REPORT 2021/11

Sustainable boreal forest management

– challenges and opportunities for climate change mitigation

Report from an Insight Process conducted by a team appointed
by the International Boreal Forest Research Association (IBFRA)

IBFRA
International Boreal Forest Research Association

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Foreword by IBFRA

Based on the White Sea Declaration, the International Boreal Forest Research Association (IBFRA, www.ibfra.org) was founded in 1991 to promote and coordinate research and to increase the understanding of the role of the circumpolar boreal forests in the global environment and the effects of environmental change on that role.

During our 30-year history, we have developed into an authoritative international forum on comprehensive studies of boreal and temperate forests - evaluating their role in providing stability of the Earth-climate system and the global economy.

As IBFRA, we undertake, coordinate, and promote boreal forest research across the world’s largest land biome and through 19 IBFRA Conferences and vast collaborative research opportunities, we accomplish our objectives by:

- Connecting researchers, graduate students and others dedicated to boreal forest research
- Encouraging innovation and knowledge-sharing on key boreal forest issues
- Promoting a multidisciplinary approach for boreal forest research activities
- Assisting in generating partnerships and connections with boreal forest research institutions across the circumboreal region to provide members with networking opportunities

Along these guiding objectives, we developed the IBFRA Insight Process which involves assessing and synthesizing the science related to climate change in the boreal and - based on this review - developing evidence-based policy recommendations for adaptive and sustainable boreal forest management.

This first IBFRA Insight Process on “*Sustainable boreal forest management: challenges and opportunities for climate change mitigation”* addresses the impacts of climate change on the forests, the role of forests in mitigating climate change, and the ways in which the forest sector can contribute to removing emissions from the atmosphere.

The outcome is a transparent and balanced scientific assessment of the potential of the boreal forest to contribute to climate change mitigation.

As IBFRA, we would like to extend special thanks to the Swedish Forestry Agency and the Swedish University of Agricultural Sciences for funding this study and all voluntary co-authors and contributors under the leadership of Prof. Peter Högberg for their dedicated efforts in determining the scientific consensus among the six participating boreal countries Canada, Finland, Norway, Russia, Sweden, and the United States of America.

Florian Kraxner

Florian Kraxner
IBFRA President

Foreword by the Swedish Forest Agency

The boreal domain represents about 30 % of the global forest area and is the world’s largest terrestrial carbon pool. Hence, it is a large contributor to the global budgets of carbon dioxide and other greenhouse gases. Forests are at risk from the impacts of climate change. At the same time forest management and the use of wood products derived from forests can play important roles in contributing towards national greenhouse gas emission reduction goals.

It was against this background that the International Boreal Forest Research Association organized a science-policy workshop in conjunction with the boreal ministerial summit 2018 in Haparanda in northern Sweden. The summit provided an excellent opportunity for a diverse group of researchers and policy analysts from across the circumboreal region to engage in focused discussions on collaboration on key boreal science issues. One important result of this dialogue was the launching of this first insight process on sustainable forest management and climate change mitigation.

The report contains synthesized information from boreal forests in Alaska (USA), Canada, Norway, Sweden, Finland and Russia on changes in carbon stock in living tree biomass and a comparative analysis on how these changes are affected by different forest management regimes.

The Swedish Forest Agency has not had an active part in the preparation of the report, but still chooses to publish it in the Swedish Forest Agency's report series. The conclusions and positions that appear in the report are thus the authors’ own. The hope is that the report can serve as a source of inspiration in the continued collaborative work at the circumboreal level to address knowledge gaps associated with boreal forests and climate change. Considering the work ahead of us after the 26th UNFCCC COP the publication of this report comes at a good moment in time to inform decision-making across the boreal domain.

We convey our great appreciation to Professor Peter Högberg and his team for accomplishing this first insight process.

Peter Blombäck
Head of the policy and analysis division, Swedish Forest Agency

Summary

Can the forest sector mitigate climate change through capture of atmospheric carbon dioxide (CO_2) and the subsequent use of wood products?

We assembled experts mainly from the member countries of the International Boreal Forest Research Association (IBFRA) to synthesize information from boreal forests in Alaska (USA), Canada, Norway, Sweden, Finland and Russia on the carbon (C) stock in living tree biomass during the period 1990 to 2017. Thus, we compared C stock changes in tree biomass among boreal forests with a low intensity of forest management in Alaska, Canada and Russia, with a much higher intensity of forest management in Norway, Sweden and Finland (where rotational forestry involving clear-felling and replanting or reseeding is practiced on a large portion of the area). The lack of comparable high quality data from the larger countries and differences in national definitions of managed forests impedes a strict comparison between unmanaged and managed forests across the boreal biome.

Intensive forestry in the Nordic countries has been associated with rising C stock in the biomass of trees, which has doubled in the last century including an increase by 35 % between 1990 and 2017. The rising C stock in these forests occurred while cumulative harvests removed the equivalent of half of the original C in the initial stock in 1990. In boreal forests in Canada and Russia, the stocks of C in living trees showed no major changes. In these large countries, a lower percentage of the forest area was harvested annually as compared to the Nordic countries, but forest fires affected a much higher portion of the area. The area affected by fires was around 0.5 - 0.6 % per year in Alaska, Canada and Russia, which compares with around 0.01 % in the Nordic countries, a difference by a factor 50 - 60. Regarding soils, all countries report modest increases in C in mineral soils over the period, with greater increases in the Nordic countries as compared to Canada and Russia. Peat soils on drained fertile soils were large sources of emissions of greenhouse gases in Finland and Sweden.

We conclude that intensively managed forests on upland (mineral) soils have shown strong net uptake of C from the atmosphere by accumulating C in trees, soils and forest products. In countries with less intense management (Canada and Russia), where a lower percentage of the area is harvested annually, the uptake of C from the atmosphere has been matched by wood harvests and C releases back to the atmosphere (including from large forest fires); i.e. the C stock in living tree biomass has not changed. In Alaska, where forestry is not practiced in the boreal forests, there has been a net loss of C mainly through fires.

Forestry can obviously provide climate benefits from increased C stocks in forests (in trees, other plants, dead wood and soils), from C stored in long-lasting wood products and by substitution of wood for fossil fuel products and products associated with large emissions of CO_2, for example concrete. We recommend further quantification of the opportunities for boreal forest management to maintain and increase forest carbon sinks. Examples include empirical studies on forest

management regimes with thinnings in Canada and Russia and on mixed-stands vs. single-species stands and on continuous-cover forestry in comparison to rotation forestry across the boreal forests.

Glossary

Carbon sources and sinks. We adopt the conventional terminology, according to which a C source emits and thus adds carbon dioxide (CO_2) to the atmosphere, while a C sink takes up and reduces the concentration of CO_2 in the atmosphere.

Continuous-cover forestry (CCF) belongs to the broader class of selective felling systems. These aim at harvesting a fraction of the larger trees (usually around 20-30 % of the volume at intermittent harvests) while keeping a relatively continuous canopy cover of trees. This contrasts with rotational forestry, see below.

Greenhouse gases (GHG) are gases that absorb long-wave radiation from the earth´s surface and thus increase the time the energy contained in this radiation resides in the atmosphere, which causes warming. Prominent GHGs are water vapor, carbon dioxide, methane and nitrous oxide.

Harvested wood products (HWPs) are produced from wood and traditionally include timber, pulp, and paper, but also modern products like nano-fibers, biofuels, textiles, etc.

Managed forests. Forests may be managed for many goals (which are not necessarily mutually exclusive). We define managed forests as forests, which are routinely harvested for wood, or where the forests are planned to be harvested for wood in the future. If the latter is true for much of the landscape in the foreseeable future, we use the term less intensively managed forests. Forests in Norway, Sweden and Finland, where 70-80 % of the forest area is routinely harvested (commonly clear-felled at an age of 70-120 years), are intensively managed.

Rotational forestry (RF) or even-aged forestry involves clear-felling of older forests. It aims at establishing a forest landscape with a mix of age-classes, but also a high average growth rate to enable sustainable harvests at a high rate.

1 Background

Boreal forests (Figs. 1-2) cover an area of ca.1 370 Mha (million hectares), which is ca. 10% of the global land area and 33% of the total global area covered by forests (Chapin et al. 2012). Boreal forests grow more slowly than temperate and tropical forests on average, but store more carbon (C) in soils relative to in their living biomass, (Pan et al. 2011), which is in part due to the occurrence of thick organic soils.

In the context of the globally increasing concentrations of greenhouse gases (GHGs) in the atmosphere, the boreal biome is projected to warm more than the world average, a prediction, which is supported by measurements (IPCC 2013). Thus, the question arises whether the higher temperatures will cause greater gains of C from increased photosynthesis under warmer conditions and longer summers, or greater losses of C through enhanced decomposition of organic matter (and release of methane, a more potent GHG, from wetlands). Moreover, increases in disturbance regimes, such as wildfires and insects (Kurz et al. 2008, Schaphoff et al. 2016) have already reduced boreal forest C sinks and such disturbances are projected to increase further with global warming (Balshi et al. 2007, 2009, Flannigan et al. 2009, Shvidenko & Schepaschenko 2013, Schaphoff et al. 2016, Anderegg et al. 2020).

The important question about the future role of boreal forests in the global C cycle has no widely accepted answer. There are contrasting views on the present and future C sink strength of boreal forests. A key policy question is whether the forest sector can provide opportunities for climate change mitigation through enhanced net removal of CO_2 from the atmosphere, reduced emissions from the forest sector, and avoided emissions from using wood products in place of emissions-intensive materials or fossil fuel burning (e.g., Griscom et al. 2017, Fargione et al. 2018). The lack of scientific consensus on preferred mitigation activities was highlighted by the International Boreal Forest Research Association (IBFRA) in a report to a meeting of ministers from the six major boreal countries (Russia, Canada, USA, Sweden, Finland and Norway) in Haparanda, Sweden, in June 2018. At the meeting, the ministers asked IBFRA to assist in organizing an expert team to enhance science to policy linkages pertinent to the role of forestry in boreal forests in climate change mitigation. The team was tasked with compiling information on forest C stocks and their changes in the six boreal countries and summarizing these data in a report. Other ecological and socio-economic aspects will be dealt with in coming reports.

Sweden provided resources to cover the costs of organizing a first workshop and for the leadership and administration of what we call an IBFRA Insight Process. This was carried out by a team of 25 experts (Appendix 1) primarily from the countries concerned, but also including experts from IIASA (International Institute for Applied Systems Analysis). A workshop was held in Stockholm 20-21 May 2019. Some preliminary findings were presented at the UNECE

COFFI (United Nations Economic Commission for Europe, Committee on Forests and Forest Industry) meeting in Geneva in early November 2019.

Here, we provide a more comprehensive report on the role of the boreal forest sector in climate change mitigation. We focus in particular on the C stocks in living tree biomass. We first describe the boreal forests in terms of areas covered and the C stocks in the biomass of living trees (Figs. 1-2), and how these have developed in the six countries. We then discuss the effects of management on the C balance, followed by brief considerations of the C stored in harvested wood products (HWP) and their potential to mitigate climate change by substituting other products. Finally, we discuss the potential future role forestry may have in boreal forests as a tool to combat climate change.

