HOW CAN THE CIRCUMBOREAL FOREST CONTRIBUTE TO MITIGATING CLIMATE CHANGE?

Pierre Bernier, Rasmus Astrup, Ryan Bright, Hélène Genet, Elias Hurmekoski ,
Florian Kraxner, Jari Liski, Tomas Lundmark, David McGuire, Jon Moen,
Werner Kurz, Dmitry Schepaschenko, Linda See, Anatoly Shvidenko,
Evelyne Thiffault and Diana Tuomasjukka

DISCUSSION PAPER PREPARED FOR THE IBFRA WORKSHOP

and

MEETING REPORT

Haparanda, Sweden

24-25 June 2018

INTERNATIONAL BOREAL FOREST RESEARCH ASSOCIATION

Table of contents

Introduction 0
ACTION #1: Increase forest growth 4
ACTION #2: Enhance the use of long-lived wood products 8
ACTION #3: Replacing fossil fuels with forest biomass 13
ACTION #4: Increasing the broadleaved deciduous component in the boreal 19
ACTION #5: Make albedo management part of climate-sensitive forestry 22
ACTION #6: Pursue afforestation of abandoned agricultural lands 28
ISSUE #1: How reactive are boreal soil carbon stocks to climate change? 31
ISSUE #2: Can increased disturbance regimes negate mitigation and adaptation actions? 35
ISSUE #3: Keeping an eye on the Taiga – Policy impediments for mitigation of climate change 40
Conclusion: Opportunities and benefits of increased research collaboration among circumboreal nations 43
MEETING REPORTS 46
 Science Workshop report 46
 Science-policy Dialog report 47
ACKNOWLEDGEMENTS 49
ANNEXES 50
 Annex 1: Meeting agenda 50
 Annex 2: Questions on climate change mitigation and adaptation in the boreal forest emerging from the IBFRA Science Workshop 52
 Annex 3: The IBFRA Insight process 54
 Annex 4: Policy questions or issues from country representatives at the Science-Policy Dialog 55

Introduction

Rasmus Astrup, Pierre Bernier, Florian Kraxner and Werner Kurz, editors

The atmospheric CO_2 concentration is reaching the 410 ppm mark and its incessant increase is climatically unsustainable. There is now a general understanding that this increase must be scaled back dramatically, and even reversed through net-negative emissions, if we are to maintain the projected global temperature increases to below 2°C, the aspiration of the 2016 Paris Agreement. This is an ambitious goal as invested capital in developed and developing nations is still overwhelmingly oriented towards a fossil-fuel-based society. Contributions from all possible sectors of society and from all geographic regions of the globe are therefore needed if this temperature goal is to be met. Moreover, IPCC scenarios indicate that the goal can only be met by combining both drastic reductions in the emissions from fossil fuel use and increases in land-based sinks that remove CO_2 from the atmosphere with the goal to achieve net negative emissions by the second half of this century.

From the very beginning of our understanding of climate change and of its root causes, the land sector was seen as both a part of the problem and a part of the solution. Carbon was released through the conversion of natural prairies and forests into fields and pastures to feed growing and more demanding populations. Carbon was also released by the degradation and thinning of forests at the margins of urbanized areas or for the creation of agricultural lands. Conversely, reforestation and afforestation, as well as the development of sustainable forest management practices and the use of wood products were and are still widely viewed as low-cost climate change mitigation measures.

In spite of this good will towards forests as sources of mitigation actions, investments in concrete actions have been low in comparison to investment in other sectors. This low level of interest for mitigation action in forest was in large part for reasons linked to the uncertainty of carbon dynamics in biological systems, as well as to the complexity of issues related to international trade of wood products. And what mitigation efforts have been done with forests through international investments have focussed mostly on the tropical regions where the possibility to reach the multiple goals of carbon emission reduction, protection of biodiversity and alleviation of poverty could justify the investments. As outlined by Moen et al. (2014), forests in boreal regions were mostly excluded from international mitigation frameworks because they were carbon sinks of low apparent biological diversity and, where managed, were generally subjected to strong regulatory processes that prevented large scale degradation or deforestation.

As Moen and colleagues, we consider this failure to properly incentivize the use of boreal forests for climate mitigation a missed opportunity. Boreal forests, their biodiversity and their ability to sequester and retain carbon can no longer be taken for granted. This immense biome covers 30% of the global forest area (Brandt 2013) and contains at least 32% of global terrestrial carbon stocks in climate-sensitive pools (Pan et al. 2011). Yet, it is being subjected to the largest projected increase in temperatures of all forest biomes for this century (Price et al. 2013), with attending shifts in disturbance regimes. For these reasons alone, boreal forests matter globally. At the same time, through their unique properties, they offer critical climate change mitigation opportunities large and small, that are coupled to adaptation opportunities as well (Lemprière et al. 2013).

About two-thirds of the boreal forest area is under some form of management, mostly for wood production (Gauthier et al, 2015), which results in a planned and active access to the land of more than two million hectares each year. This, coupled with generally high forest management expertise and strong regulatory frameworks, means that ground-based mitigation measures can be planned and carried out every year over vast areas of forests. Boreal countries are also major exporters of solid wood products, thus creating a flow of carbon from their forests to markets where sequestration and substitution effects can further contribute to climate change mitigation (Lemprière et al. 2013). The boreal forest is also occupied by populations dispersed in thousands of communities spread across its breadth. Their residents provide the workforce and expertise to create change but they also depend on a healthy and safe living environment that may be jeopardized by climate change. And while governance of the forests is generally strong, areas exist where it could be further strengthened, in particular with respect to the implementation of sustainable forest management. All these points present examples of specific mitigation and adaptation opportunities.

This document was prepared as a discussion paper for a science workshop and a follow-on policy-science dialog on enhancing the use of the boreal forests to be held in Sweden in June of 2018 (see the section “Meeting Reports” below). In it, we provide a short list of climate change mitigation **actions** that could be undertaken or are actually on-going but could be enhanced or spread more broadly across the managed boreal forest. We also present a short list of overarching **issues** that are not connected to a specific action but rather whose impact could affect the efficacy of most.

We chose to cover the actions and issues briefly so as to make the document as easy as possible to interpret in terms of possible policy points. We also highlight for each the associated knowledge gaps and research opportunities. Although we have limited the domain of interest to the areas of managed forest, we need to recognise the significant challenges we still face in the quantification and understanding of climate change impacts on the immense climate-sensitive stores of carbon in the vast unmanaged areas of the boreal forest. The document concludes with a description of possible next steps to enhance research collaboration among circumboreal countries.

The sections were written by individual scientists, often based on previously-published papers, and do not constitute an official position of their governments, institutions or IBFRA.

References:

Brandt, J. P. 2013. An introduction to Canada’s boreal zone: ecosystem processes, health, sustainability, and environmental issues. Environmental Reviews 21:207–226.

Gauthier, S., Bernier, P., Kuuluvainen, T., Shvidenko, A.Z., Schepaschenko, D.G. 2015. Boreal forest health and global change. Science, 349:819-822. doi:10.1126/science.aaa9092.

Lemprière, T.C., W.A. Kurz, E.H. Hogg, C. Schmoll, G.J. Rampley, D. Yemshanov, D.W. McKenney, R. Gilsenan, A. Beatch, D. Blain, J.S. Bhatti, and E. Krcmar. 2013. Canadian boreal forests and climate change mitigation. Environmental Reviews 21: 293–321

Moen J., et al. 2014. Eye on the taiga: removing global policy impediments to safeguard the boreal forest. Conserv. Lett. 7, 408–418.

Pan, Y., R.A. Birdsey, J. Fang, R. Houghton, P.E. Kauppi, W.A. Kurz, O.L. Phillips, A. Shvidenko, S.L. Lewis, J.G. Canadell, P. Ciais, R.B. Jackson, S. Pacala, A.D. McGuire, S. Piao, A. Rautiainen, S. Sitch, D. Hayes. 2011. A Large and Persistent Carbon Sink in the World's Forests, Science: 333: 988-993

Price, D. T., et al. 2013. Anticipating the consequences of climate change for Canada's boreal forest ecosystems. Environmental Reviews 21:322–365

ACTION #1: Increase forest growth

Tomas Lundmark (Swedish University of Agricultural Sciences, Umeå)

Context and proposal:

Boreal forests are mostly managed extensively, except in the Nordic countries (Norway, Sweden, Finland) and parts of eastern Canada where intensive forest management is practiced. In the intensively managed boreal forests, silvicultural practices and forest governance have aimed for a concept of sustainable forest management transforming natural forests to forests with high rates of productivity, and low rates of natural disturbances. Such a transformation has allowed for both large transfers of raw material from forests to society and increases in the carbon stock in living biomass in the forests. In such a system, forestry is largely based on clear-cut system within a normalized forests, that is a forest in which stands are even-aged and stand age classes have an even area representation on the landscape level.

To obtain a long-term sustainable flow of timber from the forest, annual harvest is adapted to annual forest growth so that growing stock is not reduced on the landscape level. By that no carbon debts occur after harvest in this kind of forest systems at the landscape scale. As an effect of active management, improved silviculture and increased standing volumes, the growth and potential harvest of managed boreal forests have increased. For these reasons, the amount of carbon stored in the forest ecosystem has increased while simultaneously providing an increasing stream of wood raw materials for use by society. This concept of sustainable forest management is well in line with the strategy identified by IPCC generating the largest sustained climate change mitigation benefit in the long term.

Mitigation and adaptation:

In the wake of the Paris Climate Agreement, societal expectations are now increasingly being placed on forests for climate change mitigation. Concurrently, available global forest resource per capita is decreasing due to deforestation and land use change as well as an increasing population. As a consequence, forest and natural resources are under increasing pressure to provide a variety of economic and environmental services, some of which are in conflict as more is expected from less forest land. Some of this potential conflict could be released if forest growth on already managed land could be further enhanced.

In intensively managed landscapes with low rates of natural disturbances, the most important factors defining the long term mitigation benefit of forests are their growth rate (harvest potential) and the use of forest based products (substitution potential). Field based forest research and practical observations spanning centuries have shown that both silvicultural methods and the choice of tree species can significantly affect forest yield and profitability. Classical practises intended to increase forest growth and yield include: (i) soil preparation, (ii) use of genetically improved forest trees, (iii)

the introduction of exotic, fast-growing tree species; (iv) forest fertilization; and (v) drainage of peatlands and mineral soils. These measures differ in terms of how much forest growth can increase on the stand level, when the increase occurs (short or long term response), and how this affects the potential to enhance future harvesting. The potential to increase future growth and harvest will also depend on the scale at which a given measure can be deployed within a managed forest landscape.
In commercial forestry, the regeneration phase sets the arena for the rest of the rotation cycle. The landowner can choose tree species, breeding material, stand density and site preparation to form the future forest stand. Site preparation can be applied on most forest land and result in higher survival of seedlings and enhanced early growth. Important aspects of soil preparation are that it reduces competition from field vegetation (Nilsson & Örlander 1999) and has been shown to be one way to protect seedlings from damage by insects such as pine weevils (Petersson et al. 2005). Higher seedling survival and enhanced early growth of the seedlings can be expected from this measure (Johansson et al. 2013).

Many studies have demonstrated significant genetic gains from tree breeding programs. Breeding has mainly focused on improving volume growth, although improvements in stem and wood quality have also been considered. The objectives vary between countries and for different species. Breeding for tolerance against pests and diseases has also recently been considered as a way to prepare for climate change (e.g. Stener 2015). Cultivated forest ecosystems can be based on native tree species or on introduced species, and the transfer of tree germplasm (selecting provenances of native species or introducing new more fast growing species) has shaped the management, ecology and genetic diversity of forests, both planted and natural, in many parts of the world (Koskela et al. 2014). Establishing new stands from genetically superior seeds or seedlings is a crucial investment for high and sustainable production in future forests, and successful forest regeneration is key to high productivity at a site.

The capacity of boreal forests to sequester carbon (C) and to produce raw material for transformation and bioenergy is strongly linked to the availability of nitrogen (N) (Tamm 1991). The Nordic countries use N fertilisation with ammonium nitrate as a means of increasing forest growth. Fertilization is an effective way of increasing carbon sequestration as nitrogen addition leads to an increased carbon dioxide uptake that is 10-15 times higher than the emissions caused by the production of the fertilizer and the transport and spread of the fertilizer (Börjesson et el. 1997). The simplicity of the idea of N limitation of growth is however in stark contrast to forest ecosystems' complexity of N cycling and tree N acquisition. Obvious contradictions to this idea include the existence of large N stocks in forest soils, a lack of consistent coupling between the large variability in tree growth and soil N availabilities, and the ephemeral effect of N fertilisation on tree growth. Importantly, claims that the addition of N to forests would lead to sustained long-term increases in forest growth capacity have been disproven, as soil N immobilisation efficiently removes added N from circulation, thus making N unavailable for tree uptake (Högberg et al. 2017). From the above it is apparent that our understanding of the phenomenon of N limitation is still inadequate. The potential use of recycled fertilizers and its effects on forest growth, carbon footprint and economy should also be included in future studies.

At sites with either peat or mineral soils in large areas of boreal forests, high soil-water contents hamper tree growth and drainage can significantly increase growth. Lowering the ground water level, and thus the soil-water content in the unsaturated water-zone, makes conditions more favourable for tree roots. This can substantially increase tree growth, provided that other production factors, e.g.

plant-available nutrients, are not growth limiting. When soil water content is too high drainage is known to improve seedling establishment and significantly increase tree-growth (Sikström & Hökkä 2016). The carbon balance of organic soils will however be determined also by changes in the decomposition and leaching of soil carbon. Drainage is known to increase respiratory oxidation and leaching of dissolved organic carbon to runoff which may cause an overall effect of draining organic soils resulting in increased carbon emissions (Silvola et al 1996).

Conclusion:

The silvicultural practice with greatest potential to promote forest productivity in the short term is fertilisation of already existing forests (Nilsson et al. 2011). With a longer time perspective, forest regeneration that take advantage of the opportunities of new species, better genetics and greater degree of micro-site adaption offers significant growth increases in the future. A comprehensive study of growth enhancing silviculture in Sweden showed that using existing tools to increase forest growth could double the long term productivity of the boreal forest compared to present practices (Larsson et al. 2008) indicating that there is a significant potential to increase growth and yield in the boreal forest. In order for society to be prepared to take action to increase forest growth if desired, more research is needed to develop today's forest management tools to meet future demands on our forests.

