests.

Overall, it is important to consider holistic approaches to forest conservation, restoration, ecosystem usage, and management. The protection of remaining old-growth forests and a sufficient proportion of all forest ecosystems is especially important. This will play a crucial role in maintaining their resilience and ability to deliver the full range of ecosystem services. Forest connectivity is but one of many aspects contributing to resilience and sustaining ecosystem services. Indigenous communities have been forest stewards for generations and can impart important knowledge and management strategies.

Ecosystem services provided by northern forests

Northern forests are not only important components of the climate system, they also provide vital ecosystem services, such as:

- the mitigation of carbon emissions and carbon storage,
- biodiversity,
- providing protection against flooding
- stabilising soil and minimising erosion
- nutrient recycling
- provision of water resources
- recreational benefits.[5]

The provision of many ecosystem services, for example the production of berries and game, is highest in old forest stands. Old stands further increase the multifunctionality of forests.[97] Old growth forests not only store vast amounts of carbon that risk being released upon disturbance but also continue to sequester carbon and thus contribute to the forest carbon sink.[98, 99]

Case study on trade-offs between ecosystem services in the Mediterranean

In an example study in the Mediterranean forest management options were investigated following current EU forest policy developments and discussions. The study investigated a selection of ecosystem services including timber harvest, water provisions, carbon storage, provision of suitable habitat for biodiversity, and mitigation potential of soil erosion.

Stimulated by EU internal markets and incentives for forest owners and strongly linked to the current bioeconomy strategy of the EU, a **wood energy** scenario would focus on forest productivity to contribute to increased bioenergy generation. While this scenario provides the best results for timber harvest and water provisions, it does so at the expense of the other services. It revealed severe trade-offs between timber production and the ecosystem services of carbon storage, soil erosion prevention, and biodiversity habitat.

When focussing on **carbon storage**, the bio-economy sector would need to advance the sustainable production of long-lasting wood products. This scenario is based on the implementation of carbon credits to incentivise projects aiming to increase soil and biomass carbon sequestration and could lead to a better balance of ecosystem service provisions. Strong limitations on timber harvest are outweighed by high carbon storage and large areas of suitable biodiversity habitat. However, this scenario remains unrealistic unless ecosystem services and products other than timber start being valued.

Another scenario focused on the **reduction of forest vulnerability. This** could be guaranteed if EU funds or tax benefits for forest owners were implemented to encourage the use of sustainable forestry practices and secure forest ecosystem functions under climate change. This scenario would lead to smaller timber harvest but could improve values for all other ecosystem services.

In the last scenario, **silvicultural interventions,** low-intensity cutting and the promotion of biomass build-up were added in addition to business-as-usual practices. This would be the best scenario for soil erosion mitigation and carbon storage, but the high biomass build-up could lead to low water provisions.

It shows that all management strategies will have to deal with trade-offs between ecosystem services, the provision of which is directly impacted by climate change. Many of the trade-offs are further dependent on forest site, site productivity and indicator choice. In order to incentivise the implementation of sustainable management options, ecosystem services other than timber production need to be valued.[100]

Critical reflection on sustainable management strategies and the ecosystem approach

The formulation of sustainable forest management strategies emerged after the 1992 Earth Summit in Rio de Janeiro. Several criteria were formulated as a common target. These include: the maintenance of the extent of forest resource, conservation of biodiversity, conservation and enhancement of forest health and vitality, maintenance of forest productivity, maintenance of forest ecosystem services including water and carbon cycling, and the maintenance of socioeconomic benefits from forest resources.[9] While this would be a balanced approach in theory, in practice it is often used to push for increased logging if an increase in socioeconomic benefits is promoted while the other criteria such as biodiversity and forest health are ignored.[18, 26]

The idea of sustainable forest management was followed by the formulation of the ecosystem approach. This approach provides a strategy to integrate the management of land, water, and living resources. Conservation and sustainable use of forest products should be considered together. It is centred around the interactions between organisms and their environment, encompassing ecosystem structures, processes, and functions.

The ecosystem approach recognises humans as an integral part of the system and aims to maintain benefits for present and future generations. Targets should consider the management effects on adjacent ecosystems, making the maintenance of ecosystem structure and function a priority. They should also incorporate the time and space needed for long-term management, find the balance between conservation and biodiversity usage, and consider all forms of information including traditional knowledge.[9]

Forest restoration

One of the main challenges of forest management is to increase forest resilience in the face of multiple stressors. This requires reinstating high structural complexity by improving overall habitat and landscape conditions that promote higher biodiversity. This includes the retention of deadwood, structures such as understory vegetation and uneven-aged forests. Lichen and polypore fungi are sensitive to a lack of old-growth forests, structural diversity and landscape fragmentation, the conservation of which is also important for food availability, nesting opportunities, and hiding spots.[5]