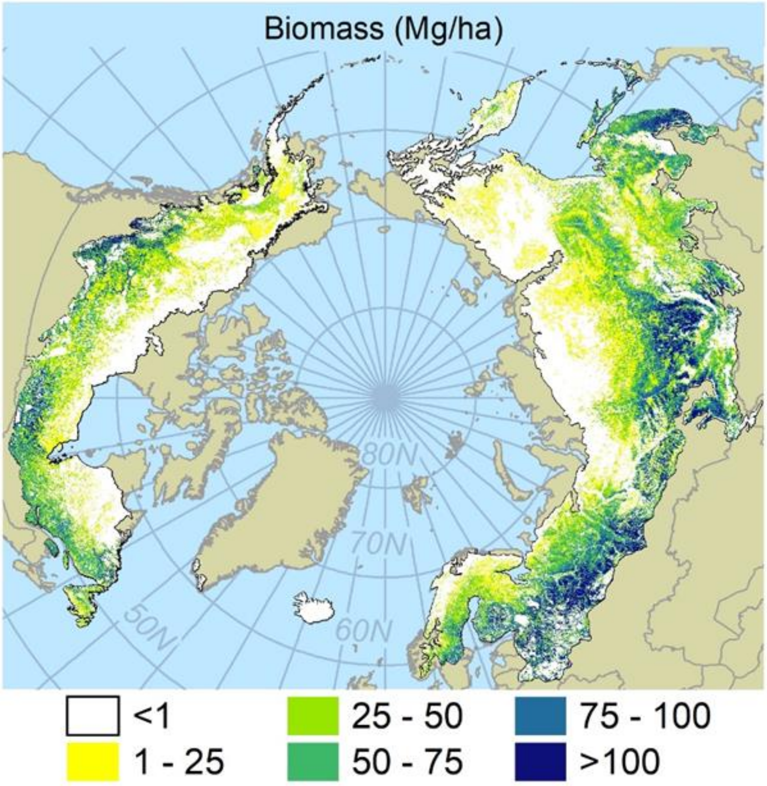

Figure 1*. The approximate distribution of the boreal forest biome and its variations in average biomass (some white areas are lakes, tree-less mires and areas above the tree-line). Multiplication by 0.5 gives the figures in metric tonnes C per ha. From Gauthier et al. (2015), courtesy Sylvie Gauthier and Science.*

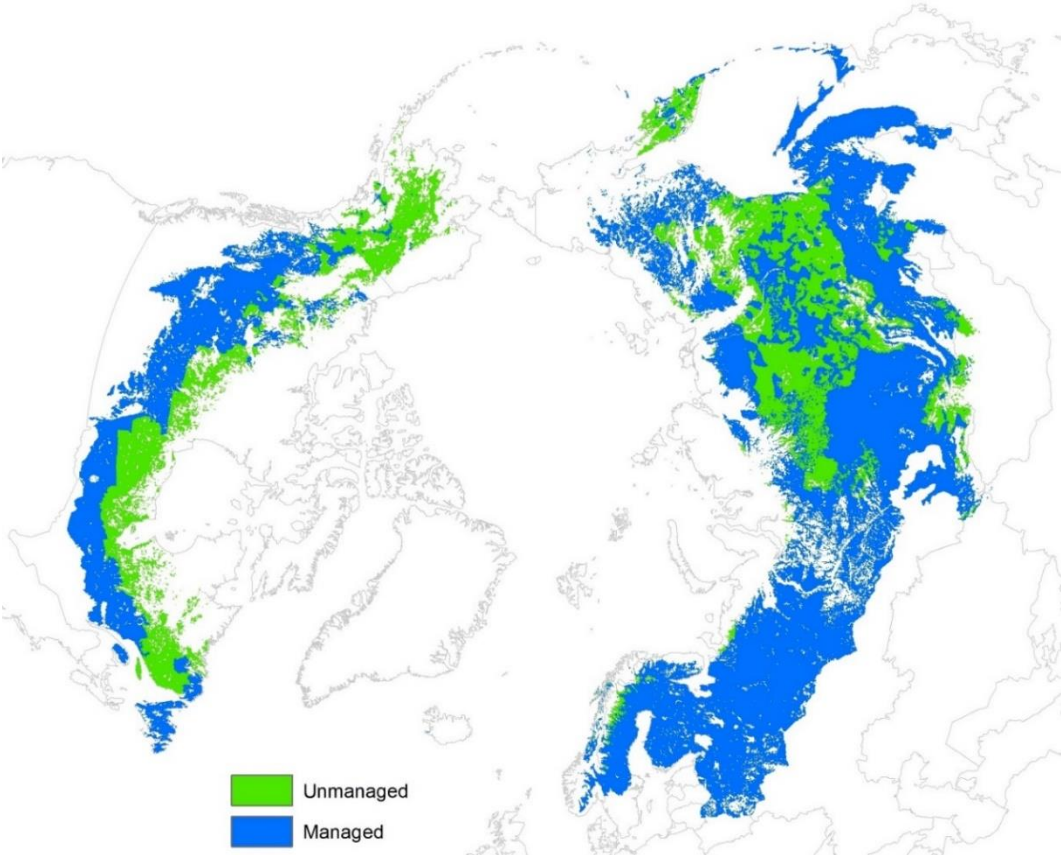

Figure 2. *Boreal forests: the map indicates the global boreal forests at 1x1 km2 resolution, while distinguishing between managed and non-managed forest. Note that the objectives and intensities of management for wood harvests vary considerably among managed forests (see text under 4.1. and Table 2). The map is a hybrid product by IIASA © 2021, modified after Kraxner et al., 2017, Ogle et al., 2018 and NFIS Canada.*

2 An introduction: To harvest, or not to harvest?

The goal to constrain global warming to well below 2 degrees C cannot be achieved without significant contributions from the land sector, which is expected to contribute towards net-negative emissions in the latter half of this century (IPCC 2018 1.5 degree report, IPCC 2019 SRCCL). Many countries have declared their intent to use enhanced sinks and reduced sources in the land sector as a contribution to their GHG emission reduction goals (e.g., Forsell et al. 2016). However, the ways in which the forest sector can contribute to net negative emissions is debated.

The C budgets of forests vary in response to management (or absence of management), and a clear evidence base is needed for informed discussions of best management practices. Here, we focus the analysis on boreal forests, which in general are managed according to country-specific strict rules and regulations and where rates of deforestation (the conversion of forest to non-forest land uses) and of illegal logging are much lower than in many other forest biomes, especially tropical forests. We mainly discuss C exchanges between forests and the atmosphere. Our discussion concerns not only how much C is stored per ha or for the total boreal forest areas and how this has changed from 1990 to 2017, but also the net GHG balance between the forest sector and the atmosphere. This information is needed for discussions embracing the wider perspective that wood-based products may replace products based on other raw materials, which are usually associated with greater emissions of GHGs.

It might perhaps be expected that a landscape of non-managed boreal forests would store more C per hectare than a similar landscape with forests managed for wood production. However, this hypothesis needs to be compared with available evidence to provide a solid foundation for policy. Moreover, an effective accounting for C must also consider the wider implications of harvesting wood and using wood products, since managed forests lead to sequestration of C in both the landscape and in wood products (e.g., Lemprière et al. 2013, Lundmark et al. 2014, Smyth et al. 2014, Kurz et al. 2016). Complete C accounting includes total ecosystem C stocks (above- and belowground C pools and soils) and wood products, plus the reduction in C emissions when wood products replace fossil fuels, high-energy products (e.g., steel and concrete), the manufacturing of which causes large emissions of CO_2.

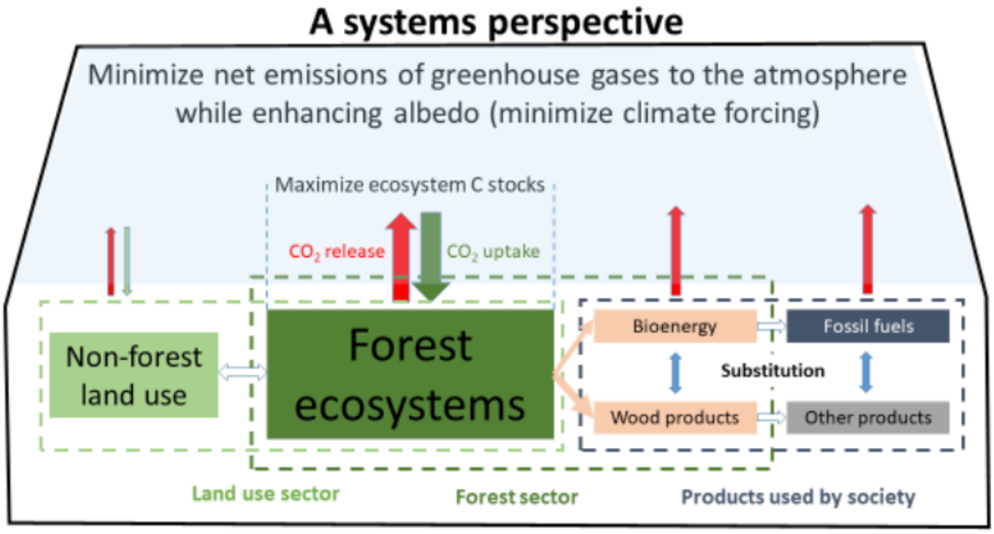

Figure 3. *A systems perspective (modified from Nabuurs et al. 2007, Lemprière et al. 2013) relevant to analyses of the potential of forestry for climate change mitigation. Green arrows show* CO_2 *uptake, red release of* CO_2*. Other arrows show transfers of C between compartments, e.g., a wood product may ultimately become a source of bioenergy and substitute fossil fuels. Albedo is the proportion of solar energy reflected back to the atmosphere, and not affecting the temperature of the vegetation and air. To reduce warming of the atmosphere forest management should balance the goals of enhancing C uptake and increase the albedo; goals, which may be in conflict (see section 5.2. below).*

Forests and forestry can cause a net removal of CO_2 from the atmosphere in three ways (Fig. 3):

- by enhancing the C stock in forest ecosystems,
- by providing raw materials to increase the C stock in long-lived products,
- and by providing raw material for products substituting fossil C, and other CO_2-emission-intensive materials such as steel and concrete, etc.

Reductions in forest harvesting could lead to increased use of fossil-based alternative materials and fuels, thereby potentially increasing global CO_2 emissions. Conversely, improved forest management and product developments can increase the possibilities to mitigate climate change by reducing emissions of fossil C. Thus, one needs to evaluate the combined effects of forestry on the forest biome and on our use of wood as raw material that can substitute alternative materials. Let us first look at the forest resources and their development in the areas studied.

3 The boreal forests: Areas and trends in C stocks

3.1 General considerations and scope

Here, we focus on the boreal forests in the USA, Canada, Norway, Sweden, Finland and Russia (Figs. 1-2). Regarding the USA, we focus on the boreal forest in Alaska and exclude the boreal forests in northern conterminous USA (as well as the maritime forests along the Pacific in Alaska). In the following, we thus write Alaska rather than the USA. In case of the three Nordic countries, we treat all forests as boreal forests, although small areas in the south are nemo-boreal (and even nemoral) rather than true boreal forests. With regard to Canada and Russia, the countries with the largest expanses of boreal and other forests, we consider only the boreal forests per se; in the case of Canada the managed southern 160 Mha part of the Canadian boreal forests (which in all cover 280 Mha, i.e., we exclude the 120 Mha considered as un-managed boreal forests). In Russia, we study the 720-810 Mha of boreal forest (Table 1); the lower and higher estimates may partly reflect differences in the delineation of forest types between the national system and that used by IIASA. Throughout, we use the FAO definition of forest land (see Appendix 2).

The objectives of forest management vary considerably across the boreal forests. In Norway, Sweden and Finland, most forests are intensively managed for wood production by rotational silviculture. The majority of the forest land is owned by individuals or private forest companies, i.e. 86 % in Norway, 78 % in Sweden and 80 % in Finland. Forestry is practiced in most of the forests (e.g., 73 % in Sweden). Forest land not used for wood harvests includes national parks, nature reserves, voluntary set asides and low-productive forest land. Importantly, effective regeneration is mandatory after harvests (should be carried out within 3 years in Norway and Sweden, while similar strict rules have recently been removed in Finland). In Finland and Sweden a few thinnings are conducted per rotation, while thinnings are uncommon in Norway. Forest fires are effectively prevented in all three countries.

In Alaska, industrial forestry is confined to the maritime forests along the Pacific Ocean, which are not treated here. In the boreal forests of Alaska, cutting for domestic purposes (fire wood, timber) occurs, but is very limited. Hence, we consider the boreal forests in Alaska as un-managed in the sense that management for wood production is not an objective. Forests are almost exclusively state- and federal-owned. Attempts to extinguish fires are made to the extent possible, but frequent fires started by lightning and challenges of fighting forest fires in vast expanses of inaccessible areas leads to large areas burned.

This latter challenge is also most prominent in the boreal forests of Canada and Russia. However, forestry is more significant than in Alaska, but a much smaller proportion of the total standing stock of wood is harvested as compared to in Norway, Sweden and Finland (Table 2).

The 160 Mha of boreal forests denoted as managed in Canada cannot be directly compared with the managed forests in the Nordic countries, with a denser network of roads and good access to most forests. In Canada, forest operations are mainly by companies commissioned to harvest timber on public forest land. They need approval of a plan for regeneration, but meeting the required regeneration standards does not have the narrow time limit used in the Nordic countries. Natural regeneration or planting with native species only are methods for regeneration after harvests in Canada's boreal forests. Around 0.7 Mha is harvested per year of which 0.4 Mha are planted or reseeded. The remaining harvested forests and forests after natural disturbances are subject to natural regeneration. A small proportion of naturally disturbed areas are planted (but it is one climate mitigation activity that is now supported by Federal Government funding). Thinning is rarely practiced in Canadian boreal forests.

In Russia, forests are almost exclusively state property and the government issues medium or long term leasing agreements with companies or individuals to manage forests. The term exploitable forests (cover ca. 50 %) is used, but most of these boreal forests are in reality not exploited for timber harvests, because of inaccessibility. Forests west of the Ural Mountains are in general more exploited than those to the east in terms of percentages of land harvested (Fig. 2). Protected forest cover around 27 % and reserve forest (not planned to be harvested within the next 20 years) cover another 23 % of the forest land. The reserve forests should be protected from fire. Reforestation operations in the forest areas are planned and carried out and paid for by the lease holders. Restoration of forests outside leased areas and on forest fund lands damaged by fires and other adverse factors is covered by the federal budget. Forest Fund lands comprise a majority of forests (96.9 %) with the exception of forests on the lands used for industrial and transportation facilities and etc., national reserves and national parks, and urban forests. As of today, the lands of the Forest Fund are under the authority of the Federal Forestry Agency, a part of the Ministry of Natural Resources and Environment of the Russian Federation. Almost the entire area of the forests that has been clear-cut (ca. 1 Mha per year) is subject to reforestation, through planting (0.2 Mha per year) or measures to promote natural regeneration (0.8 Mha per year).