References:

P. Börjesson, L. Gustavsson, L. Christersson, S. Linder. (1997). Future production and utilisation of biomass in Sweden: Potentials and CO_2 mitigation. Biomass and Bioenergy, vol. 13, no. 6, pp. 399-412

Högberg, P., Näsholm, T., Franklin, O., & Högberg, M. N. (2017). Tamm Review: On the nature of the nitrogen limitation to plant growth in Fennoscandian boreal forests. Forest Ecology and Management, 403, 161-185.

Johansson, K., Nilsson, U. and Örlander, G. (2013). A comparison of long-term effects of scarification methods on the establishment of Norway spruce, Forestry: An International Journal of Forest Research, Volume 86 (1), 91–98.

Koskela, J., Vinceti, B., Dvorak, W., Bush, D., Dawson, I. K., Loo, J., ... & Jamnadass, R. (2014). Utilization and transfer of forest genetic resources: a global review. Forest ecology and management, 333, 22-34.

Larsson, S., Lundmark, T., & Ståhl, G. (2008). Möjligheter till intensivodling av skog.[Opportunities for intensive cultivation of forests]. Slutrapport från regeringsuppdrag Jo, 1885.

Nilsson, U., & Örlander, G. (1999). Vegetation management on grass-dominated clearcuts planted with Norway spruce in southern Sweden. Canadian Journal of Forest Research, 29(7), 1015-1026.

Nilsson, U., Fahlvik, N., Johansson, U., Lundström, A., & Rosvall, O. (2011). Simulation of the effect of intensive forest management on forest production in Sweden. Forests, 2(1), 373-393.

Petersson, M., Örlander, G., & Nordlander, G. (2005). Soil features affecting damage to conifer seedlings by the pine weevil Hylobius abietis. Forestry, 78(1), 83-92.

Sikström, U., & Hökkä, H. (2016). Interactions between soil water conditions and forest stands in boreal forests with implications for ditch network maintenance.

Silvola, J., Alm, J., Ahlholm, U., Nykanen, H., & Martikainen, P. J. (1996). CO_2 fluxes from peat in boreal mires under varying temperature and moisture conditions. *Journal of ecology*, 219-228.

Stener, L.G. (2015). The status of tree breeding and its potential for improving biomass production – a review of breeding activities and genetic gains in Scandinavia and Finland. Uppsala: Skogforsk.

Tamm, C. O. (1991). Introduction: geochemical occurrence of nitrogen. Natural nitrogen cycling and anthropogenic nitrogen emissions. In Nitrogen in Terrestrial Ecosystems (pp. 1-6). Springer, Berlin, Heidelberg.

Koskela, J., Vinceti, B., Dvorak, W., Bush, D., Dawson, I. K., Loo, J., ... & Jamnadass, R. (2014). Utilization and transfer of forest genetic resources: A global review. *Forest Ecology and Management*, *333*, 22-34.

ACTION #2: Enhance the use of long-lived wood products

Elias Hurmekoski (European Forest Institute, EFI)
Diana Tuomasjukka (EFI)

Context and proposal:

Wood-based products are generally considered to cause less environmental burden compared to many competing products, both in terms of resource efficiency and climate impact (Ritter et al. 2011). Long-lived wood products such as construction products, furniture, or textiles have the additional benefit that they extend the carbon storage of biomass, thereby allowing the carbon released from forest biomass in logging operations to be at least partially reabsorbed to replanted forests before the product is discarded (typically incinerated).

Compared to using wood in short-lived products or directly in energy generation, long-lived wood products help in avoiding short-term carbon emissions, and are therefore an essential way of abating climate change. Directing wood more towards long-lived, low-emission wood products in global markets, using boreal forest resources, can be an efficient partial strategy for reducing the emissions of the global economy. In addition, increasing the reuse and recycling of wood can further extend the use of the material over multiple lifetimes and decrease the need for virgin materials.

The consumption of long-lived wood products in the boreal region is already relatively high. However, these commodities are typically traded globally, which results in a huge potential to replace the global markets based on non-renewables. Due to various path dependencies and cultural bounds, this may, however, require significant changes in global climate-related regulation and carbon pricing (Mahapatra & Gustavsson 2008).

Using wood-based products is supported by different consumer-driven (ecolabels) and political initiatives. In Europe, the EU Bioeconomy Strategy (European Commission 2017a) and the Circular Economy Action Plan (European Commission 2015) are driving national and regional development towards increased use of old and new products to replace fossil materials. Debates around circular and sustainable bioeconomy stress the need to increase the lifetime and the reusability of products. This also influences house construction and the perception and accounting of wood construction in comparison throughout the whole building lifecycle (Lifecycle Assessment of a Building (EN 15978:2011)), with an increased focus on the post-use stages (recycling, reuse of materials). In the consequence, the environmental assessment aspects are changing from the current ISO standards (e.g. ISO 21931-1 Sustainability in building construction) which are main focused on LCA aspects like Global Warming Potential, emission to air and water, as well as primary energy use, to a wider range of indicators, including various economic, social and environmental aspects.

In 2015 the European Commission initiated a study to develop an EU framework of core indicators for the environmental performance of buildings (LEVELs) and identified six macro-objectives that establish the strategic focus and scope for the framework of indicators:

- Greenhouse gas emissions throughout the building's life cycle
- Resource efficient and circular material life cycles
- Efficient use of water resources
- Healthy and comfortable spaces
- Adaptation and resilience to climate change
- Life cycle cost and value

LEVELs is currently a voluntary framework, which is expected to become binding for public procurement in the EU's Level(s) framework (European Commission 2017b). National initiatives such as "Low Carbon buildings" for Finland (Kuitinen et al 2017) are under development throughout Europe.

In Russia, the focus is not on bioeconomy *per se*, but more on biotechnologies in which also wood construction is clearly included as a requirement in state federal and regional programs through which older buildings are replaced. According to official plans, by 2030 140-150 million m^2 houses should be constructed per year, of which 46-49% will be wooden houses of improved comfort and quality. New technologies for prefabricated wooden building construction offer an excellent possibility of increased timber usage.

Mitigation and adaptation:

Harvested wood products can provide climate benefits through four main mechanisms:

1. Trees sequester CO2 in standing forests through photosynthesis, and store the carbon in wood-based products for the duration of the life cycle of the product (**storage**)
2. Substituting more energy intensive materials for wood avoids larger fossil fuel consumption (embodied energy) and consequent CO2 emissions (embodied carbon) (**substitution**)
3. Use of the byproducts of sawmilling and pulping for **bioenergy** (energy self-sufficiency) or for other products (e.g., biofuels, biochemicals).
4. **Circular use** of wood products lends multiple lifetimes to wood material and increases thus the Carbon storage and need for virgin materials.

For long-lived wood products specifically, the storage impact (1.) is important. For calculating the carbon balance impact, one needs to assume an average duration for the lifecycle of the product, often expressed as "half-life" as suggested in IPCC guidelines. For sawnwood, the half-life is specified as 35 years, meaning that when 100 units of carbon are stored in sawnwood produced today, 50 units of carbon remain stored in the products 35 years from now, on average. The values depend on the specific usage and maintenance of the products – it is not unjustified to expect a 100-year lifespan for well-maintained wooden buildings.

The substitution impact (2.) is typically measured with a "displacement factor", essentially depicting the amount of avoided fossil emissions due to the difference in process-based fossil emissions (Sathre

& O'Connor 2010). The positive balance in favor of wood products in construction generally relate to the high-energy intensity (and heavy weight) of concrete and steel and the calcination emissions in cement manufacture.

Producing one unit of sawnwood provides roughly an equal amount of by-products (sawdust, chips, bark) that can be incinerated or used to manufacture other products, including wood-based panels, which may avoid still further fossil emissions through energy and material substitution (3.).

Circular use (4.) includes reuse, recycling, repurpose, cascade use and finally incineration as possible use stages of wood products. This increases the lifetime of wood and thus of Carbon storage in different products over multiple use cycles and replaces virgin renewable or fossil materials. In this case, however, the energy balance is crucial to observe between energy needed to collect, separate and repurpose a used product versus new production or fossil sources. In comparison to fossil sources, specific fossil fuel comparator (FFC) values have been determined in the Renewable Energy Directive (European Commission 2017c).

During the next decades, one can assume the substitution benefits of wood products to generally diminish, if one expects the Paris agreement to be met. This is because the way of producing energy for industrial processes has to move towards zero emissions, which will reduce the relative advantage of wood products. However, this will not influence the additional benefit of storing carbon in long-lived wood products. Moreover, with improved cascading and recycling practices the circulation time of carbon in the technosystem can be still extended.

Environmental sustainability and social acceptance:

Construction is very much tied to regional building cultures. There appears to be a connection between the abundance of privately owned forest resources per capita and the market share of wood in construction. That is, in forested boreal regions there tend to be support for the industrial use of wood in construction, due to societal interest towards utilising these natural resources for the benefit of the public. For this reason, efforts need to be focused on improving the market conditions in export regions – think of Chinese and Indian markets, as an example.

The construction sector itself can also be characterised as path dependent, meaning that the risks and short-term costs of construction are weighted the most in project-based decision making. It requires long-term commitment and effort to change the established practices. Many experts expect little change without substantial policy intervention (e.g., carbon tax), or change in construction regulations (e.g., incorporating environmental norms). However, since the building (and with that the construction) industry is considered to be one of the largest exploiters of natural resources and has regularly been in the centre of criticism regarding energy use, waste production, greenhouse gas emissions and impacts on the landscape, sustainable construction has recently gained momentum in construction research.

When it comes to the forest management and use of natural resources, land-use planning and dialogue between different stakeholder groups play a very important role; particularly in less-populated areas of the boreal forests. There different livelihoods (forestry, tourism, reindeer husbandry, hunting and trapping, etc…) are all active on the same forest area with differing demands on the same resource, while at the same time Climate Change is affecting said forest with changing forest growth and disturbance regimes. For the social acceptance of specific forest management intervention, extensive stakeholder dialogues are necessary and are being pursued. The trend shows that cross-sectoral communication and approaches to best utilize natural resources in forests and in products for most optimal use and reuse are needed in the boreal regions.

Research gaps:

There are several research needs towards gaining a better understanding of the overall mitigation potential of (long-lived) wood products on the total carbon balance of forestry. For example, market projections do not typically consider the expected structural changes in the forest products markets, or the developments taking place in the competing industries. There is also high uncertainty in the exact rate of substitution benefits. When determining the substitution benefits, one should always compare it to a counterfactual scenario, i.e., a future in which the production of wood products would not be increased.

From the point of view of long-lived wood products, one of the most recent and potentially important lines of research would be to think of business models, technologies and regulation for increasing the rate of recycling and cascading. This includes product design for deconstruct and reuse, as well as advanced separation and sorting technology to reclaim materials according to their nature and properties.

Conclusion:

Producing long-lived wood products and increasing the cascade use of wood can play an important role in compensating the carbon emissions from fossil fuel use while meeting environmental sustainability and social acceptance requirements. This is particularly important, when aiming at GHG emission reductions within the coming decades.

References:

European Commission. 2015. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: Closing the loop - An EU action plan for the Circular Economy. Brussels.

European Commission. 2017a. Review of the 2012 European Bioeconomy Strategy. Brussels

European Commission. 2017b. Level(s): building sustainability performance. Sustainable buildings. Online: http://ec.europa.eu/environment/eussd/buildings.htm

European Commission. 2017c. Proposal for a DIRECTIVE OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on the promotion of the use of energy from renewable sources (recast) Annex. Brussels.

Mahapatra, K., Gustavsson, L., 2008. Multi-storey timber buildings: breaking industry path dependency. Build. Res. Inf. 36, 638–648.

ISO. 2010. ISO21931-1 Sustainability in building construction – Framework for methods of assessment of environmental performance of construction works. Geneva.

Kuittinen M, Roux S. 2017. Vihreä julkinen rakentaminen. Helsinki: Ministry of the Environment, Department of the Built Environment. Available from: http://urn.fi/URN:ISBN:978-952-11-4744-9 55. Helsinki.
NSAI, "I.S EN 15978:2011 Sustainability of construction works-Assessment of environmental performance of buildings-Calculation method," National Standards Authority of Ireland, 2011.
Ritter, M., Skog, K., Bergman, R., 2011. Science supporting the economic and environmental benefits of using wood and wood products in green building construction. Unites States Department of Agriculture, Forest Service, Forest Products Laboratory, General Technic Report FPL-GTR-206.
Sathre, R., O'Connor, J., 2010. Meta-analysis of greenhouse gas displacement factors of wood product substitution. Environ. Sci. Policy 13, 104–114.

ACTION #3: Replacing fossil fuels with forest biomass

Evelyne Thiffault (Université Laval, Québec, Canada)

Context and proposal:

Transitioning the global energy supply away from fossil fuels and towards energy efficient supply chains based on renewable energy resources are key elements to mitigate climate change and improve energy security. Unlike other renewable resources, biomass can be stored and converted to solid, gaseous and liquid energy carriers: this versatility and the fact that many bioenergy technologies have already reached commercial stage give it an essential role in the global energy transition. As part of the portfolio of biomass feedstocks, forest biomass could play a significant role in modern bioenergy production. Forest biomass feedstocks include:

1. primary and secondary forestry residues (by-products of silvicultural and harvesting operations, and of industrial wood processing, respectively);
2. post-consumer wood products such as construction and demolition wood;
3. roundwood from
   a. surplus forest growth that could be harvested over and above current harvesting rates while still remaining within the sustainable harvest rate of forests,
   b. dedicated plantations, and
   c. current wood production for conventional forest products (sawnwood, pulp and paper and panels).

Potential for climate change mitigation:

The Intergovernmental Panel on Climate Change (Edenhofer et al. 2011) estimated that by 2050, bioenergy (from all sources) should provide from 80 to 150 Exajoules (EJ) per year in order to meet the 440–600 ppm CO_2-eq concentration target in the atmosphere, and from 118 to 190 EJ year^{-1} for less than 440 ppm CO_2-eq. As a reference, the world total primary energy supply in 2017 was 571 EJ; 1 EJ corresponds to 163 million barrels of oil equivalent (boe), 23.9 million tonnes of oil equivalent (Mtoe) or 278 terawatt-hours (TWh). The maximum technical potential from forest biomass could reach 110 EJ (Chum et al. 2011), although global estimates vary widely. To indicate magnitudes, 110 EJ roughly corresponds to 15 X 10^9 m^3 of wood (at 7.3 gigajoules per m^3).