Heterogenous landscapes of old, uneven aged northern forests with large trees, an abundance of deadwood, and high structural variability are starting to be restored. An experimental site in Finland for restoration by controlled burning from 1989, for example, has become a hotspot for polypore fungi and hosting many red-listed species 30 years later.[9]

Canada has formulated restoration goals focussing on sustaining remaining natural forests and restoring forest areas. Restoration of natural forest structure has been done by commercial thinning to turn even-aged plantations into irregular or uneven-aged stands. This led to an increase in diversity while showing no influence on total stand yield.[101] Another experiment replants conifers on fallow land to counteract the decline in native conifer forests since colonisation in northern Québec, while simultaneously restoring carbon sequestration capacities.[9]

Strengthening forest connectivity

It is important to consider the functional connectivity of forests for proper conservation planning as ecosystem connectivity constitutes an important component of forest resilience. Species interconnectedness is an important aspect of forest ecosystems. These interlinkages can occur for example through food webs (across the food chain) or nest webs (microhabitats). Connectivity by wind or animal dispersal of seeds of isolated forest fragments is also considered.[102]

Old-growth forest patches are important safe havens for forest species, but fragmentation within disturbed forest landscapes from human management threatens this function. Intact forest landscapes by definition require an area threshold of more than 50,000 hectares and as such increasingly difficult to find. For example, woodland caribou, a threatened boreal forest species, need ranges with a maximum of 35% disturbance to be self-sustaining.[18]

Areas connecting ecosystems or habitats constitute important central points, enabling wildlife species to move across landscapes, counteracting forest fragmentation. These areas have high conservation value, the loss of which can affect the entire functional connectivity of a landscape.[102]

Retaining unmanaged forests and recognising indigenous knowledge and rights

Intact forests are critical for climate mitigation and other ecosystem functions including water quality control and harbouring biodiversity. The importance of forests is starting to be recognised and global calls for the protection and restoration of forests have been issued including the Kunming-Montreal Global Biodiversity Framework and the Glasgow Leader’s Declaration on Forests and Land.[103–105]

Forest conservation needs to include the protection of biodiversity. Natural diversity of species is important for forest health and contributes largely to ecosystem production.[106,107]

The prevention of deforestation in combination with restoration efforts has a large carbon storage potential. While prevention of deforestation would protect existing carbon stocks and maintain carbon storage potential, reforestation would restore carbon storage potential and potentially increase carbon stocks. If successful conservation and restoration were carried out, existing forests and regions with low human pressure could additionally store about one third of the current global forest carbon stock. Therefore forest conservation and restoration are vital for climate protection.[23]

Old-growth forests are important for forest resilience. For example, coastal redwoods of the Northeast Pacific temperate rainforest regrow after disturbance by using old carbon reserves and ancient buds to resprout. These ancient buds can be several hundred years old.[66]

Around 40% of remaining forests are in indigenous peoples' land.[108] Indigenous peoples are strongly connected to the land. Forests are places of hunting, trapping and fishing, of cultural and language learning, and of healing.[109] The relationship with the ecosystem is an integral part of many indigenous peoples' identity, which are increasingly affected by forest management and climate change.

Further recognition of the importance of indigenous institutions and knowledge in forest governance is also needed. The consideration of indigenous knowledge and perspective is still the exception, but an increase in participation can be observed. Recognising and deepening synergies between indigenous knowledge and western science will benefit people and ecosystems.[5]

Indigenous communities have lived off and with their lands for many generations. Knowledge is passed on over centuries and guides management practices. Knowing when and how much to take and only taking what is needed are important principles for indigenous forest stewardship.[110]

Ecosystem conservation and restoration can only function in consultation with local communities. Indigenous communities are already at the forefront of forest protection struggles and must be let to drive land-use decisions.[23] This includes land tenure rights.[111]

Northern forest conservation in the context of the Paris Agreement

While the challenges and threats for northern forests outlined in the previous sections call for increased forest conservation and restoration efforts, it is important to highlight again potential future limitations in carbon sequestration and threats towards existing carbon stocks due to human activities and continued climate impacts. The ability of northern forests to sequester carbon and retain carbon stocks is incredibly important if we are to limit global warming to 1.5°in line with the Paris Agreement. [62,89] This is critical to prevent any further feedback loops of warming reducing boreal forest cover and releasing more carbon into the atmosphere.

At the same time, climate modelling efforts that project future carbon sequestration might overestimate these potentials because of how vulnerabilities of northern forests to climate change impacts are represented in the models.[112]

The role of the northern forest region in global efforts to limit warming to 1.5°C will be covered in a subsequent report.

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