3.2 Methods of inventory (details are given in Appendix 3)

In Norway, Sweden and Finland, there is a wealth of data on tree volume and growth from detailed national forest inventories (Tomppo et al. 2010), which have been going on for around a century. These inventories cover annually all forests in the three countries, e.g., in Sweden 6 000 plots across all forests are sampled every year (Fridman et al. 2014). In contrast, such detailed data are not available from the vast less populated boreal forests of Alaska, Canada and Russia (Appendix 3). Hence, for these we use data mainly derived by remote sensing methods or combinations of ground-based inventory and remote sensing. The data we report are largely from the National Inventory Reports to UNFCCC (United Nations Framework Convention on Climate Change).

Moreover, while data from the Nordic countries would have allowed a longer retrospective analysis, the paucity of long-term data from the other countries restricted our study to the period 1990 - 2017. The exception is Alaska, where data for 1990 - 2009 only are available so far. Estimates for Alaska are embedded in the reports according to international agreements for the USA for the period 1990 - 2017. However, although the data from the six countries have been available, our Insight Process is the first concerted exercise to compile and synthesize data for all six boreal regions.

3.3 Results

3.3.1 Results: areas and stocks of C in boreal forests

According to our assessment, the area of boreal forests has had no major changes since 1990. The C stocks of the living biomass is correlated with the area of forest land, i.e., the average C stock in living biomass per area varies within fairly narrow limits (Table 1) as compared to global variations. It is highest in Canada, where the inclusion of the unmanaged, northern boreal forests with lower biomass (120 Mha) would have resulted in a lower average tree biomass C (Figs. 1 - 2). This would make the Canadian data more comparable to those from the other countries, where the northerly and least productive forests are included.

The similarities in average C stock across countries indicate that the reductions in live-tree C stocks with harvesting in the Nordic countries do not result in much lower average whole-rotation C stocks than in un-managed forests or less intensively managed forest landscapes (Table 1). In these, stand-replacing forest fires cause large local fluctuations in C stocks as they also create a mosaic of young and old forests. The above arguments rests on the assumption that there are no systematic differences in soil fertility, length of growing season, growing season temperature, etc. among the countries. Given that such differences may influence the results, we put emphasis on the changes that have occurred in each country 1990 - 2017.

3.3.2 Results: changes in C stocks of boreal forests as a result of growth and removals by harvests, fire and other causes

In contrast to the relative similarity in average C stock in living biomass, patterns of change in C stock in living biomass, removals by wood harvests and losses by fire differ substantially among the countries. Note that losses by fire include C losses from biomass, dead wood and soils, while harvests are largely removals of stems. We first discuss the changes in biomass C and the removals by harvests in the three Nordic countries, then in Alaska, Canada and Russia.

Table 1. Basic data on boreal forest area and forest C stocks in living tree biomass as per country/state. For the Nordic countries, the data are identical to those reported to the UN-FCCC (https://unfccc.int/ghg-inventories-annex-i-parties/2020). For Alaska, Canada and Russia, the data represent the boreal subsets of the country reports as clarified in foot notes. Units are million hectares, Mha, and million metric tonnes, Mt.

Country/State	*Forest area, Mha*	*Carbon stock in living trees (2015-2017, but 2009 in Alaska), Mt C*	*Average C stock in living trees per area, t C ha^{-1} (2015-2017, but 2009 in Alaska)*
Alaska (USA)	*23**	*800**	*35**
Canada	*160***	*7700***	*48***
Norway	*12*	*355*	*30*
Sweden	*28*	*1280*	*46*
Finland	*26*	*910*	*35*
Russia	*720-810****	*31000****	*37****

**Boreal forests only; **managed boreal forests, un-managed boreal forest cover an additional 120 Mha in Canada not accounted for here, ***Estimates vary: the lower is from IIASA and the higher is from the Russian country report; the latter is the basis for data on C stock.*

Table 2. The C removed by harvests as Mt per year and as % of the total C stock in living biomass in boreal forests (averages for 2015-2017). Note that substantial harvests occur in other forests in Alaska, Canada and Russia. Unit is million metric tonnes, Mt. The Table also gives the percentage of the area affected by fire per year (average for the studied period).

Country or State	*Carbon stock in living trees, Mt C*	*Carbon removed by harvests, Mt C yr^{-1}*	*Percent C removed by harvests per year*	*Percent of area affected by fire per year*
Alaska (USA)	*800*	*0**	*0**	*0.6*
Canada	*7700*	*24*	*0.3*	*0.5*
*Nordic countries ***	*2545*	*37*	*1.4*	*0.01****
Russia	*31000*	*37*	*0.1*	*0.6*

**Negligible domestic wood harvesting occurs; **Sum of Norway, Sweden and Finland; ***Assumes that the % of area affected by fire is the same in Norway and Finland as in Sweden (1996-2018)*

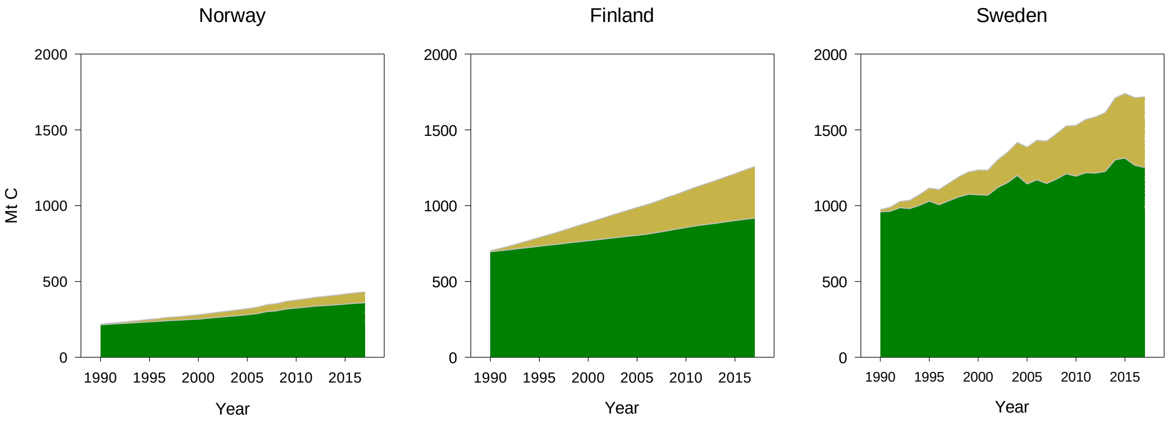

Figure 4. *Changes in C stocks of living tree biomass (green) and cumulative harvests (yellow) in Norway, Finland and Sweden 1990-2017. Carbon removed from the atmosphere is the sum of the increase in biomass C stocks plus the cumulative harvest. Additional C may have accumulated in dead organic matter and soil C pools. Some harvested C will have been released back to the atmosphere, while an increase in the biomass C (in green) represents net uptake from the atmosphere. Unit is million metric tonnes, Mt.*

All three countries showed strong increases in the stock of C in living trees, as well as large harvests for wood products. Combining Norway, Finland and Sweden, the stock of C in living biomass increased by 35 %, from 1.88 Gt C to 2.53 Gt C (Fig. 4), while during the same period 0.88 Gt C was removed in cumulative harvests. The annual removals in harvests were on average around 1.4 % of the standing C stock (Table 2). Thus, the cumulative harvests during the 27 years studied were equivalent of close to half the initial C stock in living biomass in 1990. Losses in fire were negligible. For example, in Sweden, during the period 1996 - 2018, which includes the most severe fire year (2018) in 50 years, the total area burned altogether was only 67 000 ha, i.e. 0.24 % of the forest land (on average ca. 0.01 % per year). Fires are relatively uncommon in Norway and Finland as well. The small area burned in recent years of 0.01 % per year compares with 1 % per year in Central Fennoscandia during the period 1500 - 1870 (Wallenius 2011, Fig. 9), a difference by two orders of magnitude. The parallel increases in C stock in the trees and the removals of C by harvests show that the Nordic managed forests continue to be strong sinks for atmospheric CO_2.

In Alaska, wood harvests are negligible in the boreal forests (Fig. 5). During the period 1990 - 2009, the estimated losses of C (from living biomass, litter, dead wood and soil) through fires were 88 Mt. This compares with 800 Mt C in the vegetation of these boreal forests, which means that the equivalent of more than 10 % of the living biomass C was lost in fires during the 20-year-period (i.e. a loss of 0.5 % per year). The forests showed a net decrease in C of 32 Mt during the same period, showing that plant growth did not compensate for the losses in fires. Accordingly, the Alaskan boreal forest was a source of CO_2 to the atmosphere over these two decades mainly because of fires. From 1950 to 2019 these affected on average just below 0.5 % of the area annually. During the period 1990 - 2017, the area annually affected by fire was 0.6 %.

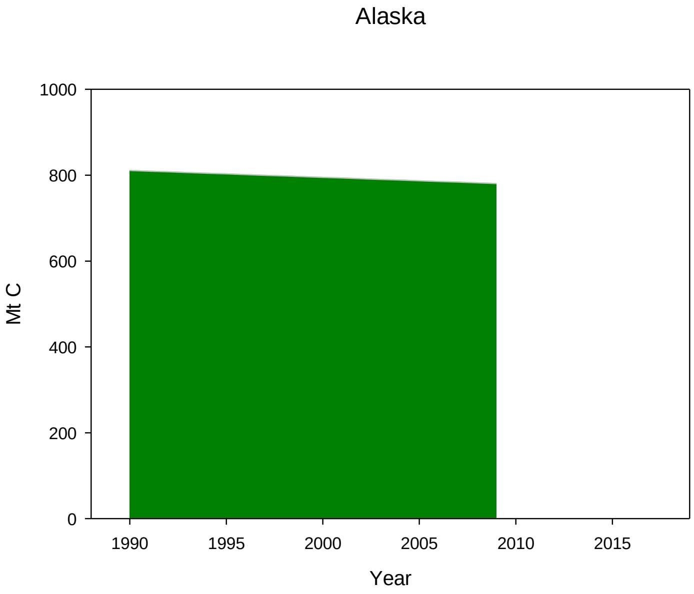

Figure 5. *Changes in C stock in living tree biomass in Alaskan boreal forest 1990-2009. Unit is million metric tonnes, Mt.*

Unlike in Alaska, managed boreal forests in Canada are harvested, but from a smaller area per year of the total area available as compared to the more intense management in the Nordic countries (Table 2). During the period of study (1990 - 2017), the cumulative harvests amounted to 642 Mt C, and the losses in fire (from living biomass, litter, dead wood and soil) were 570 Mt C. The remaining C stock in living biomass did not change significantly during the period (Fig. 6). Wildfires caused 49 % of the total losses of C from the forests. The cumulative burned area was 20.2 Mha, which gives an average of 0.75 Mha per year (0.5 % of the area). The maximum was 2.2 Mha burned in one year.

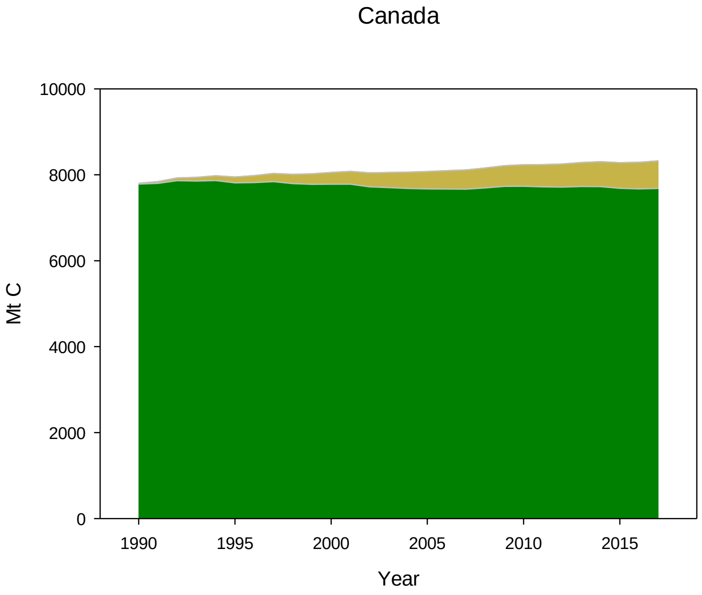

Figure 6. *Changes in C stock in living tree biomass (green) in managed Canadian boreal forests and removals in cumulative harvests (yellow) 1990-2017. Unit is million metric tonnes, Mt.*

Russia has a lower intensity of forest harvesting than Canada (Table 2). Harvests accounted for 61 % of the losses of C from the boreal forests as compared to 37 % due to loss by fire (these data are Russian records from 2003-2016). According to global fire data bases (GFED4.1 and 4.1s, Randerson et al. 2018) and two Russian remote sensing sources (Space Research Institute, Moscow and Institute of Forest, Krasnoyarsk) the average forest land area affected by fire was 4.5 - 5.5 Mha per year, which is around 0.6 % of the area per year. Outbreaks of insect pests and other pathogens regularly occur at a similar scale (Review of Sanitary and Forest Health State in the Russian Federation in 2018, Bartalev et al. 2017, Schaphoff et al. 2016). Remote sensing data indicate that on average 1.8 Mha (range 0.4 – 3.3 Mha) of forests died annually as a consequence of stand replacing natural disturbances 2002-2011 (Krylov et al. 2014). Fire frequency especially that of megafires has increased during the last decades. However, the C stock in living biomass did not change significantly during the period 1990-2017 (Fig. 7).