With their relatively mature forest sectors, boreal countries are set to play an important role in the development of modern forest bioenergy. Estimations for selected boreal countries (Canada, Denmark, Finland, Russia and Sweden) suggest a mobilisation potential for forest biomass ranging from 2.2 EJ year^{-1} to up to 15.9 EJ year^{-1}, from a current value of 1.4 EJ year^{-1} (Thiffault et al. 2016). The upper values would come as a result of two processes: intensification of forest management activities, in which forestry would appropriate a larger share of forest ecosystem net primary production (NPP), and intensification of biomass recovery from silvicultural, harvesting and wood processing operations, in which bioenergy would appropriate a larger share of forestry by-products/residues.

As an example of the potential for climate change mitigation of forest biomass, current forestry practices in Sweden result in total reduced and avoided CO_2 emissions (both domestically and abroad) of 60 million tonnes of CO_2-eq year^{-1}; fossil energy substitution with forest bioenergy accounts for 20 to 40 million tonnes of CO_2-eq year^{-1} of this total (Lundmark et al. 2014). The strategic use of an additional 0.4 EJ year^{-1} of forest biomass in Sweden could reduce CO_2 emissions by 44 million tonnes of CO_2-eq year^{-1}, and oil use by 0.23 EJ year^{-1} (Gustavsson et al. 2007).

The potential for climate change mitigation of forest bioenergy depends on the fossil fuel displaced, the source and location of forest biomass feedstock used and the time horizon considered. For example, in Cintas et al. (2017), forest biomass use for energy is estimated to displace coal with an efficiency of 0.89 and 0.38 tonne of fossil carbon per tonne of carbon in forest bioenergy products in heat boilers and power plants, respectively. Forest-based liquid biofuels are estimated to displace fossil gasoline with savings of 23 kg of carbon per gigajoule of biofuel. Average displacement factors estimated for Canadian conditions for substitution of fossil fuels in heat, electricity or combined heat and power (CHP) facilities range from 0.47 to 0.89 tonne of fossil carbon per tonne of carbon in forest bioenergy products, with a maximum value of 1.85 (Smyth et al. 2017).

Calculations for Finland suggest that in the short term (20 years), producing bioenergy from branches collected on clearcut sites in Southern Finland can reduce cumulative radiative forcing of 47–62% compared to fossil fuels, whereas the reduction would be 11–37% when using stumps as feedstock, with the highest reductions achieved by replacing coal (compared with energy-dense natural gas). In the long term (100 years), the reduction gained with the use of branches would be 68–77%, and that with stumps 29–50%. Similar bioenergy systems in Northern Finland (with colder climate and slower forest carbon cycling), would yield lower reductions (Repo et al. 2012).

Environmental sustainability:

Forest management decisions in boreal countries usually depend on market expectations for conventional forest products, which normally generate greater revenues than bioenergy. Increased forest biomass use for energy *per se* is therefore seldom associated with land-use change (Egnell et al. 2016). Readily accessible industrial by-products are initially used as bioenergy feedstock, yielding little environmental concerns. Harvest residues, non-commercial roundwood and plantations represent complementary resources that can support ramping up to significantly larger scales if bioenergy prices stimulate mobilisation. Other biomass resources such as pulpwood logs may also become used for energy, depending on the competitiveness of bioenergy compared to conventional wood products (Egnell and Björheden 2013).

Since forest biomass procurement in the boreal biome is usually not a stand-alone activity, but rather an intensification of forest management, principles of protection and sustainability should remain the same whether forests are managed for conventional forest products only or also for bioenergy. Depending on site conditions, forest biomass procurement can pose risks of deterioration of ecosystem functions such as nutrient cycling, water purification and flow regulation, biodiversity, and carbon sequestration. The data needed for specifying how much forest biomass that can be extracted while sustaining ecosystem functioning are however deficient (Lamers et al. 2013). Modifications to management practices may be needed to properly identify sensitive conditions and find mitigation strategies where field evidence suggests that the incremental removal of biomass may not be sustainable.

Forest bioenergy and carbon accounting:

On a per unit of energy basis, energy generation from biomass emits more carbon at the stack than fossil fuels (Berndes et al. 2013), but the compensation of these extra emissions by ecosystem processes may take years to decades to fully materialize depending on project parameters. Removal of organic material may also in some cases alter soil fertility and reduce the capacity of the forest ecosystem to sequester more carbon (Repo et al. 2012). Issues such as these have led to the concept of carbon parity time, i.e. the time span needed by the forest bioenergy system to recover the carbon levels of a reference fossil fuel-based scenario (Lamers and Junginger 2013). Under this concept, a bioenergy system starts achieving real GHG savings only after its carbon parity time is attained. Quantification of carbon parity time of a given project enables the evaluation of its contribution to climate mitigation objectives. However, in many accounting frameworks, the biogenic carbon from bioenergy is accounted for as neutral as if immediately sequestered from the atmosphere from biomass regrowth. Under such frameworks, when biomass for bioenergy is traded internationally, a gap in the accounting can occur if the country where the forest biomass originates does not adequately take account of Land-use, Land-use change and Forestry (LULUCF) emissions.

Forest growth rates, management systems, and timeframes of carbon sequestration and release all determine if a forest bioenergy system can achieve GHG savings. For example, a bioenergy system using live trees from slow-growing boreal stands as feedstock could take decades before any GHG savings to be recorded. By contrast, a system based on harvest residues that would otherwise quickly decompose should yield GHG benefits over only a short period of time (Laganière et al. 2017). Estimates of the climate impact of bioenergy are also highly sensitive to the assumed counterfactual (reference) scenario without bioenergy, such as the assumed displaced energy source (e.g. *de facto* fuel substitution, replacement of the average energy mix, replacement of the marginal energy production technology that would have been used had biomass not been used for energy (Lamers and Junginger 2013)).

Adaptation of forest management to bioenergy demand can also affect production of conventional wood products and the overall carbon balance of forest management systems. Bioenergy demand can affect wood use in conventional forest products in antagonistic ways, e.g., when competition for the same feedstock drives up prices and impairs the competitiveness of other products. But it can also affect wood use in synergetic ways where new opportunities from bioenergy strengthens the forest industrial value chain. Forest bioenergy systems are usually more favourable (both economically and environmentally) when biomass is sourced as a by- or co-product of a larger wood product basket that includes long-lived products (e.g. sawtimber). Synergies can also be created if biomass procurement is used as a silvicultural practice to enhance overall forest productivity and stand quality (e.g. by facilitating stand restoration, regeneration or tending) (Thiffault et al. 2016, Cintas et al. 2017). At the landscape level, converting degraded/abandoned lands to biomass plantations could also help diversify forestry activities in rural areas.

Research gaps:

The impact of bioenergy feedstock removal on forest soil carbon stocks

The fate of bioenergy feedstocks in a reference scenario without biomass procurement, i.e. the decomposition rate of leftover biomass and the fate of its carbon content (and whether and to what extent it contributes to the soil carbon pool and site productivity) has particular relevance for calculations of GHG savings and mitigation benefits of forest bioenergy. Studies based on modelling suggest long-term decrease in soil organic carbon stocks with biomass feedstock removal (Repo et al. 2011). Conversely, empirical field studies have seldom measured significant effects of such removal on soil carbon stocks, and when present, significant effects are limited to specific site and stand conditions (Nave et al. 2010). In soil carbon models (such as Yasso07), decomposition of material reaching the ground depends on its structural and chemical recalcitrance and is driven by climatic conditions; however, recent studies suggest that the amount of stable soil organic carbon is more or less independent of material recalcitrance (Cotrufo et al. 2015). Error margins in biomass and soil carbon dynamics could dramatically affect carbon parity times and actual GHG savings of bioenergy systems due to the sheer size of soil carbon stocks in boreal forests. Further research is therefore needed to reduce such uncertainties.

Bioenergy counterfactual definition and market dynamics

Research is required to help establish realistic counterfactual to forest bioenergy, including an accounting for potential displacement effects. Since boreal forest bioenergy systems are typically connected to existing forestry industries, analysis of macro-economic drivers and demand-supply patterns, and research on the linkages between temporal carbon dynamics and wood sourcing practices, market data and economic bioenergy potentials need to be performed.

Conclusion:

Integration of biomass supply chains within larger forest management systems (which is already typical in Scandinavian countries) can increase the profitability of the overall forest operations by providing an outlet for forestry residues and unutilised trees. This should contribute to the mobilisation of the forest industrial value chain, creating a flow of forest-based products such as long-lived wood products with high substitution and GHG mitigation benefits, and an increased residual stream for bioenergy. Furthermore, it may increase foresters' belief in future markets, giving them incentives to invest in measures to increase forest productivity (Bellassen and Luyssaert 2014).

However, substantial gains in global forest bioenergy mobilisation can likely only be achieved with an important increase in forest management intensity (e.g. increase in forest stand tending/silviculture, increased use of short-rotation plantations). Such intensification would require fundamental shifts in forest systems and considerable societal change in several boreal countries such as Canada and Russia which their large extensively-managed forest areas. Consequences on forest ecosystem services such as biodiversity would therefore also need to be carefully considered. The design of objectives and policies can be better informed by knowledge and experience at the lower levels of decision-making where the implementation takes place. Local planning can facilitate the identification of the most favourable forest sites and of silvicultural practices that can both deliver wood for solid products and biomass for energy within sustainable forest management systems.

References:

Barrette, J., E. Thiffault, F. Saint-Pierre, S. Wetzel, I. Duchesne, and S. Krigstin. 2015. Dynamics of dead tree degradation and shelf-life following natural disturbances: can salvaged trees from boreal forests 'fuel'the forestry and bioenergy sectors? Forestry **88**:275-290.

Bellassen, V., and S. Luyssaert. 2014. Carbon sequestration: Managing forests in uncertain times. Nature **506**:153-155.

Berndes, G., S. Ahlgren, P. Börjesson, and A. L. Cowie. 2013. Bioenergy and land use change—state of the art. Wiley Interdisciplinary Reviews: Energy and Environment **2**:282-303.

Cintas, O., G. Berndes, J. Hansson, B. C. Poudel, J. Bergh, P. Börjesson, G. Egnell, T. Lundmark, and A. Nordin. 2017. The potential role of forest management in Swedish scenarios towards climate neutrality by mid century. Forest Ecology and Management **383**:73-84.

Cotrufo, M. F., J. L. Soong, A. J. Horton, E. E. Campbell, M. L. Haddix, D. H. Wall, and W. J. Parton. 2015. Formation of soil organic matter via biochemical and physical pathways of litter mass loss. Nature Geoscience **8**:776-779.

Edenhofer, O., R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, and C. V. Stechow. 2011. IPCC special Report on Renewable Energy Sources and Climate Change Mitigation. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Egnell, G., and R. Björheden. 2013. Options for increasing biomass output from long-rotation forestry. Wiley Interdisciplinary Reviews: Energy and Environment **2**:465-472.

Egnell, G., D. Paré, E. Thiffault, and P. Lamers. 2016. Chapter 4 - Environmental Sustainability Aspects of Forest Biomass Mobilisation. Pages 50-67 Mobilisation of Forest Bioenergy in the Boreal and Temperate Biomes. Academic Press.

Gustavsson, L., J. Holmberg, V. Dornburg, R. Sathre, T. Eggers, K. Mahapatra, and G. Marland. 2007. Using biomass for climate change mitigation and oil use reduction. Energy policy **35**:5671-5691.

Lamers, P., and M. Junginger. 2013. The 'debt' is in the detail: A synthesis of recent temporal forest carbon analyses on woody biomass for energy. Biofuels, Bioproducts and Biorefining **7**:373-385.

Lamers, P., E. Thiffault, D. Paré, and M. Junginger. 2013. Feedstock specific environmental risk levels related to biomass extraction for energy from boreal and temperate forests. Biomass and Bioenergy **55**:212-226.

Lundmark, T., J. Bergh, P. Hofer, A. Lundström, A. Nordin, B. C. Poudel, R. Sathre, R. Taverna, and F. Werner. 2014. Potential roles of Swedish forestry in the context of climate change mitigation. Forests **5**:557-578.

Nave, L. E., E. D. Vance, C. W. Swanston, and P. S. Curtis. 2010. Harvest impacts on soil carbon storage in temperate forests. Forest Ecology and Management **259**:857-866.

Repo, A., R. Känkänen, J.-P. Tuovinen, R. Antikainen, M. Tuomi, P. Vanhala, and J. Liski. 2012. Forest bioenergy climate impact can be improved by allocating forest residue removal. GCB Bioenergy **4**:202-212.

Repo, A., M. Tuomi, and J. Liski. 2011. Indirect carbon dioxide emissions from producing bioenergy from forest harvest residues. GCB Bioenergy **3**:107-115.

Smyth, C., G. Rampley, T. C. Lemprière, O. Schwab, and W. A. Kurz. 2017. Estimating product and energy substitution benefits in national-scale mitigation analyses for Canada. GCB Bioenergy **9**:1071-1084.

Thiffault, E., G. Berndes, and P. Lamers. 2016. Challenges and opportunities for the mobilisation of forest bioenergy in the boreal and temperate biomes. Pages 190-213 *in* E. Thiffault, G. Berndes,

M. Junginger, J. Saddler, and T. Smith, editors. Mobilisation of Forest Bioenergy in the Boreal and Temperate Biomes: Challenges, Opportunities and Case Studies. Academic Press, Elsevier.

ACTION #4: Increasing the broadleaved deciduous component in the boreal[1]

Pierre Bernier (Canadian Forest Service)
Rasmus Astrup (Norwegian Institute of Bioeconomy Research)

Context and proposal:

Stand-replacing wildfires are common natural disturbances in most of the circumboreal forest (Rogers et al, 2015). In Canada alone, they consume on average more than 2Mha of forest annually. Climate change is increasing fire risks across that zone, and, in Russia where surface fires are more common, causing stand-replacing canopy fires to become more common. Increasing levels of stand replacing wildfires result in increased direct carbon emissions to the atmosphere, increased risks to the health and safety of local populations and increased disruption of economic activities. Both adaptive and mitigating measures are urgently required to counter the current and forecasted wildfire disturbance trends. Increasing the proportion of native broadleaf tree species in the boreal zone through forest management is a large-scale strategy that shows great promise as a coupled mitigation-adaptation measure.

Mitigation:

A shift from mature conifer to mature broadleaved forest can reduce the fire risk between three to five times for many boreal forest regions (Bernier et al, 2016). Converting just 0.1 to 0.2 % of forested area in southern Canada per year as part of regular management activities in actively managed forests, starting in 2020, may be sufficient to mitigate the expected increase in fires due to climate change (Girardin and Terrier, 2015). Decreasing the area burned, or preventing its increase in spite of on-going climate forcing thus reduces the direct greenhouse gas emissions to the atmosphere as compared to the status quo. Increasing the component of deciduous broadleaved species also increases the albedo as compared to non-deciduous conifer forests, translating to less solar energy absorbed by the earth system and cooler surfaces locally. Indeed, surface albedo is the dominant biogeophysical mechanism at play when switching from evergreen needleleaved to broadleaved forest tree species in boreal regions (Bright et al, 2017). Finally, increasing the deciduous broadleaved species component can improve soil carbon stability and forest resilience to drought risk (Laganière et al, 2015). Thus, increasing broadleaved forest cover in boreal regions is a multi-factorial climate change mitigation measure.

Adaptation:

Boreal forest fires cause significant socio-economic losses through mostly indirect human deaths, damage to physical infrastructure, and loss of raw material for transformation. For instance, the 2010

[1] Adapted from: Astrup, R., Bernier, P.Y., Genet, H., Lutz, D.A., Bright, R.M. 2018. A sensible climate solution for the boreal forest. Nature Climate Change, 8: 2-12. doi:10.1038/s41558-017-0043-3

wildfires around Moscow, Russia, were linked to roughly 11,000 deaths through their effect on air pollution (Shaposhnikov et al, 2014). In Western Canada, the 2011 Slave Lake fire resulted in losses of 1bn CAD (Pujadas Botey and Kulig, 2014), while the 2016 Fort McMurray fire resulted in estimated losses of 4.6bn CAD, an amount far greater than insured. Increasing the broadleaved forest composition is therefore a socio-economic adaptive measure towards the increased regional fire risk from climate change.

Environmental sustainability and social acceptance:

Enhancing the broadleaved component of the boreal forest would not result in profound environmental changes as it simply entails a local shift in the dominance of native species already on the landscape. Enhancing the proportion of native broadleaved tree species within conifer-dominated landscapes both reduces the risk of increased fire frequency and increases forest resilience to fire spread and drought (Rogers et al, 2015; Silva Pedro et al, 2015, Felton et al, 2016). As the footprint of sustainable harvest in the boreal forest proceeds at a modest rate, and as the practice already incorporates vegetation management, the transition process across broad forest landscapes could be carried out with modest expenditures and would proceed at a socially comfortable pace. This could be achieved by modifying forest policies that encourage or require conifer species-specific management practices (Felton et al, 2016) of boreal countries to include the promotion of broadleaved species.

Research gaps:

Changing fundamental industrial orientations across boreal nations will require strong arguments supported by credible, globally coherent and locally relevant socio-economic research on costs and benefits. The land use and forestry sector will have to play an important role in any deployment of this forest-based mitigation scenario. Yet forest management plans and capital investments are mostly still made on the assumption that needleleaved evergreen conifers will dominate the harvestable species mix of managed forests demands for decades to come in order to satisfy market demand. In addition, the current mitigation and adaptation options in this sector such as intensified management, or the assisted migration of native species or provenances within or outside of their natural range, are largely based on conifers and may therefore contribute to the projected risks of forest fires.

Known effects of deciduous broadleaved species from North-American boreal forests cannot be blindly applied to the Eurasian forests. The selectivity or avoidance of stands by wildfires as a function of their properties such as biomass, age, and composition has been relatively well studied in the North-American boreal forest, a continent where stand-replacing fires are the norm. By contrast, we are not aware of similar research in the Eurasian boreal forest where non-lethal surface fires are the norm, but where observations suggest an increase in stand-replacing fires. In addition, the Eurasian boreal forests contain large areas in forest types that are absent from the North-American one, namely the larch forests of the north, and the birch forests of the southern forest margins. These intercontinental differences in fire regimes call for increased research in this area.

A coherent circumboreal methodology to evaluate the albedo effects of forest-based actions does not yet exist and would need to be developed to take full climatic advantage of the proposed measure.

The lighter colour of deciduous broadleaved tree species gives them a higher albedo than the darker needle-leaved conifer canopies. In addition, the leafless winter condition of deciduous trees exposes the underlying high-albedo snowpack. But how that translates into reduced retention of solar radiation depends on a combination of many factors that vary from locally to regionally.

Conclusion:

The reduced fire risk and enhanced surface albedo associated with increases in the broadleaved tree component can not only mitigate climate change, but also reduce socio-economic damages from forest fire, thereby achieving a win-win strategy that couples climate mitigation with adaptation. The development of tools for quickly assessing localized carbon and non-carbon climate-related trade-offs in boreal forests could advance this effort by providing local guidance as to where this strategy is most beneficial. However, although the science is circumboreal, the ecological and socio-economic circumstances are local. The research gaps identified above can therefore be most efficiently addressed by bringing circumboreal expertise together into focussed projects dedicated to tackle these issues.

References:

Bernier PY, Gauthier S, Jean P-O, Manka F, Boulanger Y, Beaudoin A, Guindon L. 2016. Mapping Local Effects of Forest Properties on Fire. Forests 2016, 7, 157. doi:10.3390/f7080157.

Bright RM, Davin E, O'Halloran T, Pongratz J, Zhao K, and Cescatti A. 2017. Local temperature response to land cover and management change driven by non-radiative processes. Nature Climate Change 7 :296–302. doi:10.1038/nclimate3250

Felton A, Sonesson J, Felton AM, et al. 2016. Replacing monocultures with mixed-species stands: Ecosystem service implications of two production forest alternatives in Sweden. Ambio 45 Suppl 2:124-39. doi: 10.1007/s13280-015-0749-2.

Girardin MP, Terrier A. 2015. Mitigating risks of future wildfires by management of the forest composition: an analysis of the offsetting potential through boreal Canada. Climatic Change, 130: 587–601.

Laganière J, Cavard X, Brassard BW, Paré D, Bergeron Y, Chen HYH. 2015. The influence of boreal tree species mixtures on ecosystem carbon storage and fluxes. For. Ecol. Manag. 354:119-129.

Pujadas Botey A, and Kulig JC. 2014. Family functioning following wildfires: Recovering from the 2011 Slave Lake fires. Journal of Child and Family Studies, 23: 1471–1483. http://dx.doi.org/10.1007/s10826-013-9802-6

Rogers BM, Soja AJ, Goulden ML and Randerson JT. 2015. Influence of tree species on continental differences in boreal fires and climate feedbacks. Nature Geoscience 8: 228–234. doi:10.1038/ngeo2352

Shaposhnikov D, Revich B, Bellander T, Bedada GB, Bottai M, Kharkova T, Kvasha E, Lezina E, Lind T, Semutnikova E, Pershagen G. 2014. Mortality related to air pollution with the Moscow heat wave and wildfire of 2010. Epidemiology 25(3):359-64. doi: 10.1097/EDE.0000000000000090.

Silva Pedro M, Rammer W, Seidl R. 2015. Tree species diversity mitigates disturbance impacts on the forest carbon cycle. Oecologia 177:619-630

ACTION #5: Make albedo management part of climate-sensitive forestry

Ryan Bright (Norwegian Institute of Bioeconomy Research)

Context and proposal:

The albedo (reflectivity) of the land surface is an important physical property partly determining Earth's energy balance (Cess 1978, Stephens et al. 2015) where, on average, approximately one half of an albedo change at the surface is directly felt at the top-of-the-atmosphere (Qu and Hall 2006). As such, the surface albedo plays a significant role in the regulation of weather and climate (Sellers 1969, Mahmood et al. 2013). In boreal and alpine regions – or regions experiencing seasonal snow cover – differences in the surface albedo between forested and non-forested areas can be significant (Betts and Ball 1997, Loranty et al. 2014). Notable albedo differences have also been observed between forests of different species compositions and development states (Lukeš et al. 2013, Kuusinen et al. 2016, Bright et al. 2018), thereby offering climate-related forest management opportunities.

Table 1 provides an indication of the influence of forest structure and composition on the surface albedo. As for differences related to species compositions, in snow free periods, broadleaved deciduous forests often exhibit higher surface albedos relative to evergreen needleleaved forests (e.g., pines, firs, spruces) owed to their higher foliage albedos. Broadleaved deciduous forests also exhibit higher surface albedos than evergreen needleleaved forests in winter months, although the reason is attributed to differences in the amount of canopy foliage – or to their lower leaf area index (LAI) – hence exposing more of the snow-covered surface. Under snow-free conditions, albedo differences within species groups can be explained by differences in development state – or rather – forest structure. Younger or lower-productive forests with low stand volumes, LAIs, and canopy heights have higher albedos than older or higher-productive forests (Table 1).

Thus, through its influence on forest composition and structure, forest management activities directly shape surface albedo and hence Earth's shortwave radiation budget. Management driven changes in albedo may be permanent, such as the change accompanying a switch in commercial tree species or the planting of a new forest (afforestation) – or they may be temporary, such as the change accompanying a harvest or thinning disturbance. The resulting radiative imbalances at the top of Earth's atmosphere can be of comparable magnitude to those stemming from changes in atmospheric CO2 concentrations accompanying management-driven changes to carbon stocks and productivity (Betts 2000, Montenegro et al. 2009, Zhao and Jackson 2014, Bright et al. 2016, Mykleby et al. 2017), and as such, ought to be accounted for in the design of management policy in order to maximize mitigation efforts (Pielke Sr. et al. 2002, Jackson et al. 2008, Anderson et al. 2010).

Table 1. *Relationship between forest structure and surface albedo in Fennoscandic (Norway, Sweden, Finland) forests. Adapted from: Bright et al. (2018). Non-forest land cover classification is based on the 2015 land cover product of the European Space Agency's Climate Change Initiative (European Space Agency 2017). "Brd. Decid." = Broadleaf deciduous forest.*

			Forest			
	LAI_{max} ($m^2\ m^{-2}$)	**Lorey's height** (m)	**Crown length** (m)	**Stand volume** ($m^3\ ha^{-1}$)	**Albedo*, snow-covered conditions**	**Albedo*, snow-free conditions**
Pine 1	0.9	7.5	4.6	21	0.42	0.12
Pine 2	2.4	11.6	6.7	80	0.31	0.11
Pine 3	2.3	17.0	9.4	130	0.27	0.10
Pine 4	4.4	17.2	8.4	236	0.20	0.10
Spruce 1	1.4	7.5	6.3	22	0.36	0.12
Spruce 2	4.3	12.3	10.1	92	0.34	0.10
Spruce 3	6.7	16.8	13.2	201	0.20	0.10
Spruce 4	9.1	22.0	15.8	374	0.18	0.09
Brd. Decid. 1	0.5	4.9	3.2	7	0.58	0.13
Brd. Decid. 2	1.8	8.4	5.5	36	0.46	0.13
Brd. Decid. 3	3.9	12.2	7.9	98	0.44	0.14
Brd. Decid. 4	7.0	18.3	10.3	227	0.27	0.12
			Non-forest			
Freshwater					0.48	0.03
Urban					0.18	0.12
Grass					0.73	0.18
Crop					0.35	0.15
Wetland					0.59	0.13
Shrub					0.77	0.16

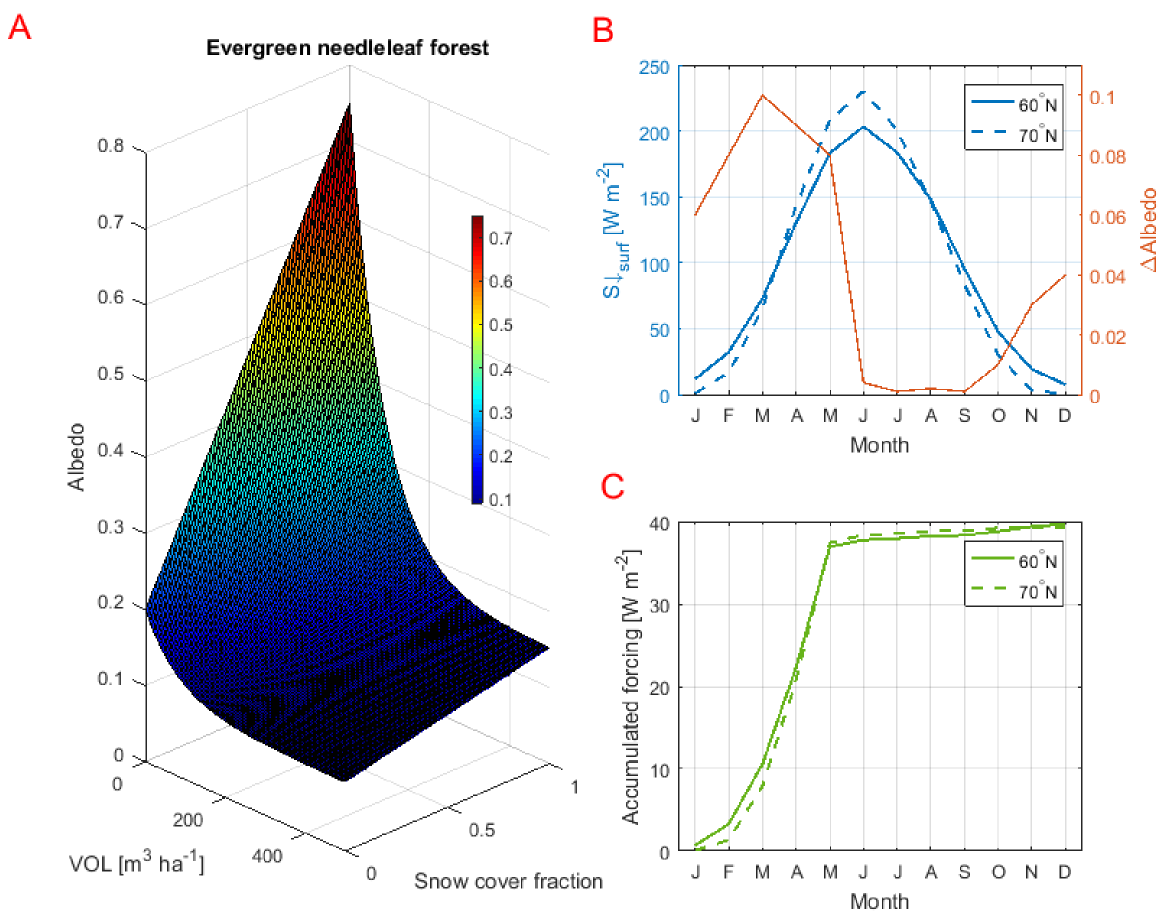
***** 2001-2011 mean, direct hemispherical/"black-sky"

The accounting challenge:

The climate impact of a surface albedo change depends on two factors: The magnitude of the albedo change itself, and the local radiation budget. Both are highly variable in time and space. The first factor is determined by the change to vegetation structure and by the local environmental background conditions. A thinned evergreen needleleaf stand can slightly increase the surface albedo in the short-term yet slightly decrease the albedo in the longer-term (Otto et al. 2014), while a clear-cut harvest can notably increase the albedo, usually confined to the short- to medium-terms (Cherubini et al. 2012). The vegetation-related albedo changes can be significantly amplified when snow is present at the surface (Figure 1 a); annually, the magnitude of the albedo change is largely determined by the duration of the snow season.