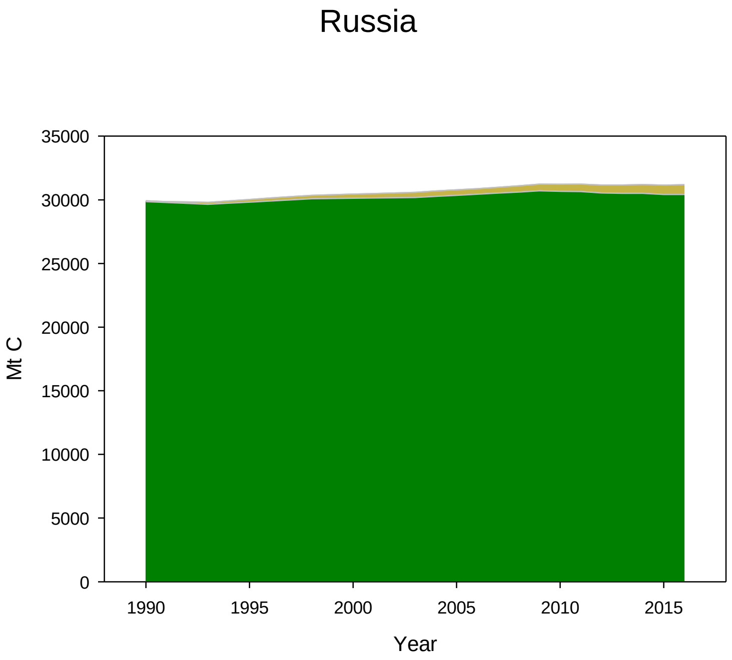

Figure 7. *Changes in C stock in living biomass (green) in Russian boreal forests (according to the country report) and removals in cumulative harvests (yellow) 1990-2017. Unit is million metric tonnes, Mt.*

3.3.3 How comparable are the data from the different countries and how do our data compare with other studies?

Do our data allow valid comparisons among the countries involved in this study? The data we show are the most up-to-date data available at the time of this study from the different countries. However, as discussed above, the methods differ with long-term detailed field measurements available for the Nordic countries as compared to mainly remote sensing data combined with data on disturbances and management activities integrated in models for Alaska and Canada.

Assessment of boreal forest resources in Russia is especially challenging because of the size of the forest area and vast areas that are inaccessible. Colleagues based in Russia and at IIASA (where Russian experts are active) have both provided data. The Russian data are partly from older field inventories; modern inventory data are currently not available for all of Russian boreal forests. The data on Russia reported by IIASA are based on remote sensing. There are differences between these estimates, which we so far have not been able to reconcile (Table 1). However, we find that these differences are not large enough to invalidate our major conclusions about trends in living biomass C stocks.

One may also ask how the data presented above compare with other assessments pertinent to the C dynamics of boreal forests. For example, Song et al. (2018) recently reported an increase in forest area in Russia, but this mainly occurred outside the boreal forests. Moreover, we have concentrated on the living biomass, while some other reports provide estimates for the ecosystem, which includes also the components dead wood, litter and soil. We find that more accurate estimates of these components are not available for most of the boreal region.

We note that inclusion of the northern, un-managed Canadian boreal forests, i.e. forests without harvests, would make the Canadian data more comparable to those from the other countries. For example, in Finland the northern half of their forests has a tree biomass which is 60 % of that in the south. A similar difference in the Canadian boreal forests would result in an estimate of 40 t C ha^{-1}. On the other hand, Pan et al. (2011) provide a higher estimate for Canadian boreal forest than we do in this report, because they classified all of Canada’s forests as boreal. Regarding the three Nordic countries the data shown by us and by Pan et al. (2011) are directly comparable.

Over the last three decades, plenty of reports based on modelling, remote sensing of vegetation or atmospheric inversions (studies based on large-scale temporal and spatial variations in atmospheric CO_2) have addressed the state and change of boreal forests. Several of these reports have suggested that northerly forests are a continuing and significant sink for atmospheric CO_2 (e.g., Ciais et al. 2019). Our data on living biomass C indicate that in the largest areas of boreal forests, i.e. in Canada and Russia, the forests are a relatively weak sink for C (Figs. 6-7), while the unmanaged boreal forest in Alaska are a source of C (Fig. 5). The development of the Nordic boreal forests does support the idea of a strong northerly sink (Fig. 4), but their area is too small to make the large imprint needed to affect the atmospheric inversion calculations. On the other hand, our data from the Nordic countries very clearly refute the proposition that the Nordic forests were a source of C 2010 - 2015 (Scholze et al. 2019). Such discrepancies point at the urgent need to reconcile global-model estimates and country reports (e.g., Grassi et al. 2018). The detailed and reliable inventory data from the Nordic countries are suitable for tests of the global models.

4 Effects of management on the C balance of boreal forests

4.1 Do un-managed forests take up more C than forests managed for wood production? General considerations.

This seemingly simple question hides considerable complexity. Un-managed forests are also dynamic (non-static), as they are subject to frequent natural disturbances. An intense, stand-replacing fire can release as much CO_2 in a day as the forest accumulated over a period of decades or centuries. Thus, landscapes of unmanaged forests are composed of larger and smaller areas of forests regenerated after severe fires, windstorms, and outbreaks of insects. Some portions of landscapes may avoid major disturbances allowing trees to become hundreds of years old. The average age across a landscape or region is typically less, as patchy disturbances reinitiate young stands.

Managed forests also vary in age across landscapes. Rotational forestry dominates in managed forests in the boreal zone, where mature forests (commonly 70 - 120 years old) are clear-felled and replaced by planted seedlings or seedlings emerging from natural regeneration. In such settings, older trees or forests occur in national parks, nature reserves, or more informal set-asides, including occasional retention trees (Gustafsson et al. 2012). Moreover, rotational forestry in Finland and Sweden also involves thinnings. Usually this is “from below”, i.e. removes trees that grow more slowly than the dominant trees.

In the absence of disturbance, forests are sinks for atmospheric CO_2 when their uptake of CO_2 through photosynthesis exceeds its release from plant respiratory processes and the microbial decomposition of organic matter. This is a dynamic balance; boreal forests are sinks during days from late spring to early autumn. They are sources at night and even during the day for the coldest portions of the year (albeit a small source because decomposition is reduced at low temperatures). Rates of photosynthesis during summer days are so large that CO_2 uptake across the course of the year can exceed respiration releases despite long hours and even months when photosynthesis is not occurring.

When the majority of trees in a forest are killed by natural disturbances or clear-felling, the forest becomes a net source of CO_2 back to the atmosphere. The re-growing forest becomes a net sink again when the forest canopy re-establishes and photosynthesis once again exceeds respiration. The sink (the rate of net uptake of CO_2) is stronger in young to middle-aged forests as compared to in older forests, but the exact time of maximum sink strength varies among forests and sites.

Would an area covered by an old forest be a stronger sink if the forest remained unharvested (and would not burn) for another century or if the old forest was harvested and the site managed as a century-long rotational stand? Harvesting drops photosynthesis and may increase decomposition, so post-harvest sites are net sources of C to the atmosphere. The re-establishment of the forest canopy takes one or more decades, and eddy-flux studies (where the net flux of C is measured in towers above forests) indicate that boreal sites become net sinks again after 5-20 years (Amiro et al. 2010, Coursolle et al. 2012, Taylor et al. 2014, Gao et al. 2018, Rebane et al. 2019). The length of time a site spends as a net source to the atmosphere varies with the intensity of disturbances, forest management and soil fertility. Most studies of recent clear-fellings in boreal forests have been in N. America, where laws allow a slower artificial or natural regeneration to take place as compared to in the Nordic countries. Requirements for more rapid forest regeneration in the Nordic countries shorten the time necessary for forests to re-establish as CO_2 sinks.

These rates of change vary across sites, and there may not be a useful, universal answer to the question posed at the beginning of this paragraph. The available evidence clearly indicates that rotational forests would have higher wood accumulation rates than forests older than a century (see section 5.2., esp. Fig. 10), and the available soil inventory trends do not show a decline in soil C with rotational forestry (Stendahl 2017). This combination would indicate rotational forests would sequester C at a faster rate than old forests, but this issue would benefit from a great deal more research that aimed to capture the range of outcomes across locations in the boreal forest zone.

Stand thinning and other selective felling methods (including continuous-cover forestry) remove a fraction of the stem volume at a time, with harvesting operations recurring at time scales of one or more decades. Thus, selective felling methods have a smaller effect on forest C balance at the scale of a stand in the shorter term, but a larger land area must be harvested to meet the same demand, which means that the total effect in terms of the amount of CO_2 released from the landscape may differ less. In the longer term, the differences in productivity between selective felling and rotational felling systems is the most important factor to consider. In a recent review, Lundqvist (2017) concluded that uneven-aged Norway spruce forests grow 10 – 20 % less than even-aged (rotational) stands, with larger differences when the harvest intensity is high in the uneven-aged stands. In a recent comprehensive study in Finland, Hynynen et al. (2019) found a similar difference in growth between uneven-aged forests and rotational forests.

The profitability of forest practices depends on markets, characteristics of tree species used and site-specific details. Continuous-cover forest management may be a more profitable option than rotational systems when the initial stand diameter distribution is wide (Juutinen et al. 2018; Juutinen et al. 2020). Moreover, it is possible that continuous-cover forestry has a more favourable GHG balance compared to rotational forestry on nitrogen-rich organic soils (Korkiakoski et al. 2020), where there is a greater release of the potent GHG N_2O after clear-felling. More direct investigation would be needed to inform the magnitude and extent of any GHG-balance patterns in relation to site N status.

In the context of rotational forestry, there is consensus that middle-aged forests are stronger C sinks than old forests (e.g., Pregitzer & Euskirchen 2004; Luyssaert et al. 2008; Coursolle et al. 2012; Kashian et al. 2013). However, old forests may continue to function as weak sinks (Luyssaert et al. 2008), but may flip to sources in some years (Wharton & Falk 2016) or most years.

The ecophysiology that drives the age-related trends in the strength of forest sinks remains somewhat unclear. An early speculation was that old trees required higher respiration rates to sustain large biomass (Odum 1969), but evidence shows that tree respiration declines in older forests, but not as much as the decline in photosynthesis (Ryan et al. 1997, Tang et al. 2014). Importantly, the amount of C stored in the live biomass and the soil can become comparatively large if the forest is not disturbed, but the net rate of C uptake, the sink strength, clearly decreases in aging forests (Kashian et al. 2013).

Effects of fire are superimposed on these patterns. When mega-fires (large stand-replacing fires) sweep landscapes, forests of all age classes are killed and become C sources before the area is green again. This needs to be taken into account, especially with regard to forests in Alaska, Canada and Russia, where forest fires are common (Figs. 8-9). The conversion of old forests into younger forests releases C, but the C uptake of medium-age forests may determine the landscape's overall C balance. Hence, the net C balance across a landscape needs to account for the net C balance of the mosaic of young, medium, and old forests. This accounting also needs to consider whether a forest that reached a given age in 1980 would have the same C balance as the same-aged forest in 2020. Over periods of decades, forest growth rates change in managed forests as a result of changing forest practices and environmental conditions (Henttonen et al. 2017).

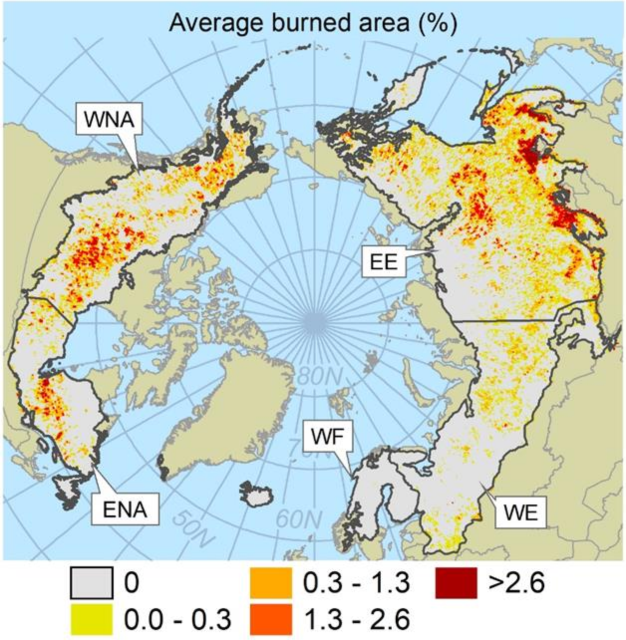

Figure 8. *Average burned area per year across the boreal forests 1997-2014. Note low frequency of fire in the Nordic countries (WF) as compared to the vast areas of un-managed or less intensely managed forests in Alaska, Canada and Russia. WNA, Western North America; ENA, Eastern North America; WF, Western Fennoscandia; WE, Western Eurasia; EE, Eastern Eurasia. From Gauthier et al. (2015), courtesy Sylvie Gauthier and Science.*

It is sometimes claimed that leaving forests as they are would lead to the highest long-term C sink based on the observation that old forests can still act as sinks (e.g., Luyssaert et al. 2008). However, old forests are most often much weaker sinks than middle-aged forests (e.g., Kashian et al. 2013). Moreover, studies comparing old forests with younger may not be appropriate if they overlook the fact that some forests belonging to the same initial age-cohort as the remaining old forests are now young forests as a consequence of a natural disturbance event.

The state of today´s old forests may not be reached by all young forests today even in the absence of forest harvests. Landscape-scale inferences on C balances need to account for the range of forests within a landscape, including the age distributions for both managed and unmanaged forests. While conserving forests is positive from many perspectives, e.g. maintaining biodiversity, forests are vulnerable to the risk of damage by fire or pathogens, and hence loss of C.

Fires lead to a direct loss of C to the atmosphere. Unless salvage logging is possible, fires result in lost opportunities to produce wood products and substitute other products, with a negative effect on the global C balance. Another fundamental difference between harvests and fires is that the former removes most often stem wood only (sometimes in the Nordic countries tree tops and branches are used for district heating), while fires consume C in the organic mor-layer of the soil and tree foliage, branches and stems; the loss of C increases with the severity of the burn. In cases where dead trunks are around after the fire, these and stumps will decompose quite slowly. Common to both fire and clear-felling is that fine roots and mycorrhizal fungal mycelium will start to decompose directly after the disturbance. Remote sensing observations in Canada documented more consistent and faster forest recovery after harvest compared to wildfire (White et al. 2017).

Fires in Asian Russia can result in a situation where 15-20 % of the land affected is not naturally regenerated in the shorter term (Vaschuk & Shvidenko 2006). In critical situations (zonal and altitudinal ecotones, steep slopes, on permafrost), forest areas may completely lose productive potential for reforestation for a long time after mega-fires (Yefremov & Shvidenko 2004, Schaphoff et al. 2016). Infrequent seed years further delay the regrowth of forests by natural regeneration.

What is then the combined results of management versus non-management in a larger landscape perspective and over a longer time scale? In some quarters, the assumption is held that natural ecosystems by definition will always store more C than managed systems. For example, Erb et al. (2018) modelled and made maps of potential biomass, which were compared with actual biomass stocks. They “adjusted the maps where necessary, so that the actual biomass would not surpass the potential biomass stocks”. By assuming that C stocks of the managed systems could never become higher than the modelled potential stock, these authors prevented a test of this question. An un-biased assessment should recognize that managed boreal forests can be a stronger C sink and have a larger C stock than un-managed boreal forests. Furthermore, the impact of the natural disturbance regime must also be considered (Figs. 8-9). This is especially important since climate change is predicted to increase the risk of losses of C by fires (Anderegg et al. 2020).

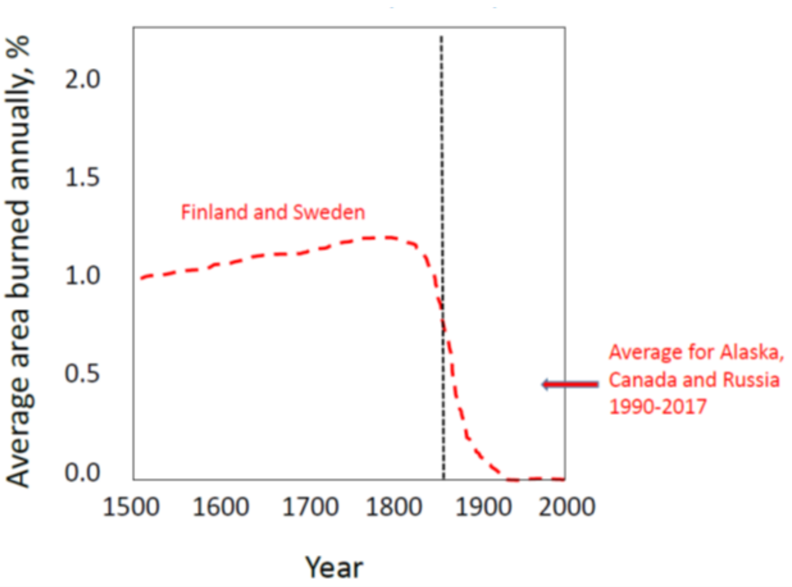

Figure 9. *Average area burned annually in Central Fennoscandia 1500 - 2000 (Wallenius 2011, our data 1990-2017) and in boreal Alaska, Canada and Russia 1990 - 2017 (our data). The large decline in fires in Finland and Sweden was driven by fire protection motivated by the rapidly increasing industrial value of wood in the mid-1850´s (dotted line).*

4.2 Do un-managed forests take up more C than forests managed for wood production? What do our data tell us?

The intensity of management of boreal forests spans a wide range among countries, and some general insight on the long-term, large-scale effects of forest management could come from comparisons among countries. Most boreal forests in Norway, Sweden and Finland are subject to rotational forestry and are, thus, routinely harvested and then regenerated, but the management intensity is much lower in the rest of the boreal zone. In Alaskan boreal forest, wood is not harvested for industrial use. In Canada and Russia, parts of the huge forest lands are under management including clear-felling and regeneration, while large areas are not used for forest harvests (Table 2). The description of management intensity or level of management may be ambiguous, so we report harvests as a percentage of stock as a quantitative descriptor of the average intensity of forestry (Table 2). This metric varies a lot among the countries, but also hides a large local variability, i.e. that some regions in Canada and Russia may approach the higher intensity of forest management in the Nordic countries. Hence, our comparisons deal with the broader average situation.

The countries with the largest harvest removals in percent of standing stock C, the Nordic countries, showed significant and large increases in C stock in living biomass (Fig. 4 and Table 2). It is particularly interesting that this increase 1990 - 2017 is around a third of the original C stock in 1990, despite the very substantial harvest removals during the studied period. Losses in fire were negligible, and have been small in the last century as a result of effective fire suppression (Fig. 9).

Changes in the content of C of a region’s forests might come from increased forest coverage, increased average stand age, and increased growth rates. In the Nordic countries, the major change since 1990 was increased growth rates of managed forests, not expansion of forest areas or increases in stand age across landscapes.

Over the longer term of the whole 20th century, inventory data uniquely available for the three Nordic countries show that both woody biomass and growth rate doubled (Fig. 10). The starting point of that development around a century ago (almost 90 years before the period studied here) varied. Some areas, especially far north and other inaccessible areas had un-managed forests with very little human impact (Henttonen et al. 2020). In other areas, extensive selective logging had taken place and there were large areas of forests used mainly for grazing (Myllyantus & Mattila 2002, Framstad et al. 2013, Henttonen et al. 2020). In a recent analysis, Henttonen et al. (2019) found that forests in southern Finland today contain very few trees older than 150 years, whereas such trees are much more common further north, where the previous use of forests was much less intense. In Finland in particular, but also to some extent in Norway and Sweden, wetter forests were drained, which resulted in more productive forests (Päivänen & Hånell 2012).

Thus, the development one hundred years ago often started from a low point in terms of both biomass and growth (Myllyantus & Mattila 2002, Henttonen et al. 2020). We lack accurate data on these parameters several hundred years ago, except for a few local sources, and there is thus no reliable evidence that forests nation-wide grew faster centuries ago and contained larger stocks of C on average than today´s forests. Undoubtedly, however, forest fires were common (Niklasson & Granström 2000, Framstad et al. 2013, Rolstad et al. 2017). According to Wallenius (2011) the area burned annually 1500 - 1870 was around 1 % in Central Fennoscandia and 2 % in southern Fennoscandia (Fig. 9), which is 100 - 200 times higher than today (Table 2). Now, forest trees are considered economically valuable, and an extensive road network is a crucial asset for firefighters. It should be noted that the average C stock in living biomass per ha in today´s Nordic boreal forests is not very much different from that in the evidently less intensely harvested and managed forests in the other countries/state, despite the very low biomass C stock in recent clear-fellings in rotational forestry (Table 1).

The high growth rate in the Nordic forests is largely a result of management. In the first half of the 20th century, selective felling methods dominated, but became replaced by rotational forestry after 1950. Henttonen et al. (2017) estimated that approximately one-third of the increase 1971-2010 can be attributed to global environmental changes, such as a warmer climate, longer season of growth and a higher concentration of CO_2 in the atmosphere. Nitrogen deposition is also assumed to contribute to greater forest growth elsewhere, but we note that it has only local and thus marginal effects on the boreal biome at large (Ackerman et al. 2019). A crucial aspect of management is that a relatively large share of the managed forests are middle-aged, and hence strong sinks for C (Fig. 10).

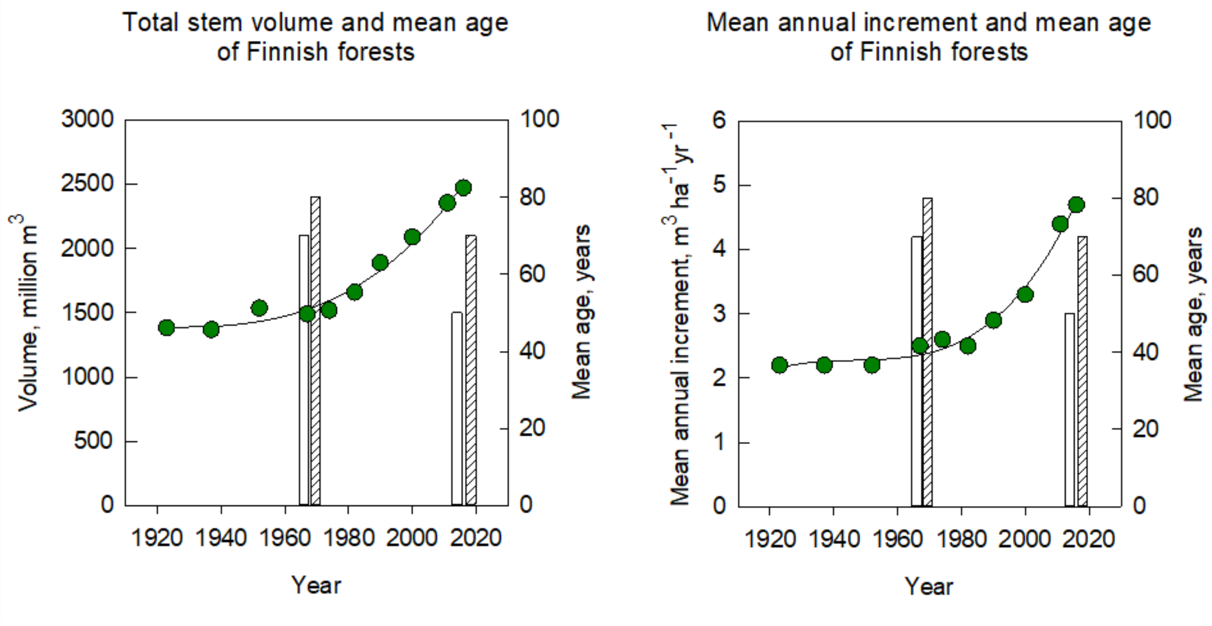

***Figure 10**. The development of total stem volume (left, green circles) of forests and their mean annual increment (right, green circles) in Finland the last hundred years and the change in average stand age the last 40 years in northern (hatched bars) and southern (unfilled bars) Finland. Rotational forestry replaced selective felling forestry around 1960. Note that stem volume increased by close to 70 % from 1960 to 2018, while the average forest stand age declined by 10 years in the north and by 20 years in the south. Data from official Finnish Forest Statistics (https://stat.luke.fi/suomen-mets%C3%A4tilastot-2019-2019_fi).*

For example, in Finland the volume of living trees increased, while management resulted in progressively younger stands and the average mean annual growth rate increased in 1960 – 2016 (Fig. 10). Another important aspect is the requirement by law to promptly establish a new productive stand after clear-felling. Furthermore, planting after clear-felling allows introduction of genetically selected seedling material.

Countries where much less of the forests are managed for wood harvests, Alaska, Canada and Russia (Table 2), showed little or no increase in C stocks in living biomass 1990 - 2017 (Figs. 5-7). Their boreal forests are on average either small sources (Alaska) or very small sinks (Canada and Russia) when fluxes are expressed on an area basis. Losses of C from aboveground biomass by fire constitute 90, 49 and 37 % of the total losses (due to harvests, fire, pathogens) in Alaska, Canada and Russia, respectively (the data for Russia are from the country report). This compares with close to nil in the Nordic countries, where removals by harvests prevail (along with a substantial build-up of the C stock). The percentage forest area burned annually on average, roughly 0.6 %, 0.5 % and 0.6 % in Alaska, Canada and Russia, respectively, compares with 0.01 % in Sweden, a difference by a factor 50 - 60 (Table 2, Fig. 9). Importantly, the available inventory data for the boreal forests in Alaska, Canada and Russia show no substantial increase in tree biomass in response to a warmer climate, earlier spring thaw and increasing concentration of CO_2 in the atmosphere. These factors have been inferred to contribute to the increased tree growth in the Nordic context (Henttonen et al. 2017), where standing stock C has increased in all three countries (Fig. 4), as has harvests in Finland and Sweden, in particular. Canadian data from permanent sample plots and tree rings are inconclusive and show regional differences in forest responses to environmental changes (Girardin et al. 2016, Hember et al. 2017, 2019).