The second factor surrounds local geographic, topographic, and atmospheric conditions affecting the quantity of solar radiation that is transmitted by the atmosphere and incident at the surface. Identical albedo changes in overcast and clear regions – or in two regions with drastically different terrain features – can lead to different magnitudes of radiative forcing due to their different exposures to solar radiation. An albedo change at lower latitudes need not necessarily lead to a larger annual radiative forcing than the same albedo change at higher latitudes given the seasonal asymmetry of the albedo change in relation to incoming solar radiation (Figure 1 b&c).

Figure 1. *A) Surface albedo as a function of stand volume and snow cover fraction ("fraction" = fraction of the stand area or a given time period) in a Fennoscandic evergreen needleaf forest; B) Differences in surface incident solar radiation for two locations in the north and south of Fennoscandia (left y-axis) sharing the same surface albedo change (Δα; right y-axis); C) Annual accumulated surface forcing for the two locations shown in panel B).*

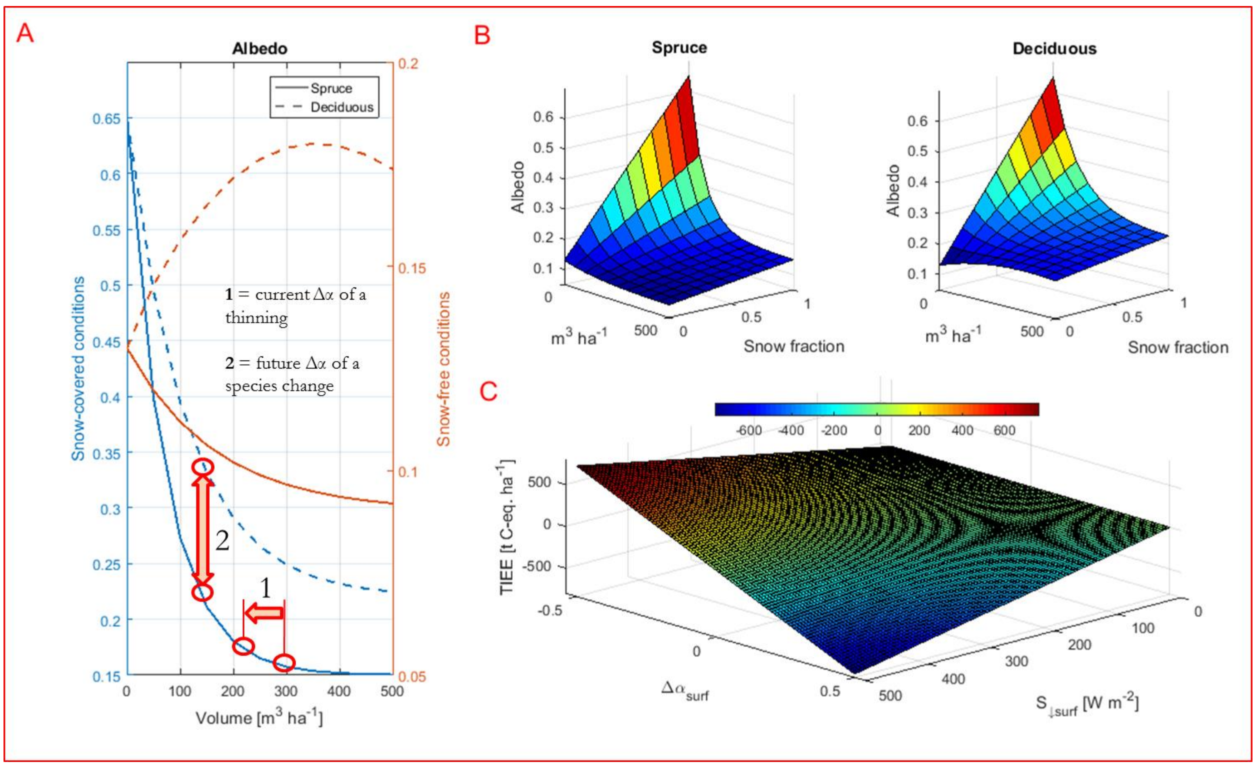


Scientifically, while these factors are well-understood, from the perspective of the resource manager they remain largely intangible. A forest manager can more easily intuit the amount of carbon being stored in his/her forest relative to its albedo and role in the climate system. Making albedo-management an integral part of climate-sensitive forestry therefore requires accounting tools that explicitly link structural metrics familiar to forest managers (i.e., stand volume, site index, dominant species, etc.) to common impact currencies (i.e., CO2-equivalents) that take into account local variations in environment and topography.

A path forward:

Recent advancements in the remote sensing of forest structure, surface albedo, and snow cover now provide unique scientific opportunities to robustly characterize surface albedo as a function of forest composition (i.e., dominant species) and structure (i.e., stand volume, aboveground biomass, etc.). Such research outcomes may then be easily adapted for use in local- to regional-scale planning of management activities. At the scale of any given administrative unit, management district, or even map pixel, look-up tables providing local surface albedo values as a function of stand-level attributes (Figure 2 a) can be easily combined with look-up tables of important local environmental information – like monthly average snow cover – to gauge the magnitude of the albedo change associated with a management intervention (Figure 2 b). Additional look-up tables providing key information about the local solar energy budget (S↓surf) can then be applied with the estimated albedo changes (Δα) to translate the radiative impact into a stand-level carbon-equivalent metric (t C-eq. ha-1; Figure 2 c) that facilitates direct comparison with carbon stocks (see for e.g., Figure 3 in Bright et al. (2016)).

Figure 2. *A) Example surface albedo evolution in Fennoscandic spruce- and broadleaf deciduous-dominant stands as a function of stand volume under both snow-covered (left y-axis) and snow-free (right y-axis) conditions; B) Actual surface albedo in spruce and broadleaf deciduous stands as a function of snow cover fraction; C) Stand-level carbon-equivalence as a function of a local surface albedo change (Δα) and the local solar radiation incident at the surface (S↓surf; see Bright et al. (2016) for details surrounding the C-eq. calculation).*



Conclusion:

Sustained, coordinated research activities among forestry, remote sensing, and climate scientists is needed to further develop and refine scientific tools that facilitate albedo management and minimize uncertainties. In addition to their utility in management planning, such tools (and methods) may be standardized and applied in albedo monitoring, reporting, and verification schemes (MRV), although additional collaboration between scientists, resource managers, and local inventory agencies is encouraged to ensure design effectiveness and application efficiency.

References:

Anderson, R. G., J. G. Canadell, J. T. Randerson, R. B. Jackson, B. A. Hungate, D. D. Baldocchi, G. A. Ban-Weiss, G. B. Bonan, K. Caldeira, L. Cao, N. S. Diffenbaugh, K. R. Gurney, L. M. Kuepper, B. E. Law, S. Luyssaert, and T. L. O'Halloran. 2010. Biophysical considerations in forestry for climate protection. Frontiers in Ecology & Environment 9:174-182.

Betts, A. K., and J. H. Ball. 1997. Albedo over the boreal forest. Journal of Geophysical Research 102:28901-28909.

Betts, R. A. 2000. Offset of the potential carbon sink from boreal forestation by decreases in surface albedo. Nature 408:187-190.

Bright, R. M., W. Bogren, P. Bernier, and R. Astrup. 2016. Carbon-equivalent metrics for albedo changes in land management contexts: relevance of the time dimension. Ecological Applications 26:1868-1880.

Bright, R. M., T. Majasalmi, S. Eisner, G. Myhre, and R. Astrup. 2018. Inferring Surface Albedo Prediction Error Linked to Forest Structure at High Latitudes. Journal of Geophysical Research - Atmospheres https://doi.org/10.1029/2018JD028293.

Cess, R. D. 1978. Biosphere-Albedo Feedback and Climate Modeling. Journal of the Atmospheric Sciences 35:1765-1768.

Cherubini, F., R. M. Bright, and A. H. Strømman. 2012. Site-specific global warming potentials of biogenic CO2 for bioenergy: contributions from carbon fluxes and albedo dynamics. Environmental Research Letters 7:045902.

European Space Agency. 2017. Land Cover CCI - Product User Guide Version 2.0. Accessed Sept. 03, 2017 at: http://maps.elie.ucl.ac.be/CCI/viewer/download/ESACCI-LC-Ph2-PUGv2_2.0.pdf UCL-Geomatics, Belgium.

Jackson, R. B., J. T. Randerson, J. G. Canadell, R. G. Anderson, R. Avissar, D. D. Baldocchi, G. B. Bonan, K. Caldeira, N. S. Diffenbaufh, C. B. Field, B. A. Hungate, E. G. Jobbágy, L. M. Kueppers, M. D. Nosetto, and D. Pataki, E. 2008. Protecting climate with forests. Environmental Research Letters 3:044006 (044005pp).

Kuusinen, N., P. Stenberg, L. Korhonen, M. Rautiainen, and E. Tomppo. 2016. Structural factors driving boreal forest albedo in Finland. Remote Sensing of Environment 175:43-51.

Loranty, M. M., L. T. Berner, S. J. Goetz, Y. Jin, and J. T. Randerson. 2014. Vegetation controls on northern high latitude snow-albedo feedback: observations and CMIP5 model simulations. Global Change Biology 20:594-606.

Lukeš, P., P. Stenberg, and M. Rautiainen. 2013. Relationship between forest density and albedo in the boreal zone. Ecological Modelling 261–262:74-79.

Mahmood, R., R. A. Pielke, K. G. Hubbard, D. Niyogi, P. A. Dirmeyer, C. McAlpine, A. M. Carleton, R. Hale, S. Gameda, A. Beltrán-Przekurat, B. Baker, R. McNider, D. R. Legates, M. Shepherd, J. Du, P. D. Blanken, O. W. Frauenfeld, U. S. Nair, and S. Fall. 2013. Land cover changes and their biogeophysical effects on climate. International Journal of Climatology 34:929-953.

Montenegro, A., M. Eby, Q. Mu, M. Mulligan, A. J. Weaver, E. C. Wiebe, and M. Zhao. 2009. The net carbon drawdown of small scale afforestation from satellite observations. Global and Planetary Change 69:195-204.

Mykleby, P. M., P. K. Snyder, and T. E. Twine. 2017. Quantifying the trade-off between carbon sequestration and albedo in midlatitude and high-latitude North American forests. Geophysical Research Letters 44:2493-2501.

Otto, J., D. Berveiller, F. M. Bréon, N. Delpierre, G. Geppert, A. Granier, W. Jans, A. Knohl, A. Kuusk, B. Longdoz, E. Moors, M. Mund, B. Pinty, M. J. Schelhaas, and S. Luyssaert. 2014. Forest summer albedo is sensitive to species and thinning: how should we account for this in Earth system models? Biogeosciences 11:2411-2427.
Pielke Sr., R. A., G. Marland, R. A. Betts, T. N. Chase, J. L. Eastman, J. O. Niles, D. S. Niyogi, and S. W. Running. 2002. The influence of land-use change and landscape dynamics on the climate system: relevance to climate-change policy beyond the radiative effect of greenhouse gases. Phil. Trans. R. Soc. Lond. A 360:1705-1719.
Qu, X., and A. Hall. 2006. Assessing Snow Albedo Feedback in Simulated Climate Change. Journal of Climate 19:2617-2630.
Sellers, W. D. 1969. A Global Climatic Model Based on the Energy Balance of the Earth-Atmosphere System. Journal of Applied Meteorology 8:392-400.
Stephens, G. L., D. O'Brien, P. J. Webster, P. Pilewski, S. Kato, and J.-l. Li. 2015. The albedo of Earth. Reviews of Geophysics 53:141-163.
Zhao, K., and R. B. Jackson. 2014. Biophysical forcings of land-use changes from potential forestry activities in North America. Ecological Monographs 84:329-353.

ACTION #6: Pursue afforestation of abandoned agricultural lands

Dmitry Schepaschenko (International Institute for Applied Systems analysis - IIASA)
Anatoly Shvidenko (IIASA)
Linda See (IIASA)
Florian Kraxner (IIASA)

Context and proposal:

Urbanization, regional changes in economic and social conditions, as well as intensification of agriculture have led to an abundance of formerly cultivated land, particularly in marginal areas for crop production. This is especially pronounced in boreal forest biomes where the small field sizes, the severe climate and the lack of an adequate labor force make agriculture less profitable. Following the collapse of the Soviet Union, about 59 Mha were taken out of agricultural production in Northern Eurasia alone (Lesiv et al., 2018) 52% of which is situated in the forest biome. Natural afforestation is gradually taking place across these abandoned farmlands, with 12% of the area (19% in the forest biome and 4% in the steppe biome) now with a tree cover at least 10%. The same trend, although less intensive, is observed in many countries (e.g. afforestation of mountain pastures in Europe).

The conversion of former agricultural land to natural zonal vegetation (i.e. grassland, shrubs or forest) leads to an increase in carbon sequestration and carbon stocks in vegetation and soil. However, abandoned arable land (AAL) is not typically dealt with in forest management plans because of its designation as agricultural land, or due to different stakeholder preferences and legislative limitations in some countries. Yet, AAL is an attractive option for intensive forest management because these areas are usually not valuable from a conservation or biodiversity perspective and they both have a high climate change mitigation and wood production potential, as well as providing other important ecosystem services.

Climate change mitigation:

Within the paradigm of sustainable forest management, afforestation of AAL can contribute substantially to climate change mitigation. Additional carbon accumulates in all major carbon pools (i.e. vegetation, detritus and soil). Wertebach et al. (2017) suggest that the carbon sequestration rate for soils of abandoned cropland in European Russia was on average 0.66 Mg C ha^{-1} yr^{-1} (for the first 20 years after abandonment, 0-5 cm soil depth). Other studies report similar estimates (0.96±0.08 Mg C ha^{-1} yr^{-1} in the upper 20 cm), which vary according to vegetation zone and the quality of the soil (Kurganova et al., 2014). Grasslands sequester twice as much carbon in their soils as do wooded lands (Larionova et al., 2003) while forests sequester much more carbon in live biomass and detritus, the amount depending greatly on the management practices. Carbon sequestration potential of AAL afforestation is estimated in the range of 2-4 t C ha^{-1} yr^{-1}. Providing substantial carbon sequestration with assisted afforestation requires appropriate forest management practices, including the selection of the right tree species for afforestation.