Unmanaged forests contain more dead wood, which thus constitutes an important storage of C. Not all countries report changes in C in dead wood to UNFCCC. Canada and Russia do, but show differences; in Canada there was a decreasing accumulation rate of C in dead wood 1990-2017, while there was an increase in dead wood in Russia. Norway and Sweden report substantial increases in percent in the accumulation rate of C in dead wood, but still very low amounts.

The data on C in living trees from the Nordic countries clearly show that managed boreal forests can provide large quantities of wood as raw material to the society, while at the same time their capacity as C sink increases significantly (Fig. 4). Forest management for wood production enhanced the C stock in living biomass and wood products that stored additional C and provided substitution benefits (see section 6). Unmanaged forests do not provide C storage in wood products and substitution benefits for other materials.

The C stocks in living biomass are only part of the overall C balance across forest landscapes, and the C balance is only part of the total effect of forests on the atmosphere and climate. Hence, we must ask if there are other aspects relevant to climate change mitigation we need to consider. Prominent among these are potential effects of harvesting, fires and other disturbances on:

- Losses of soil C as an effect of forest operations and natural disturbances
- Releases of more potent greenhouse gases (GHGs)
- Albedo, i.e. chiefly a transformation from mixed forests to conifer-dominated forests with lower albedo

4.3 Changes in soil C stocks and emissions of other GHGs than CO_2.

Canada, Norway, Sweden, Finland and Russia all report to UNFCCC modest increases in C in mineral soils over the period, which range from 20-30 kg C ha^{-1} yr^{-1} in Russia and Canada (where the data refer also to other forests than just boreal forests in both countries) to above 100 kg C ha^{-1} yr^{-1} in the Nordic countries. For all countries except Sweden, these estimates are based on modelling. Sweden has a long-term Forest Soil Inventory, which has sampled forest soils along with the Swedish Forest Inventory (Nilsson et al. 2015). This large sustained effort allows monitoring of changes in soil C including the uppermost organic mor-layer (O-horizon) and the mineral soil down to 50 cm soil depth. This sampling applies to the 85 % of the forest land that is on mineral soils, but not to peatlands (organic soils with an organic horizon > 30 cm thick). For the peat soils, repeated measurements of the soil C stock are not available and estimates are based on modelling in all countries, which also includes modelled emissions of methane (CH_4) and nitrous oxide (N_2O), much more potent GHGs than CO_2.

The predominant mineral soils in Sweden have a C stock of on average 73 t per ha (in the mor-layer and the mineral soil down to 50 cm depth). Given that Sweden was de-glaciated around 10 000 years ago, the average increase in soil C was a modest 7 kg C ha^{-1} yr^{-1}. At century time-scales, soil C likely increased between fires, but declined due to fires. Wardle et al. (2003) calculated an increase of 50 kg ha^{-1} yr^{-1} for centuries without a fire during the last thousands of years. Today's estimated or measured accumulation rates in mineral soils in Norway, Sweden and Finland, countries with a similar glacial history, are clearly higher, 40 - 190 kg C ha^{-1} yr^{-1} (Liski et al. 2002, Peltoniemi et al. 2004, de Wit et al. 2006, Ågren et al. 2008, Rantakari et al. 2012, Dalsgaard et al. 2016, Strand et al. 2016). These studies support the reports to UNFCCC of accumulation rates around 100 kg C ha^{-1} yr^{-1}.

The net C sink in mineral soils may be offset in part by emissions of GHGs from peat soils (e.g., Korkiakoski et al. 2020). For the purpose of the climate reporting in relation to forestry, only emissions from drained peatlands are included. For Sweden, modelling emissions of CH_4 and N_2O lead to climate-forcing estimates on par with about 380 kg C ha^{-1} yr^{-1} in CO_2 equivalent release (CO_2 from decomposition of organic matter plus the CO_2-equivalent effects of other gases) if applied to all peat soils. If only the drained soils (ca. 25 % of the peat soils in forest land) are considered, the estimate is ca. 1500 kg C ha^{-1} yr^{-1} for those soils, which contribute 3.7 % of the total forest land. Given the much larger area of forest on mineral soils, the average for all forest soils in Sweden is a sink of c. 100 kg C ha^{-1} yr^{-1}. Norway has less of drained organic soils than Sweden, but Finland has considerably more. Hence, Finland has more emissions of CH_4 and N_2O. The overall result for Finland is that the build-up of soil C in mineral soils compensates for less of the GHG emissions from peat soils than in Norway and Sweden. Peatlands are not drained for forest management in Canada and Alaska.

4.4 Can we attribute the enhanced soil C sink on mineral soils to forest management?

Evidence is not available to clearly separate any effects of management from other potential factors. A common assumption is that the soil C stock should increase with increasing inputs from the trees, but decrease if higher temperatures enhance rates of decomposition of organic matter (Liski et al. 2002; Ågren et al. 2008). Hence, the national estimates reflect the long-term balance between inputs and losses under the prevailing climate, management or disturbance regime. This integrates the local spatial and temporal variability, which may be considerable. Thus, we can conclude that mineral soils in the Nordic forests on average sequester C, despite substantial harvests from the forests. Note also that in the three Nordic countries the soil C stocks are almost twice the C stocks in living tree biomass (cf. Table 1).

There has been attention to the possibility of C losses from the soil after clear-felling, based on the ecosystem being a source of C in that context (see 5.1. above, and Yanai et al. 2003). Losses can occur because of lower inputs or accelerated decomposition of soil organic matter due to perturbation of the soil and changed microclimate. In a wider global context, it is commonly held that significant amounts of soil C are lost in the years to decades after clear-felling of forests (Mayer et al. 2020); for tropical forests there is strong evidence for large losses when the forests are converted to arable lands or pastures. Many local studies in boreal forests focusing on the uppermost soil layers and period immediately after clear-felling suggest loss of soil C, but sampling to greater depths show smaller or no effects (Clark et al. 2015, Mayer et al. 2020). How important are such losses of soil C in the longer term and across larger landscapes and regions?

We have already concluded that soil C is accumulating at a significant rate in the mineral soils of the three Nordic countries, where rotational forestry involving clear-felling is practiced on most of the forest land. This suggests that these practices do not cause a widespread decline in soil C in the longer term. Furthermore, Stendahl (2017) used a large data set involving 3500 sites sampled by the soils inventory in Sweden to examine if the soil C stock changes with the age of the forest stand (with 10 age-classes from 4 to 143 years old and on average 175 samples per age-class per region studied), e.g., if it decreases after clear-felling. This approach is associated with the methodological problem of substituting “space for time”, because forests of different ages (now found on different plots, areas) have experienced different changes in environment and management. The problem is less important if smaller rather than large differences in stand age are studied and if there are many geographical sampling points (Stendahl used many age-classes and a large number of samples distributed over the regions studied). In the study by Stendahl (2017), the southernmost 20 % of Swedish forests indicated a temporary decrease after clear-felling; in the remaining 80 % of the forests, there were no significant differences in soil C stock depending on forest stand age. Superimposed on this, was the overall increase mentioned of about 100 kg C ha^{-1} yr^{-1} across all forest age-classes. In southern Finland, Peltoniemi et al. (2004) measured the soil C stock in 64 forests, spanning a range of stand ages. They found no clear minimum in soil C in the organic layer in young forests, no change with age in the mineral soil and overall an increase in the organic layer by 42 kg C ha^{-1} yr^{-1} in these managed forests.

Soil scarification is a common management method, which leads to a net release of C (partial removal of the upper soil organic layer is a method often used before replanting). However, analysis of all ecosystem components have revealed that decreases in soil C after soil scarification or more drastic deep plowing have been compensated by greater uptake of C through enhanced tree growth (Egnell et al. 2015, Mjöfors et al. 2017, Mayer et al. 2020). Presumably, the disturbance leads to greater release of soil nitrogen (the nutrient commonly limiting forest growth in boreal forests), especially from the dying mycelium of mycorrhizal fungi (Högberg et al. 2017). This extra N adds to the alleviation of the competition for N experienced by tree seedlings caused by the removal of the larger trees by the previous clear-felling.

4.5 What about the possibility of forest management increasing emissions of other GHGs?

As noted above, peat soils in wet areas can be major sources of the potent GHGs CH_4 and N_2O. Ditching (to improve soil aeration of tree roots) and clear-felling could have substantial effects on the releases of these gases (e.g., Korkiakoski et al. 2020), as soil oxygen levels strongly influence their biogeochemistry. In contrast, forests on mineral soils are commonly minor net sinks for CH_4 and N_2O (e.g., Sitaula et al. 1995, Kasimir Klemedtsson & Klemedtsson 1997, Chapuis-Lardy et al. 2007). Emissions of N_2O occur transiently after clear-felling or more continuously in local hot-spots like N-rich groundwater discharge areas. However, most boreal forest soils are very poor in available N (Högberg et al. 2017) and the tendency seen in runoff water from larger watersheds is that leaching of inorganic N is declining, despite enhanced leaching of N locally and temporarily after clear-fellings (Lucas et al. 2016). Hence, it seems the N limitation to forest growth will prevail. This picture would change, however, if N fertilization became more common. Nitrogen fertilization may transiently increase N_2O emissions, but also greatly increase C sequestration in both tree biomass and soils (e.g., Johnson & Curtis 2001). There are no reports suggesting that the effect of commercial fertilization of forests is negative in terms of the overall effect on the GHG balance (note that N-rich organic soils should not be fertilized).

4.6 Can forest management decrease the albedo and hence increase warming?

About half of the sunshine falling on forests is reflected back to space, with no effect on temperatures of trees and air. The rest of the radiation is either absorbed by the vegetation and soils (leading to warming) or consumed in evaporation of water. The proportion that reflects away from forests (the albedo) varies over time as a function of the characteristics of forest canopies, ground vegetation and snow cover (Fig. 11, Table 3). Disturbances such as clear-felling (along with subsequent choice of tree species) and fires affect albedos at landscape scales (e.g., Astrup et al. 2018, Bright et al. 2013, 2017, Randerson et al. 2006). Clear-felling and fire both increase the winter-time albedo by increased exposure of snow-covered ground. In the summer, newly burned areas will have a very low albedo, which is true also for very dense stands. Our data on living biomass C (Table 2) indicate that across countries there are no large differences in average living biomass C per hectare, which suggests that the albedo may not differ much between managed and un-managed conifer forests despite the dynamic variations after disturbances.

Regarding choice of tree species, evergreen conifers in general have a lower albedo than deciduous broadleaves, especially when considering the annual cycle of leaf-fall (Chapin et al. 2012). Conifers dominate boreal forest landscapes, though deciduous trees are important in some areas. Larch, a deciduous conifer, has a high albedo compared to other conifers. Siberian Larch (*Larix sibirica*) is the most widespread tree species in Russian forests. Larch-dominated forests account for 36 % of the total forest area in Russia and is locally dominant in Siberia and the Russian Far East. These forests are rarely harvested; but larger albedo changes occur after fires. Broadleaved trees sometimes form stable communities, like the mountain birch forests of the Nordic countries. Other fast growing broadleaves are common after disturbances, but over time become replaced by slower growing conifers.

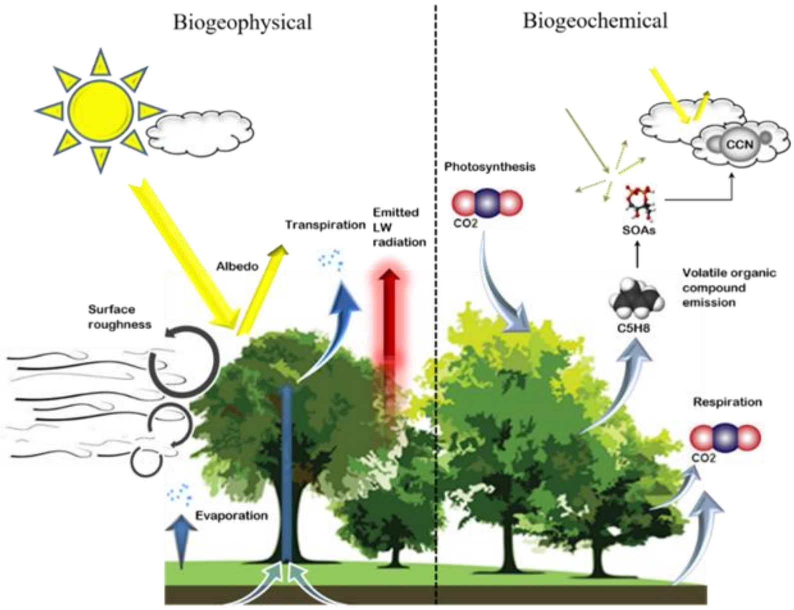

Figure 11. *Simplified depiction of factors and processes affecting climate forcing (see also Table 3). LW, long-wave (radiation), C5H8, isoprene, an example of a volatile organic compound, which may oxidize forming a secondary organic aerosol, SOA, which in turn can form cloud condensation nuclei, CCN which reflect incoming radiation and cool the atmosphere. Graph made by Ryan Bright.*

4.7 Could management to increase forest albedo counter warming from increased concentration of GHGs?

Forest management could aim for higher albedos by using frequent clear-fellings and thinnings to maintain open stands, and by increasing the dominance of broadleaves or larch. However, some of these measures would decrease the C sink strength of the forest, e.g., conifers commonly grow faster in the longer term than the broadleaves and denser forests accumulate C faster than open forests. In any case, active harvests lead to higher albedo as compared to management aiming at just keeping a high C stock in the living tree biomass. A recent analysis (based on satellite remote sensing of surface albedo) revealed that the structure of boreal forest had more influence on albedo than did the balance between conifers and broadleaves, especially at high latitudes as compared to lower latitudes (Hovi et al. 2019). Moreover, differences in forest structure affect the albedo more in the period with snow-cover as compared to the snow-free season (Kuusinen et al. 2016).

The combined effect of changes to surface albedo and the C balance can be measured in terms of a radiative forcing – or the perturbation to Earth’s shortwave radiation balance. However, additional measures like changes to surface or air temperature are needed to account for non-radiative biophysical forcings (i.e., changes to surface roughness (unevenness of the upper plant canopy) and evapotranspiration) that often accompany a surface albedo change. These may or may not carry the same sign as the radiative forcing (Table 3), depending on a multitude of physical processes and feedbacks occurring at or near the surface and lower atmosphere (e.g., Bright et al. 2017). While the so-called non-radiative biophysical forcings can be important at local scales and near the surface, only the albedo change radiative forcing is a true external forcing (i.e., it can affect Earth's radiative balance) and hence has the capacity to alter regional and global climate (Winckler et al. 2018).

Table 3. Factors and processes increasing or decreasing the climate forcing, i.e. warm (+) or cool the atmosphere (-). See also Fig. 8. Arrows show whether forests in general provide more cooling (arrows pointing upward) or more warming (arrows pointing downwards) than the open vegetation in a pasture.

	Climate regulation mechanism	*Description*	*Value relative to pasture*	*Climate forcing*
Biogeophysical	*Surface roughness*	*Rough surfaces (like forests) promote vertical mixing of air*	↑	-
	Surface albedo	*Determines radiative energy available at the surface*	↓	+
	Transpiration	*Transfer of moisture from soil to atmosphere via plant stomata*	↑	-
	Evaporation	*Transfer of moisture from soil and vegetation to atmosphere*	↓	+
	Emitted longwave radiation	*Determines surface temperature*	↓	-
Biogeochemical	*Photosynthesis*	*Removes CO_2 from the atmosphere via plant stomata*	↑	-
	Respiration	*Adds CO_2 to atmosphere via plant stomata/roots; heterotrophic metabolism*	↑	+
	Volatile organic compound emission	*Promotes secondary organic aerosol (SOA) formation, which can in turn serve as cloud condensation nuclei (CCN)*	↑	-

The production of biogenic volatile organic compounds (BVOCs) by forests add further complexity (e.g., Ehn et al. 2014, Holopainen et al. 2017, see also Fig. 11 and Table 3). This is because condensable oxidation products of BVOCs, secondary organic aerosol (SOAs), also affect the Earth's radiation. The SOAs contribute to atmospheric cooling by scattering the solar radiation and by functioning as cloud condensation nuclei (clouds have high albedo). Importantly, loss of production of BVOCs in clear-cuts results in an effect on the climate in the opposite of direction to the effects of albedo and there are also differences in the production among volatiles among tree species (Kalliokoski et al. 2020). These complex interrelations deserve further study.

As regards the major question asked in this section (section 4), we conclude that the choice between managing the forest for harvesting or leaving the forest must also consider the potential for climate change mitigation by storing C in products and substituting products associated with much higher GHG emissions. Any accounting of a subset of the full C effect will not provide an adequate basis for effective policy development.

5 Harvested wood products (HWPs): we must look beyond the forests!

To satisfy the demand for HWPs is a key purpose of forestry. Some wood-based products have unique properties and cannot be replaced at present by other products, while other wood products may substitute products based on other raw materials (Fig. 3). One may indulge in an intricate analysis of the forest sector per se, or restrict the analysis to what happens in the forest, but the more interesting future societal perspectives involve the role of forestry and forest products in comparison to the impact on the environment of other sectors supplying alternative products. Thus, we need to account for the C in wood products through production, use and post-consumer treatment, as well as the use of wood products in place of CO_2-emissions-intensive materials and energy.

Forestry is a sustainable bio-economy from the C balance point of view if it does not decrease the C stock on average across the managed forest landscapes and given that the harvested material substitutes fossil-based products and concrete. Our data show that in Nordic countries, forest management involving rotational silviculture does not lead to a decrease in the C stock of living tree biomass. On the contrary, the intensive management of the Nordic forests increased the C stock 1990 - 2017 (Fig. 4). The high economic value of these forests have motivated an effective suppression of forest fires (Fig. 9). Only in the Alaskan boreal forests, which are not harvested, did we see a decline in the C stock of living tree biomass (Fig. 5).

The forest sector compares with other sectors providing alternative materials, e.g., the production of plastics from fossil C sources, and construction materials such as steel and concrete. These alternatives are associated with major emissions of CO_2, and thus un-sustainable from the point of view of the global GHG balance. Moreover, industrial and logging residues can be used to produce biofuels like ethanol and diesel, which can substitute fossil-C based fuels. In the future, wood will be used to make many more products than previously, e.g., textile fibers and new composite materials, as markets adapt to a future with minimal use of fossil-C. Political decisions may play a vital role in that development.

Various numerical factors are used to calculate the substitution effects when wood products are used to replace other products. A recent EFI (European Forest Institute) report (Leskinen et al. 2019) compiled information on substitution factors (GHG emissions avoided if a wood product is used instead of another product, per unit of product). They found a wide variation among products, but also that on average substitution factors were >1 (a factor of 1 denotes that a unit of C in the wood product replaces 1 unit of C in a fossil-derived product), with reduced emissions resulting from lower production emissions and using post-consumer wood for energy (Leskinen et al. 2019). Therefore, substitution benefits need to be added to the forest ecosystem and HWP carbon pool tracking to assess the overall net GHG emissions (e.g., Lempriére et al. 2013, Smyth et al. 2014, Iordan et al. 2018). There is substantial variability and uncertainty in substitution benefits (which some state are overestimated, e.g., Harmon et al. 2019), with a strong focus on long-lived construction products and limited information on other products (e.g. paper, textiles, and biochemicals).

The analysis of substitution benefits is commonly quite complex, especially since a full life cycle analysis must consider that products are often re-cycled. Fibers in paper may, for example, be used in secondary products through several cycles, and finally be used for energy production (e.g., Lundmark et al. 2014). The C in these products remains withdrawn from the atmosphere, and the final combustion for energy production may substitute fossil fuel combustion. However, the international protocols used to report GHG balances do not attribute the full-life cycle effects of all forest products to the forest sector. Where substitution benefits are realized, these are expressed as emission reductions in other sectors. The analysis is further complicated by the fact that use and recycling is constantly evolving.

Harvest residues are treated differently in the six countries. The climate benefits of bioenergy production from harvest residues depend critically on the alternative uses of the residues. If they are used for energy production, this speeds up the forest C cycle, and leaves less C in the forest (Repo et al. 2011), but decreases emissions of fossil C. In Finland and Sweden, treetops and branches left over after stem harvests are to some extent used in municipal heating and power plants together with disposals from households. The use of forest harvest residues for energy production has expanded at the expense of the use of fossil C. In Sweden, bio-energy constitutes 25 % of the total energy production (Statistics from Swedish Energy Agency, data for 2017), which almost equals the energy supply from petroleum and coal. In some Canadian provinces, tree-tops and branches are burned on the site to abate the risk of accidental fire. In Canada at large, some post-consumer wood material is deposited in landfills, where much of the material can remain undecomposed for a long time, but where the more readily decomposable portion of the material releases CO_2 under aerobic conditions and methane under anaerobic conditions. Flaring can reduce landfill methane emissions, and capture, purification, and burning of landfill methane for energy production instead of fossil fuel burning can also reduce emissions.

The further development of the use of wood as raw materials depends on technical innovations, but also on developments within other sectors. An increase in fossil fuel prices would make materials or fuels from wood more competitive. Political decisions, especially with regard to the fulfillment of the Paris agreement also have a very important role in this context.

We would like to stress, once again, that most of the discussions about the environmental effects of forestry, including the role in the GHG balance, see forestry in isolation and do not compare the sector and its products with other alternative ways of supplying similar products. A more holistic analysis, which better integrates the effects of humans on the composition of the atmosphere, has greater relevance to the development of sustainable societies.

6 Future projections, conclusions and final recommendations

Climate change mitigation requires reduction of GHG emissions and enhancement of C sinks. The forest sector clearly has a potential to contribute positively in this context. However, as outlined in the last section, the use of the HWPs and their relations to alternative products will develop in dynamic and complex ways. We submit that this requires a separate in-depth analysis by another team of specialists.

The major question addressed here was whether un-managed boreal forests have a greater net uptake of C than forests managed for wood production. As shown by the data from Alaska, Canada and Russia, un-managed boreal forests and forests with a low intensity of management do not, on average show any increase in the C stock in living tree biomass. In Alaska, with no major tree harvesting, the losses of C from the forests in fires exceed the tree net C uptake and turned the forest ecosystem into a C source. In contrast, the data from the three Nordic countries show that intensive management involving high rates of harvesting, combined with enhanced regeneration and other management methods including effective fire suppression, can enhance the C stock in living tree biomass and the soil. Moreover, intensive forest management results in additional C storage in wood products. Intensively managed forests in the Nordic countries now carry a similar total stock of C as in the less intensively managed boreal forests in other countries (Table 1).

Thus, more intensive management also of larger parts of the vast forests of Alaska, Canada and Russia could potentially increase forest growth. This would allow larger harvests without loss of C from the average standing stock. At present, this stock does not increase in Canada and Russia, and large losses of C occur in wildfires. These losses are not much smaller than the removals by harvests and represent lost opportunities to store C in wood products or use them to substitute materials associated with large net C emissions to the atmosphere.

Future projections suggest that in the Nordic boreal forests, the increase in C stock in living biomass will level off, but continuous removal of CO_2 from the atmosphere can be maintained through wood harvests, which will increase C stocks in wood products and achieve ongoing substitution benefits. As noted earlier, the magnitude of C benefit from harvested wood products varies among types of products. The economic revenue benefits the society at large, but in a narrower perspective also provides the resources for effective fire suppression. In a situation without the income from forestry, other sectors need to bear the cost of protecting the forests from devastating fires and hence drastic reductions in ecosystem C.

We found that the average standing biomass does not vary much between un-managed and managed forests, which suggests that the albedo does not vary much on average either, although the managed forests shift between a low albedo in the dense older forests prior to clear-felling and a high albedo after felling. The albedo could be increased by increasing the clear-felling harvest intensity and by maintaining a greater cover of broad-leaved species. However, at most sites, the latter would require very active management to exclude conifers from reaching dominance. Moreover, recent research provided higher estimates of the cooling effect of the SOAs above forests and the challenge to minimize the combined climate effect on the atmosphere of the GHG balance, albedo and SOAs.

Forestry can have negative effects on biodiversity (Framstad et al. 2013), and these effects need to be reduced. In the Nordic countries, policies have addressed such problems over the last three decades. This has resulted in increases in amounts of dead wood and deciduous trees in the forests, but not to the satisfaction of all quarters in the on-going debates. However, just like the effects on the GHG balance, the negative effects of forest management should not be seen in isolation, but rather be compared to the impacts of the production and use of alternative products, with associated GHG emissions and other effects on the environment, e.g., climate impacts on biota, including effects on biodiversity. Political decisions must, of course, also value socio-economic and cultural dimensions.

We conclude that the forest sector can be a sustainable component of the bioeconomy. It has potentials to increase, especially in the large countries with a low intensity of forest management. There it can become even more important in storing C in forests and long-lived forest products, and avoiding CO_2 emissions by replacing concrete and materials and fuels based on fossil C. Moreover, opportunities to increase boreal forest resilience to wildfire and to reduce future wildfire emissions through measures such as fuel management, thinning, use of prescribed fires and use of biomass in a bioeconomy need to be explored in the countries, which currently practice less intensive management. The potential negative effects of intensive forest management on biodiversity will always warrant attention and appropriate prescriptions to ensure C benefits are not unduly linked with undesirable impacts.

Finally, we also found that the countries with boreal forests have much to learn from each other and much to gain by continued collaboration on projects addressing the state and use of these forests.