Adaptation:

AAL has a number of advantages for timber production, e.g. it is easy to start (no clearcut residuals), is often surrounded by managed forest, and has no management limitations such as the need to set aside protected or recreational areas. Moreover, most of the AAL is accessible and has been allocated to productive soil because these sites were initially selected for agricultural production. Hence these were areas with the best soils, good transport infrastructure and an ambient population. In contrast, natural afforestation usually takes time and does not necessarily include the most valuable species for wood production, nor the best species from an adaptation standpoint.

Environmental sustainability and social acceptance:

AAL can be subject to intensive forest management, which then decreases the anthropogenic pressure on other forest areas where carbon storage, conservation or biodiversity are primary targets. Moreover, afforested areas can markedly increase the stability of landscapes due to the protection of soil and water, provide jobs for local people and improve the overall living conditions of the population.

Research gaps:

As a rule, areas suitable for AAL do not tend to be included in any management plans, and hence their extent and status are poorly known. To improve this situation, a better definition of their land use status is required, a proper inventory and mapping of AAL must take place, and corresponding management plans must be developed and implemented. Moreover, many areas of AAL do not have appropriate reference data (such as models of growth and productivity, manuals for thinning, etc.) and require specific forest modelling and scenario development actions.

Both natural and assisted afforestation of AAL will affect the albedo in a way that may significantly offset the climate benefits of carbon sequestration. Management practices such as favoring deciduous species may reduce this offset. Research is needed to support assisted afforestation in order to maximize the net climate benefits of this activity.

Conclusion:

Afforestation of AAL has great potential as a climate mitigation option with positive consequences for wood production, and environmental and social sustainability. In order to achieve a win-win strategy, restoration and management options should be logically tied to the expected portfolio of the ecosystem services, taking into account the specifics of the entire landscape such as the structure and legal designation of the land cover and the need for soil and water as protective mechanisms.

References:

Kurganova, I., de Gerenyu Lopes, V., Six, J. & Kuzyakov, Y. (2014) Carbon cost of collective farming collapse in Russia. Glob. Change Biol. 20: 938–947. DOI: 10.1111/gcb.12379.

Larionova A.A., Rozanova L.N., Yevdokimov I.V., Yermolayev A.M., Kurganova I.N., Lagodatsky S.A. (2003) Land-use change and management effects on carbon sequestration in soils of Russia's South Taiga zone. Tellus, 55B, 331–337. DOI: 10.1034/j.1600-0889.2003.00042.x.
Lesiv M, Schepaschenko D, Moltchanova E, Bun R, Dürauer M, Prishchepov AV, Schierhorn F, Estel S, et al. (2018). Spatial distribution of arable and abandoned land across former Soviet Union countries. Scientific Data 5: e180056. DOI: 10.1038/sdata.2018.56.
Wertebach TM, Hölzel N, Kämpf I, Yurtaev A, Tupitsin S, Kiehl K, Kamp J, Kleinebecker T. (2017) Soil carbon sequestration due to post-Soviet cropland abandonment: estimates from a large-scale soil organic carbon field inventory. Glob. Change Biol. 23(9):3729-3741. DOI: 10.1111/gcb.13650.

ISSUE #1: How reactive are boreal soil carbon stocks to climate change?

Jari Liski (Finnish Meteorological Institute, Helsinki, Finland)

Brief overview of current knowledge:

Boreal soils store a huge amount of carbon. They may contribute notably to solving the global climate change problem or worsening it. These soils help to mitigate climate change if additional atmospheric carbon can be sequestered into them. On the other hand, these soils enhance climate change if carbon is released from them to the atmosphere. In both cases, the impact can be considerable, because the boreal soil carbon stock is large and it exchanges carbon with the atmosphere effectively.

The estimates of the boreal soil carbon stock range from 170 to 1100 Pg with the mid-point equal to 640 Pg (Bradshaw and Warkentin 2015). These estimates include permafrost soils across the boreal zone plus tundra (about 1000 Pg, Schuur et al. 2015) but exclude peatlands (130 to 410 Pg, Bradshaw and Warkentin 2015). Carbon stock estimates of upland soils alone range from 90 to 500 Pg (DeLuca and Boisvenue 2012).

The mid-point estimate equal to 640 Pg is 43 % of the worldwide soil carbon stock frequently estimated at around 1500 Pg. This percentage is notably high considering that boreal forests cover only a little more than 10 % of the global soil area. The atmosphere contains currently about 860 Pg carbon (403 ppmv), and the amount is increasing 5 Pg per year (Le Quére et al. 2018). The mid-point estimate of the boreal soil carbon stock is thus 75 % compared to the current atmospheric carbon stock and 0.8 % compared to the current growth rate of atmospheric carbon. This illustrates how already relatively small changes in the boreal soil carbon stocks affect the atmospheric carbon levels significantly.

Soil plays a particularly important role in the carbon budget of boreal land ecosystems. Boreal soils have a relatively high carbon content per land area, especially relative to the carbon content of biomass, which is low compared to that of the biomass in temperate or tropical zones for example. Soil stores two to five times as much carbon as trees and other biomass in boreal land ecosystems (DeLuca and Boisvenue 2012, Bradshaw and Warkentin 2015). The main reason for the high carbon content of the boreal soils is a slow microbial decomposition of organic matter under the cool climate conditions.

Boreal soil carbon stocks were estimated to have increased 0.2 Pg per year between 1990 and 2007 (Pan et al. 2011). This represented 50 % of the total carbon sink in the boreal forests equal to 0.4 Pg per year during this period excluding harvested wood products. Pan et al. (2011) listed changes in harvest patterns relative to growth and regrowth over abandoned farmlands as factors enhancing the carbon sink of boreal forests and increasing disturbance regimes as a factor decreasing the sink. In addition, warming climate has probably enhanced biomass production (Myneni et al. 2001) and carbon uptake (Pulliainen et al. 2017) and, consequently, increased the input to carbon to the boreal soils. However, increased temperatures were not observed to have increased forest growth across Canada if they were associated with moisture limitations (Girardin et al. 2016).

Potential impact:

Climate of northern high latitudes, such as the boreal zone, has already warmed about twice as much as the global average and this trend of rapid climate change in boreal zone is estimated to continue in the future (IPCC 2013). Soil temperatures (top 10 cm) are estimated to increase 3.1 to 8.0 degrees during this century (RCP 8.5 business-as-usual emission scenario, Todd-Brown et al. 2014). This is slightly less than the warming of surface air temperature because of a simultaneous loss of snow cover and consequent increase in winter heat flux to the atmosphere.

The changing climate conditions will affect the boreal soil carbon stocks and sinks remarkably. On the one hand, higher temperatures and increasing atmospheric carbon dioxide levels may enhance the growth of vegetation in these commonly temperature-limited ecosystems and consequently increase carbon input to the soils (Todd-Brown et al. 2014). Moisture limitations as well as increased abiotic and biotic forest disturbances may, however, reduce the favourable effects on the growth (Girardin et al. 2016). On the other hand, warmer climate favours also the decomposition of soil carbon, an effect that will increase the release of carbon and the emissions of carbon dioxide from the soils (Davidson and Janssens 2006). The fate of the huge boreal soil carbon stock will depend on the balance between these two effects opposing each other.

Earth System models (ESM), which combine these effects, give currently quite contrasting results on the changes in the boreal soil carbon stocks in response to climate change. In a comparison of 11 ESMs, the estimates ranged from a loss equal to 28 Pg to a gain equal to 62 Pg in the boreal region during the 21st century (Todd-Brown et al. 2014). These differences were caused by varying estimates of the current soil carbon stocks as well as diverse estimates of changes in the plant growth and the decomposition of soil carbon.

The results of the ESMs are variable and uncertain because the soil carbon modules are still lacking some central soil processes (Todd-Brown et al. 2013, He et al. 2016). Regarding the effects of increasing temperatures on different fractions of soil organic matter, a particular gap is the inability to distinguish between the intrinsic temperature sensitivity and the apparent sensitivity, the latter of which is additionally affected by soil properties and environmental conditions (Davidson and Janssens 2006). As a result of these two different features, some soil carbon may actually be many times more sensitive to warming than thought today whereas some may be less sensitive (Karhu et al. 2010). Overall, after adding these processes to the ESMs, the ESMs will likely give smaller estimates of soil carbon accumulation and higher estimates of soil carbon losses in response to climate change (e.g. DeLuca and Boisvenue 2012, Todd-Brown et al. 2014). To avoid losses of soil carbon under these conditions and sequester more carbon into the soils, it is necessary to increase soil carbon input. Treating forests for larger tree volume and biomass is a way to increase carbon input to soil in managed forests (Liski et al. 2006).

Peatlands and permafrost soils are particularly important for the future carbon balance of the boreal zone. The increasing temperatures and changes in precipitation and evaporation patterns will expose currently inert organic matter in these soils to conditions favourable for decomposition. This may release 40 to 170 Pg carbon from these soils by 2100 (Schuur et al. 2015). Such soil emissions correspond to four to 17 years of the current annual fossil carbon emissions equal to 10 Pg (Le Quére et al. 2018). An estimated few percent of this carbon will be released as methane, which will increase the warming potential by 35 to 48 % (Schuur et al. 2015). Majority of these peatlands and permafrost soils are found on unmanaged land. For this reason, it is difficult to mitigate these emissions by means of land management at a large scale.

Knowledge gaps:

Considering the importance of the boreal soil carbon stocks for the climate impacts of the boreal zone and the global climate change as a whole, our knowledge of changes in these soils is inevitably poor. For example, we do not know which of these soils will gain carbon in response to climate change and which will lose it and for which reason. Remarkable improvements in our understanding are needed to reliably foresee the changes, inform climate and forest policies and guide land and forest management decisions.

There are numerous individual topics about boreal soil carbon we must learn to understand better. These include, for example, the effects of changing temperature and moisture conditions on different soil carbon fractions (Davidson and Janssens 2006), priming effects, i.e. the effects of increasing soil carbon inputs on the decomposition of stable soil organic matter, links between carbon and nutrient cycles and soil temperatures under changing climate and snow conditions (Pulliainen et al. 2017).

In addition to such topics, it is noteworthy that different models, which are necessary to make scenarios and large-scale estimates, are lacking features that are known to be crucial based on experimental work or other measurements. Furthermore, the models may be unable to reproduce some measurements on soil characteristics that are critical for reliable carbon calculations, such as the amount and spatial distribution of soil carbon across the boreal zone (Todd-Brown et al. 2014) or the residence times of carbon fractions in soil (He et al. 2016).

Many of these knowledge gaps must be filled in by continued and expanded research work. Monitoring changes in the boreal zone is an essential part of this work to continuously test the validity of future scenarios and improve them. In addition and in particular, disagreements between measurements and model-calculated results indicate that closer, broader and more practical collaboration is needed between experimental, measurement-oriented research and mathematical modeling of soil carbon.

References:

Bradshaw, C.J.A. and Warkentin, I.G. 2015. Global estimates of boreal forest carbon stocks and flux. Global and Planetary Change 128: 24-50.
Davidson, E.A. and Janssens, I. A. 2006. Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. Nature 440: 165-173.
DeLuca, T.H. and Boisvenue, C. 2012 Boreal forest soil carbon: distribution, function and modelling. Forestry 85(2): 161-184.
Girardin, M.P., Bouriaud, O., Hogg, E.H., Kurz, W., Zimmermann, N.E., Metsaranta, J.M., de Jong, R., Frank, D.C., Esper, J., Buntgen, U., Guo, X.J. and Bhatti, J. 2016 No growth stimulation of

Canada's boreal forest under half-century of combined warming and CO2 fertilization. Proceeding of the National Academy of Sciences 113(52): E8406-E8414.
He et al. 2016 He, Y.J., Trumbore, S.E., Torn, M.S., Harden, J.W., Vaughn, L.J.S., Allison, S.D. and Randerson, J.T. 2016. Radiocarbon constraints imply reduced carbon uptake by soils during the 21st century. Science 353(6306): 1419-1424.
IPCC. 2013. Climate Change 2013: The physical science basis. Fifth Assessment Report of the Intergovernmental Panel on Climate Change.
Karhu, K., Fritze, H., Hämäläinen, K., Vanhala, P., Jungner, H., Oinonen, M., Sonninen, E., Tuomi, M., Spetz, P. and Liski, J. 2010. Temperature sensitivity of soil carbon fractions in boreal forest soil. Ecology 91(2): 370-376.
Le Quére et al. 2018. Global carbon budget 2017. Earth System Science Data 10:405-448.
Liski, J., Lehtonen, A., Palosuo, T., Peltoniemi, M., Eggers, T., Muukkonen, P. and Mäkipää, R. 2006. Carbon accumulation in Finland's forests 1922-2004 – an estimate obtained by combination of forest inventory data with modelling of biomass, litter and soil. Annals of Forest Science 63(7): 687-697.
Myneni, R.B., Dong, J., Tucker, C.J., Kaufmann, R.K., Kauppi, P.E., Liski, J., Zhou, L., Alexeyev, V. & Hughes, M.K. 2001. A large carbon sink in the woody biomass of Northern forests. Proceedings of the National Academy of Sciences 98(26): 14784-9.
Pan, Y.D., Birdsey, R.A., Fang, J.Y., Houghton, R., Kauppi, P.E., Kurz, W.A., Phillips, O.L., Shvidenko, A., Lewis, S.L., Canadell, J.G., Ciais, P., Jackson, R.B., Pacala, S.W., McGuire, A.D., Piao, S.L., Rautiainen, A., Sitch, S. and Hayes, D. 2011. A Large and Persistent Carbon Sink in the World's Forests. Science 333(6045): 988-993.
Pulliainen, J., Aurela, M., Laurila, T., Aalto, T., Takala, M., Salminen, M., Kulmala, M., Barr, A., Heimann, M., Lindroth, A., Laaksonen, A., Derksen, C., Makela, A., Markkanen, T., Lemmetyinen, J., Susiluoto, J., Dengel, S., Mammarella, I., Tuovinen, JP., and Vesala, T. 2017. Early snowmelt significantly enhances boreal springtime carbon uptake. Proceedings of the National Academy of Sciences 113(52): E8406-E8414.
Schuur, E.A.G., McGuire, A.D., Schadel, C., Grosse, G., Harden, J.W., Hayes, D.J., Hugelius, G., Koven, C.D., Kuhry, P., Lawrence, D.M., Natali, S.M., Olefeldt, D., Romanovsky, V.E., Schaefer, K., Turetsky, M.R., Treat, C.C. and Vonk, J.E. 2015. Climate change and the permafrost carbon feedback. Nature 520: 171-179.
Todd-Brown, K.E.O., Randerson, J.T., Hopkins, F., Arora, V., Hajima, T., Jones, C., Shevliakova, E., Tjiputra, J., Volodin, E., Wu, T., Zhang, Q. and Allison, S.D. 2014. Changes in soil organic carbon storage predicted by Earth system models during the 21st century. Biogeosciences 11(8): 2341-2356.