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9 Appendix

9.1 Appendix 1

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9.2 Appendix 2. Definition of forests according to FAO 2015

Definition of forest land and explanatory notes

Land spanning more than 0.5 hectares with trees higher than 5 meters and a canopy cover of more than 10 percent, or trees able to reach these thresholds in situ. It does not include land that is predominantly under agricultural or urban land use.

Explanatory notes:

1. Forest is determined both by the presence of trees and the absence of other predominant land uses. The trees should be able to reach a minimum height of 5 meters.

2. Includes areas with young trees that have not yet reached but which are expected to reach a canopy cover of at least 10 percent and tree height of 5 meters or more. It also includes areas that are temporarily unstocked due to clear-cutting as part of a forest management practice or natural disasters, and which are expected to be regenerated within 5 years. Local conditions may, in exceptional cases, justify that a longer time frame is used.

3. Includes forest roads, firebreaks and other small open areas; forest in national parks, nature reserves and other protected areas such as those of specific environmental, scientific, historical, cultural or spiritual interest.

4. Includes windbreaks, shelterbelts and corridors of trees with an area of more than 0.5 hectares and width of more than 20 meters.

5. Includes abandoned shifting cultivation land with a regeneration of trees that have, or are expected to reach, a canopy cover of at least 10 percent and tree height of at least 5 meters.

6. Includes areas with mangroves in tidal zones, regardless whether this area is classified as land area or not.

7. Includes rubberwood, cork oak and Christmas tree plantations.

8. Includes areas with bamboo and palms provided that land use, height and canopy cover criteria are met.

9. Excludes tree stands in agricultural production systems, such as fruit tree plantations, oil palm plantations, olive orchards and agroforestry systems when crops are grown under tree cover. Note: Some agroforestry systems such as the “Taungya” system where crops are grown only during the first years of the forest rotation should be classified as forest.

9.3 Appendix 3. Brief country by country descriptions of the methods of forest inventory

9.3.1 Alaska (part of the USA)

The results presented are extracted from a C and GHG assessment conducted by scientists from the U.S. Geological Survey (USGS), the U.S. Department of Agriculture (USDA) Forest Service, and the University of Alaska-Fairbanks [1]. The assessment results partially fulfilled requirements set forth by the U.S. Congress through the Energy Independence and Security Act (EISA) of 2007 for a national C sequestration and GHG flux assessment.

The methods included (1) the organization of input data for models parameterization and simulations; (2) modeling of processes in biogeography, fire regime, permafrost, and hydrologic dynamics; (3) syntheses of C dynamics via biogeochemical modeling for upland and wetland ecosystems. The assessment was prepared for a historical period (1950–2009) and a future projection period (2010–2099). Input data were organized for soil C; soil texture; permafrost distribution; active-layer thickness; vegetation C; historical forest harvest; future forest management; land-cover distribution; fire disturbance; wetland and surface-water distribution; historical and future climate; upland and wetland biogeochemistry; and the transport, emission, and burial of aquatic C. The assessment uses the Alaska Frame-Based Ecosystem Code (ALFRESCO; [2], [3]) to simulate changes in fire regime and vegetation distribution from 2010 through 2099. ALFRESCO was calibrated based on historical data about fire occurrence for Alaska from 1950 through 2009. The Dynamic Organic Soil version of the Terrestrial Ecosystem Model (DOS-TEM; [4]–[7]) was used to estimate changes in ecosystem pools and fluxes for the two time periods for upland and wetland ecosystems. DOS-TEM used input data on soil texture, land cover, historical climate, historical fire, historical forest harvest, and model projections of future climate, fire disturbance, and forest management. The Methane Dynamics Module of the Terrestrial Ecosystem Model (MDM-TEM; [8], [9]) was used to estimate methane consumption in upland ecosystems and both methane consumption and emissions in wetland ecosystems.

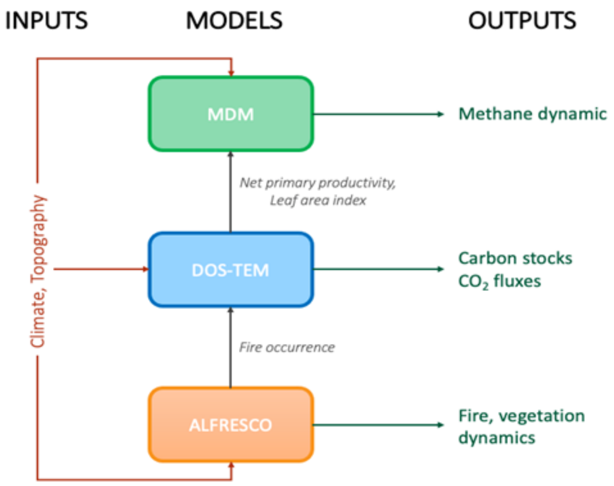

***Figure:** Modeling framework for the C and GHG assessment for Alaska.*

9.3.1.1 Literature

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9.3.2 Canada

The estimates of carbon stocks and fluxes summarised here are derived from Canada’s National Forest Carbon Monitoring, Accounting and Reporting System (NFCMARS). The Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3, Kurz et al. 2009) is used to combine forest inventory data, growth and yield information, activity data on forest management, natural disturbances and land-use change (Stinson et al. 2011, Kurz et al. 2013), to derive estimates of carbon dynamics in natural and anthropogenic components of the GHG inventory (Kurz et al. 2018) for Canada’s managed forest (Ogle et al. 2018) and to estimate the uncertainties of these estimates (Metsaranta et al. 2017). Forest ecosystem and harvested wood product carbon dynamics are provided to Environment and Climate Change Canada for inclusion in Canada’s annual National Inventory Report (ECCC 2020). The NFCMARS uses the IPCC “gain-loss method” that yields annual estimates of GHG emissions and removals with attribution to their causes (fire, harvest etc.). This approach is also suitable to make projections of future GHG emissions and removals to support analyses of forest sector mitigation options (e.g. Smyth et al. 2014) and for Emissions Trends Reporting.

In Canada, resource management is the responsibility of provincial and territorial governments, and their forest extensive inventory data are used to inform NFCMARS. In addition, Canada’s new National Forest Inventory conducted its first 10-year measurement cycle between 2008 to 2017 (Gillis et al. 2005). NFI establishes ground plots and measures all carbon pools (biomass, dead wood, litter and soil carbon) using nationally-consistent methodologies. These ground plot data were used to assess the performance of the CBM-CFS3 (Shaw et al. 2014) and to explore opportunities to refine modelling parameters (Hararuk et al. 2018).

9.3.2.1 Literature

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9.3.3 Finland

The National Forest Inventory in Finland (NFI) is a monitoring system with the aim to report land use area changes, development of forest resources, increment, silvicultural status of forests, forest health and biodiversity. The basis of NFI is statistical sampling. The NFI sample plots cover whole Finland, and consist of over 70 000 sampled locations. The NFI field data consist of three main categories: stand description, tree data, and dead tree data, and the total of registered variables is over 150 characteristics for each sample plot. The inventories are repeated in 5 year intervals. The sampling intensity varies in different parts of Finland, and the sample consists of permanent and temporary clusters. The distance between sample plot clusters, shape of the cluster, number of field plots in a cluster, and distance between plots within a cluster varies in different parts of the country according to spatial variation of forests and density of roads. Field measurements together with models, map information, cutting statistics and household surveys provide information on land-use, forest resources, silviculture, forest protection and biodiversity, increment and drain, and wood quality and use.

9.3.4 Norway

The National Forest Inventory (NFI) in Norway is a monitoring program, which provides a nation-wide survey of Norway’s forest resources based on a statistical representative sample of permanent plots (Breidenbach et al. 2020). The majority of the plots are spread over a 3 x 3 km grid, with the remaining plots distributed over 3 x 9 km (mountainous/high altitude regions) and 9 x 9 km grid (Finnmark county, northern of Norway). 1/5th of the forest plots are surveyed every year, providing full national coverage after 5 years. There are 22 008 plots, with approx. 12 700 plots covering the land meeting the forest definition (Forest land, but also some wooded grasslands and mires). While only areas meeting the forest definition are physically surveyed, all other plots are monitored through aerial photography providing land-use classification needed for the national greenhouse gas (GHG) inventor reporting of land-use, land use change, and forestry (LULUCF) under the UNFCCC. In addition to area representation, the NFI further provides the tree diameter and height which – using biomass models – supplies the biomass estimates needed for the GHG accounting of living biomass on the scale of each NFI plot. Estimated living biomass compartments of foliage, branches and roots multiplied with annual turn-over rates in addition to NFI-based estimates of natural mortality and harvest residues provide input to the soil-and decomposition model Yasso07, which is used on upland forest areas to estimate C stock change (CSC) of mineral soil and dead organic matter (litter + dead wood). Undrained organic soils on forest land are presumed to be in equilibrium, and have a net emission of zero. Estimated of emissions from drained organic soils on forest land are based on IPCC default emission factor with statistics on subsidies for draining forest soils. Non-CO_2 GHG emission estimates of forest fires are based on areas subject to wildfires, provided by the Norwegian Directorate for Civil Protection (DSB), and 2006 IPCC guideline Tier 1 methodology. CO2 emissions from forest fires are indirectly accounted for through living biomass losses registered through the NFI.

9.3.4.1 Literature

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9.3.5 Russia

At present, the quantitative estimation of the C stocks, as well as of C removals, and emissions and C balance in Russian boreal forests are built upon the data from the State Forest Register (SFR) (from 2008) and State Account of the Forest Fund (SAFF) (before 2008). According to the Forest Law (Article 91, Forest Code, 2006), the State Forest Register is a documented source for information on forests, their use, forest protection management and forest reproduction. Strictly speaking, State Forest Register (SFR) is the annually updated forest statistical reporting data. The input data for SFR relating to qualitative and quantitative indicators of the forests is collected by forest inventory and planning. These data are collected, not from sampling plots, but from forest stands during forest taxation, and the procedure is implemented at different times. The growing stock volume, input parameter for C assessments, have been determined with different accuracy; for instance, acceptable standard deviations in estimating growing stock may vary from ±15 to ±30% while systematic errors should not exceed 10%. The data collected in the course of forest inventory and planning is consolidated by forest species, age groups, site classes and stand density groups, and summed over compartments, forest management units and constituent members (subjects) of the Russian Federation, to be entered in the SFR at the end of each year. Apart from qualitative and quantitative indicators of the forests, the SFR provides information on all changes in forests during the reporting year, including harvest volumes resulting from clear and selective felling, sanitary clear and selective felling; areas damaged by forest fires and insect outbreaks, etc.

The state (national) forest inventory with the measurement of forest characteristics on permanent sample plots gives an estimate of the growing stock volume with an error of ±1-4 %. The first full cycle of State forest inventory in Russia should be completed in 2020. The data obtained would make it possible to significantly improve the assessment of C stocks in boreal forests and further harmonize the assessments of forest C sequestration in Russian forests and other boreal zone countries.

9.3.6 Sweden

The Swedish numbers are mainly based on data from permanent sample plots inventoried by the National Forest Inventory (NFI; Fridman 2014). The NFI plots were established 1983-1987 and are re-inventoried every fifth year. The NFI is an annual, systematic, cluster-sample inventory of Sweden's forests. Each year roughly a thousand survey sample clusters, or 6000 sample plots, are inventoried in the field. The clusters are distributed all over the country in a pattern that is denser in the southern part than that in the northern part. On each circular sample plot, with a radius of 10 m, measurements are made on trees, thereafter allometric models are used to estimate biomass (Marklund 1987; Petersson and Ståhl 2006). Land use is assessed in the field and a sample plot can be delineated into more than one land use category. Area based sampling is applied and one sample plot represent a certain area and all sample plots together represents the total area of Sweden. The idea is to correctly measure variables on the plots and thus most of the uncertainty of the estimates arises from the random sampling process. The estimated area of forest land (FAO-definition) is around 27-28 Mha and the sample error is around 0.3 Mha (1%). The gross growth (whole tree biomass) is around 165 M ton CO_2 yr^{-1} and the sample error is 3.0 M ton CO_2 yr^{-1} (2 %) for change in stock. The model error for estimates of change in stock is around 1 % (Peterson et al. 2017).

9.3.6.1 Literature

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The Swedish Forest Agency participates in several international collaborations, including with the International Boreal Forest Research Association (IBFRA). In June 2018, representatives of the governments of six boreal countries met in Haparanda in northern Sweden to discuss the contribution of boreal forests and forestry in efforts to mitigate climate change. At the meeting, IBFRA was asked to prepare a scientific background sketch to further discussions.

This report is the result of a so-called IBFRA Insight Process, in this case a collaboration between 25 researchers from the USA, Canada, Norway, Sweden, Finland, Russia and the International Institute of Applied Systems Analysis (IIASA).

The report provides information on the carbon balance in boreal forests under different management regimes. These forests cover approximately 30% of the area globally covered by forest. The report affirms that the carbon stock of the boreal forests is large, that unused forests suffer to a very large extent from carbon losses in fires, while the managed forests show a rapid build-up of the carbon stock at the same time as they supply raw materials to the bio-economy.

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