ISSUE #2: Can increased disturbance regimes negate mitigation and adaptation actions?

Hélène Genet (University of Alaska Fairbanks)
David McGuire (University of Alaska, Fairbanks)

The dynamics of boreal ecosystems are largely determined by an ensemble of biotic (e.g. insect outbreak) and abiotic (e.g. wildfires) disturbances that range from several square meters to millions of hectares (Figure 1). The nature and occurrence of these disturbances vary greatly across the circumboreal region and recent and future climate changes are projected to drive widespread changes in disturbance regimes across the region. Because the circumboreal region contains about a third of the world's carbon (C) stocks and these disturbances strongly affect C cycling and albedo, shifts in disturbance regimes in the circumboreal region have the potential to affect global climate systems.

Disturbance regimes across the circumboreal forest

Fire is a predominant force of change across the circumboreal region, but fire regimes vary substantially among and across continents. Most fires in boreal North America (NA) are high-intensity stand-replacing crown fires, while most fires in Eurasia are reported to be low- to medium-severity surface fires (Van der Werf et al. 2017). In Fennoscandia, efficient fire suppression has almost totally eliminated the fire regime.

Large-scale host-specific insect outbreaks can trigger massive forest dieback in NA (e.g., eastern spruce budworm and the hemlock looper in the east and mountain pine beetle in western forests), Fennoscandia (e.g., spruce bark beetle and the autumnal moth) or Siberia (e.g., Siberian moth; Kneeshaw et al. 2011).

Climate disturbance such as temperature-driven drought stress or windstorm damage can also affect large regions of the boreal forest. Earlier springs, summer warming and precipitation deficit have affected forest productivity and induced mortality in western NA and Russia (Allen et al. 2010). Wind storms can also cause large-scale forest morality (i.e. coastal Alaska in NA, in coastal areas of Fennoscandia, and in the central part of Russia).

Finally, about a third of the circumboreal region is underlain by permafrost. In these landscapes, thermokarst disturbance can occur where ice-rich permafrost is actively thawing to trigger land subsidence. Although individual thermokarst features are relatively small in size, they can potentially affect 20% of the boreal permafrost region (Olefeldt et al. 2016).

Changing disturbance characteristics

The circumboreal region, along with the circumarctic region, is projected to experience the larger increases in temperatures than temperate and tropical regions. In response to climate warming, biotic

and abiotic disturbances are generally predicted to increase in size, frequency, or severity over the region, although large uncertainties persists.
Except for eastern NA, the projected increase in precipitation appears to be insufficient to fully compensate for the increased evaporative demand associated with higher temperatures, resulting in drier climate, and increased drought stress (Gauthier et al. 2015). Projected drier climate is also associated with a two- to three-fold increase in fire frequency during the present century in Eurasia and western NA. It is also associated with an increased frequency of megafires that burn over 10,000 ha and an increased frequency of intense crown fires in Russia (Van der Werf et al. 2017).

A growing number of studies suggest climate-change-related increases in the extent or severity of insect disturbance. In western NA, warmer temperatures have shortened the life cycle of spruce beetle resulting in unprecedented damage to spruce forests. Similarly, warmer annual temperatures have caused an altitudinal shift in mountain pine beetle to invade high-elevation pine forests in western Canada (Kurz et al. 2008).

Analyses of repeated imagery and long-term terrain surveys have shown an acceleration of thermokarst formation and expansion over the last 5 decades across the circumboreal region, which may become substantial in the coming decades as permafrost continues to thaw in response to climate warming (Olefeldt et al. 2016).

Finally, interactions among disturbances (Figure 1, dotted black arrows) may alter forest resilience via two main pathways: the material legacies of one disturbance can alter the likelihood, extent, or severity of another disturbance (i.e. ecosystem resistance) or can affect ecosystem recovery following a subsequent disturbance (i.e. ecosystem resilience) (Johnstone et al. 2016). For instance, defoliators such as spruce budworm reduce seed production for several decades in boreal black spruce, delaying regeneration of black spruce after subsequent fires (Simard and Payette 2005).

Impact of disturbance dynamics on ecosystems and the climate system

Disturbance regimes in the circumboreal region interact with ecosystems and the climate system by triggering decline in forest productivity, tree mortality and canopy removal, soil carbon loss, and changes in vegetation composition and age distribution (Figure 1). Several of these structural and functional ecosystem changes have the potential to influence energy exchange and undermine the ability of boreal forests to sequester atmospheric C and provide timber volume. For instance, model projections indicate a six fold increase in the timber volume at risk of being impacted by fire, mountain pine beetle, and drought in many regions of Canada by the end of the Century (baseline period [1981-2010]; Boulanger et al. 2018).

Historically, C loss from fire emissions in the circumboreal region can represent about 35% of the C sequestration for the same region (Van der Werf et al. 2017). The projected increase in intense megafires may further increase C emissions in the future. For instance, the single megafire that occurred in the Northwest Territories in 2014 burned 3.4 Mha and represented about half the historical mean annual circumpolar fire emissions (Walker et al. 2018). Intensification of the fire regime is also likely to change the age distribution and trigger a regime shift of forest stands from conifer to deciduous forest dominance in NA (Johnstone et al. 2016), while re-enforcing larch dominance in Russia. However, the warming effect of the massive fire C emissions can be offset by (1) the increase in productivity and summer albedo resulting from a relatively younger and more deciduous vegetation compared to the pre-fire stage, and (2) the increase in winter albedo from loss of overstory canopy and increased snow exposure during spring and fall (Randerson et al. 2006). In addition, the lower flammability of younger and more deciduous vegetation may attenuate the climate-driven intensification of the fire regime (Bernier et al. 2016).

Insect outbreaks can generate massive decline in forest productivity and increase in forest mortality that will affect short-and long-term C storage within the ecosystems. For instance, modeled C loss resulting from the recent mountain pine beetle outbreaks in British Columbia were estimated as equivalent to 75% of the historical annual average of forest fire emissions from all of Canada during 1959–1999 (Kurz et al. 2008).

Recently, severe drought has been identified as a major cause of transient decreases in forest productivity in Alaska, Canada, Russia, and Fennoscandia affecting both deciduous and conifer tree species (Allen et al. 2010). In addition, prolonged pre-fire drought can increase fire-related tree mortality. Drought stress also weakens conifer defenses to bark beetle attack, increasing tree mortality. Warmer temperatures may therefore amplify forest drought stress and associated tree mortality from both fires and insects, and increased fuel loads during drought years can lead to unusually severe fires (Johnstone et al. 2016).

Windstorms can cause heavy mortality, produce canopy disruption, reduce tree density and size structure, and change local environmental conditions. Consequently, disturbance may trigger regeneration, seed germination, and accelerated seedling growth. For instance, windthrow can facilitate regeneration of surviving understory saplings of shade-tolerant species such as fir and spruce. Yet, when windthrow is followed by fire, regeneration may be compromised as cones near the ground on fallen conifer trees are burned (Johnstone et al. 2016).

The development of thermokarst causes the replacement of permafrost plateau forest communities by treeless wetlands or lakes (Jorgenson et al. 2001). This transition to wetlands is accompanied by an increase of organic soil carbon stocks, but also an increase in methane emissions. At the regional level, these methane emissions from the wetlands could compensate the increase of soil carbon sequestration (McGuire et al. 2018).

Future research directions

A growing body of evidence emphasizes the importance of interactions between climate and disturbances on post-disturbance recovery and the emergence of alternative outcomes, depending on the types and sequence of interacting disturbances (Johnstone et al. 2016). More empirical and process-based modelling studies are required to improve our understanding of post-disturbance forest dynamics in the face of changing disturbance regimes and climate, and their influence on carbon and energy balance (Figure 1).

In addition, current ecosystem and climate models that are used to assess global carbon balance and climate dynamics, represent non-linear consequences of a limited suit of disturbances. While more models used in high latitude ecosystems are getting better at representing the effect of vertical permafrost thaw, and wildfire on soil and vegetation C loss, most of them do not represent the effect other critical disturbances such as insect outbreaks, thermokarst and windthrow (McGuire et al. 2018).

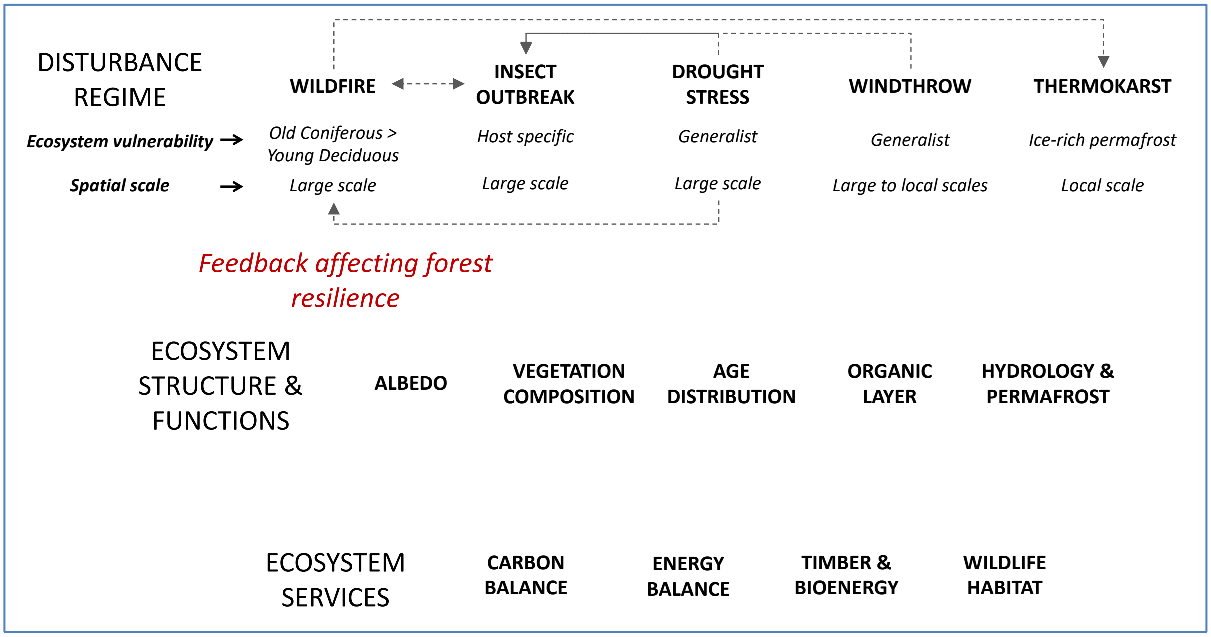


Figure 1: Impact of changes in disturbance regimes on ecosystem structure and functions and consequences for ecosystem services.

References

Allen, C.D., A.K. Macalady, H. Chenchouni, D. Bachelet, N. McDowell, M. Vennetier, T. Kitzberger, A. Rigling, D.D. Breshears, E.H. Hogg, P. Gonzalez, R. Fensham, Z. Zhang, J. Castro, N. Demidova, J.-H. Lim, G. Allard, S.W. Running, A. Semerci, and N. Cobb. 2010. A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. Forest Ecology and Management 259, 660684. https://doi.org/10.1016/j.foreco.2009.09.001

Bernier, P.Y., S. Gauthier, P.-O. Jean, F. Manka, Y. Boulanger, A. Beaudoin, and L. Guindon. 2016. Mapping Local Effects of Forest Properties on Fire Risk across Canada. Forests **7**: 157. https://doi.org/10.3390/f7080157.

Boucher, D., Boulanger, Y., Aubin, I., Bernier, P.Y., Beaudoin, A., Guindon, L., Gauthier, S., 2018. Current and projected cumulative impacts of fire, drought, and insects on timber volumes across Canada. Ecol Appl. https://doi.org/10.1002/eap.1724

Gauthier, S., P. Bernier, T. Kuuluvainen, A.Z. Shvidenko, and D.G. Schepaschenko. 2015. Boreal forest health and global change. Science **349**: 819-822. https://doi.org/10.1126/science.aaa9092

Johnstone , J.F., C.D. Allen, J.F. Franklin, L.E. Frelich, B.J. Harvey, P.E. Higuera, M.C. Mack, R.K. Meentemeyer, M.R. Metz, G.L. Perry, T. Schoennagel, and M.G. Turner. 2016. Changing disturbance regimes, ecological memory, and forest resilience. Frontiers in Ecology and the Environment **14**: 369-378. https://doi.org/10.1002/fee.1311.

Jorgenson, M.T., C.H. Racine, J.C. Walters, and T.E. Osterkamp. 2001. Permafrost degradation and ecological changes associated with a warming climate in central Alaska. Climatic Change **48**: 551-579.

Kneeshaw, D., Y. Bergeron, and T. Kuuluvainen. 2011. Forest ecosystem structure and disturbance dynamics across the circumboreal forest, in: The SAGE Handbook of Biogeography. pp. 263-280. McGuire, D., H. Genet, A. Lyu, N. Pastick, S. Stackpoole, R. Birdsey, and Z. Zhu. 2018. Assessing historical and projected carbon balance of Alaska: A synthesis of results and policy/management implications. Ecological Applications (In press).

Olefeldt, D., S. Goswami, G. Grosse, D. Hayes, G. Hugelius, P. Kuhry, A.D. McGuire, V.E. Romanovsky, A.B.K. Sannel, E. A. G. Schuur, and M.R. Turetsky. 2016. Circumpolar distribution and carbon storage of thermokarst landscapes. Nature Communications **7**: 13043. https://doi.org/10.1038/ncomms13043

Randerson, J.T., H. Liu, M.G. Flanner, S.D. Chambers, Y. Jin, P.G. Hess, G. Pfister, M.C. Mack, K.K. Treseder, L.R. Welp, F.S. Chapin, J.W. Harden, M.L. Goulden, E. Lyons, J.C. Neff, E.A.G. Schuur, C.S. Zender. 2006. The impact of boreal forest fire on climate warming. Science 314, 1130–1132. https://doi.org/10.1126/science.1132075

Simard, M., S. Payette. 2005. Reduction of black spruce seed bank by spruce budworm infestation compromises postfire stand regeneration. Can. J. For. Res. 35, 1686–1696. https://doi.org/10.1139/x05-083

Xanthe J. Walker Brendan M. Rogers Jennifer L. Baltzer Steven G. Cumming Nicola J. Day Scott J. Goetz Jill F. Johnstone Edward A. G. Schuur Merritt R. Turetsky Michelle C. Mack 2018 Cross-scale controls on carbon emissions from boreal forest megafires, Global Change Biology https://doi.org/10.1111/gcb.14287

Werf, G.R. van der, J.T. Randerson, L. Giglio, T.T. van Leeuwen, Y. Chen, B.M. Rogers, M. Mu, M.J.E. van Marle, D.C. Morton, G.J. Collatz, R.J. Yokelson, and P.S. Kasibhatla. 2017. Global fire emissions estimates during 1997–2016. Earth System Science Data **9**: 697-720. https://doi.org/https://doi.org/10.5194/essd-9-697-2017

ISSUE #3: Keeping an eye on the Taiga – Policy impediments for mitigation of climate change[2]

Jon Moen (Umeå University)

Context:

The boreal forest covers approximately 25% of the world's forested area. It contains a substantial portion of the remaining large tracts of continuous forests, and is the home to many marginalized or indigenous cultures that depend on forest goods and services for their livelihoods. From a climate change perspective, the boreal forest biome is a major global carbon storage pool, and recent estimates suggest that it may even be the largest terrestrial carbon pool in the world, most of it buried in soils and peatlands. The boreal forest is also situated in the part of the world that is most rapidly warming, which raises strong concerns about the fate of the buried carbon.

The boreal forest is already experiencing severe and escalating impacts from climate change. This includes increases in the severity and frequency of forest fires, increased melting of permafrost in cold regions, a greater likelihood of drought, and more intense and frequent insect outbreaks. All of these disturbances may result in massive releases of carbon to the atmosphere, potentially creating a tipping point where the boreal forest converts from being a carbon sink to a carbon source. About half of the boreal forest biome is also influenced by human industrial activity, including forestry, oil and mineral extraction, and hydropower development, leading to losses in biodiversity and ecosystem services which in turn may further affect the release of carbon to the atmosphere.

Given these trends and the increasing likelihood of the boreal forest losing its key climate-mitigating potential as a carbon sink, it is surprising that it has been largely absent from global policy agendas on sustainable development and climate change mitigation. The goal of this summary is thus to identify current obstacles to why this is the case, and to suggest some future solutions that may improve the situation.

Obstacles:

More than 90% of the boreal forest lies within the borders of just six nations: USA, Canada, Russia, Finland, Norway and Sweden. All have functioning political systems, long-established forest inventories and management infrastructure, well-developed markets for wood-based products, and technical forestry expertise. So, why have these nations not pressed the issue of the role of climate change mitigation from the boreal forest harder in international negotiations?

One of the obstacles may be weak incentives for carbon sequestration and storage in international frameworks, such as the Kyoto Protocol and the Paris Agreement. Some of the reasons for this

[2] Adapted from: Moen J., et al. . 2014. Eye on the taiga: removing global policy impediments to safeguard the boreal forest. Conserv. Lett. 7, 408–418.

include uncertainties in the reporting of forest growth and of carbon sinks, opposition to using the forest sector as tool for off-setting industry-level emissions, a strong interest in conservation and the environmental integrity of forest ecosystems, and uncertainties about the permanency of forest-based carbon sequestration. Although countries are allowed to collect carbon credits from forest-based carbon sequestration through net gains from afforestation and reforestation in the international agreements, these credits are strictly limited which is a disadvantage for the timber-rich boreal countries. This is due in part to a "cap" that sets the maximum allowable amount of credits under the forest management sector, leaving a potentially large portion of the forest carbon non-incentivized. It can be argued that the boreal forest sector could take a much greater role in mitigating climate change.

Another obstacle may, somewhat paradoxically, lie in the strong and effective governance structure and the long history of forestry in the circumpolar countries. Forest industries are an important economic backbone in many of these countries, which has strengthened the industry's political position. There has also been a long-held emphasis on even-aged forest management regime (i.e. a clear-cutting paradigm) that has been considered ecologically sound. While being seriously challenged by more recent ecological research, the management method is successful in providing sustained and high yields of biomass for the timber industry, especially in Scandinavia. This has led to a knowledge lock-in, where focus has been on optimizing the efficiency of this management regime rather than researching and testing alternative management methods. This overconfidence in the existing management paradigm to meet the challenges now facing boreal forests has resulted in a mismatch of science, research and policy, and produced path dependent investments in relatively inflexible long-term management regimes that will be expensive and even impossible to reverse.

Solutions:

The boreal forest holds considerable potential for climate change mitigation, for instance through high rates of carbon sequestration in managed, young-stand landscapes, carbon substitution using harvested wood products, or long-term increases of carbon storage in unmanaged forests and their soils. However, the risks of climate- and development-driven carbon emissions are also great. To minimize these risks, policy changes are important at all scales: from the management of forest stands through engagement in international processes. The first step is that the global role of the boreal forest in climate change mitigation, biodiversity conservation, and provisioning of ecosystem services must be acknowledged and considered in forest management at all scales. This will feed into national forest policies that, in turn, directly affect forest stand management. This also means that it is important to scale-up knowledge of the consequences of different silvicultural actions to regional, national and global levels. A tall order indeed. As a first step, the following solutions are suggested:

1. *Increase incentives for carbon sequestration and storage in international agreements*.
The IPCC already provides a clear framework for reporting on forest carbon pools and flows in national accounts, but continued improvements in accounting methodologies, particularly with respect to effects of disturbances, are critical in the support of this issue. In addition, the following policy-related actions are needed: i) within the on-going post 2020 negotiations, specifically consider measures to incentivize mitigation actions in the boreal forest sector, ii) provide funding for climate-friendly, forest resource-based activities, iii) support the use of

mitigation options in the full forest value chain, and iv) support local actors to achieve a productive and resilient forest ecosystem that also fulfills the biodiversity objectives.

2- *Support "climate smart forestry" (CSF)*, a forest management approach that includes climate change mitigation as one of its objectives. CSF considers the whole value chain from forests to wood products and energy, and tries to achieve synergies between climate change mitigation, biodiversity conservation, ecosystem services, and the bioeconomy. This could be achieved by a combination of more intensive forestry to increase growth on sites with low biodiversity values, expanding forests on abandoned agricultural sites, producing bioenergy from secondary residues and low-quality thinning wood, and setting up strict forest reserves to strengthen short-term carbon sequestration while at the same time meeting the Aichi targets within the Convention for Biodiversity.

3. *Integrate the socioeconomic needs of local communities, long-term carbon sequestration and storage, biodiversity conservation, and the provisioning of ecosystem services.* Some of these efforts may have win-win outcomes, for instance where old-growth forests preserve biodiversity while at the same time store carbon. Others may require decisions on trade-offs where it is impossible to get more of everything, for instance where timber harvesting has negative effects on biodiversity and carbon storage.

4. *Maintain options for the future by increasing forest resilience.* This could for instance include the ability of institutions to respond quickly and efficiently to change by fostering leadership, trust and social networks to create more flexible decision processes. Incorporation of resilience as a forest management objective given projections of local environmental changes could result from such institutional change. It may also be important to keep sufficient amounts of intact primary forests to preserve biodiversity and increase the capacity of forests to respond to disturbances.

Further reading:

Bradshaw, C.J.A. & Warkentin, I.G. 2015. Global estimates of boreal forest carbon stocks and flux. Global and Planetary Change 128: 24-30.

Nabuurs et al. 2017. By 2050 the mitigation effects of EU forests could nearly double through climate smart forestry. Forests 8: 484.

Watson et al. 2018. The exceptional value of intact forest ecosystems. Nature Ecology and Evolution 2: 599-610.

References:

Brandt, J. P. 2013. An introduction to Canada's boreal zone: ecosystem processes, health, sustainability, and environmental issues. Environmental Reviews 21:207–226.

Pan, Y., et al. 2011. A large and persistent carbon sink in the world's forests. Science 333:988–993.

Price, D. T., et al. 2013. Anticipating the consequences of climate change for Canada's boreal forest ecosystems. Environmental Reviews 21:322–365.

Conclusion: Opportunities and benefits of increased research collaboration among circumboreal nations

Werner Kurz (Canadian Forest Service),
Pierre Bernier (Canadian Forest Service)
Rasmus Astrup (Norwegian Institute of Bioeconomy Research)
Florian Kraxner (IIASA, Austria)

Background:

The circumboreal region covers vast areas and is mostly distributed across six countries. In the boreal region, temperature increases resulting from climate change are expected to be well above the global averages, and boreal ecosystems are characterised by processes that are strongly affected by temperature and water balance: growth, decomposition, and disturbances in particular wildfire. Carbon stored in biomass, soils, peatlands and permafrost systems will be affected by changes in environmental conditions resulting in changes in carbon cycling and greenhouse gas balances. While some of these could provide positive feedback to climate change – "the warming will feed the warming" – there are significant opportunities for these regions to support the development and implementation of both climate change mitigation and adaptation strategies in support of bioeconomies and reductions in the emissions of GHGs. The actions outlined in this document provide a short list of potential large-scale mitigation actions, many with a range of co-benefits.

Increasing the probability of positive outcomes from such actions will require a sound and credible scientific foundation. The text above has identified areas of investigation for improved scientific understanding of climate chance impacts and the projected outcomes of mitigation and adaptation strategies. Beyond biophysical and ecological systems, the text has also identified areas of investigation in the socio-economic systems as a large proportion of the boreal population lives in resource-dependent communities whose livelihoods (forest resources, infrastructure and permafrost) and health (fire, smoke, water) are threatened by the impacts of climate change on boreal systems.

Despite important regional differences, circumboreal forest ecosystems have many common features and are affected by the same threats from climate change impacts. With limited financial and human resources to monitor, understand and predict the impacts of a rapidly changing environment, enhanced collaboration among circumboreal nations on research in support of science and policy development seems like an obvious way to address some of these challenges. However, to date there are limited formal avenues that support collaborative research involving all six circumboreal countries. National funding agencies are rarely willing to fund significant international collaboration or activities outside their own countries. The research focus in the Fennoscandic countries are often driven by the European research agenda and focused on Europe through the H2020 program.

Opportunities:

All boreal forest countries have well-established forest research institutions. Expertise among the scientists of these research institutions is not equally distributed with centres of excellence on specific topics dispersed among boreal countries. Many are developing analytical tools, scientific computer models, observation systems, and other forms of decision support. Many are engaged in diverse research aimed at addressing at least some of the questions listed above. However, despite these ongoing efforts, constraints in human and financial resources combined with the urgent need for answers to these (and related) questions limit the reach, progress and efficacy of research. Considerable gains could be achieved through enhanced scientific and policy collaboration among boreal countries.

Examples of potential areas of collaboration could focus on those topics in which complementary expertise, data or tools are distributed across two or more countries. For example, while all countries have well-established permanent sample plots from which growth and mortality responses to environmental changes may be inferred, much remains to be done to develop analytical and predictive capabilities on forest growth and mortality that are required to inform sustainable forest management in a future affected by environmental changes.

There are also significant differences in the extent to which intensive forest management is practiced across the boreal. Enhanced and carbon-focused management expertise in Fennoscandic countries can inform boreal forest management in Canada, Russia and the US. The design and implementation of mitigation approaches should go beyond carbon objectives and also address other environmental and socio-economic values.

The relative importance of natural disturbances and forest management differs among boreal countries. Boreal forests in Canada, Russia and the US are strongly affected by fires and insects, and with climate change the risks of such natural disturbances will also increase in Fennoscandia countries. Expertise in and tools to assess disturbance risks and impacts can be shared among boreal countries.

Impacts on the climate system that are mediated through processes other than greenhouse gases, such as changes in albedo, water cycles and volatile organic compounds (VOCs) are increasingly recognized as important but scientific understanding of the impacts of forest management actions is still limited.

Ownership structures also are very different among countries which affects the way in which large scale, landscape level experiments could be implemented: large carbon management demonstration areas might be more easily implemented in regions with one or a few land owners compared to regions with hundreds of small private land holdings that make it more difficult to implement coordinated strategies.

Finally, the social acceptance of novel forest management practices for climate change mitigation or adaptation should not be taken as a given. Social acceptance will be key to the successful deployment of such practices. Understanding the pathways to social acceptance and its influence on policy is therefore an important area of research.

Benefits:

Many research questions that we need to answer in order to pursue or enhance climate change mitigation have no simple answers, require long time series of observations and data, and may require sophisticated computer models and analytical tools that are costly and time-consuming to develop and maintain. However, progress can be accelerated and research costs reduced if some of the more complex issues are addressed using coordinated research approaches, and by sharing data, models and expertise. While enhanced cooperation and coordination of research requires investments of time, expertise and financial resources, the net gains in terms of accelerated research results, and overall reduced costs can be significant. For example, collaboration on open-source scientific models and sharing of data processing and analytical tools will reduce costs and development time and increase overall productivity.

Enhanced research collaboration among circumboreal countries can be achieved through diverse mechanisms and with various levels of funding. Enabling such circumboreal collaboration among the science and policy communities will require foremost the support and encouragement of senior management and political leaders. One possible approach to enhancing the research collaboration among boreal countries is to draw on the informal scientific networks established by the International Boreal Forest Research Association (IBFRA). IBFRA's role could be to facilitate and coordinate the development of a policy-relevant research agenda, defined in collaboration with the circumboreal working group. The outcome of the science workshop and of the follow-up science-policy dialog to be held in Haparanda on June 24-25 2018 will ideally be a proposed mechanism by which such collaborative circumboreal interaction can happen and be supported by national agencies.

MEETING REPORTS

Science Workshop report

The boreal summit held in Haparanda, Sweden on June 26 2018 offered the International Boreal Forest Research association (IBFRA) an opportunity to support the science-policy dialogue required to move forward on boreal forest-based climate change mitigation actions. An IBFRA science workshop was therefore held in Haparanda, Sweden, on June 24 and 24, 2018, prior to the Ministerial meeting. The event was planned by IBFRA Steering Committee members Rasmus Astrup (NIBIO, Norway), Werner Kurz (CFS, Canada), Pierre Bernier (CFS, Canada), and Brian Bonnell (CFS, Canada) in close dialog with the Circumboreal Working Group. The science workshop was followed by a ½ day science-policy dialog to which were invited participants to the Ministerial meeting, or their policy staff. The program of both events can be found below. Both the science workshop and the science-policy dialog were chaired by Werner Kurz and supported by Rasmus Astrup, Pierre Bernier and Florian Kraxner (IIASA, Austria) (core team).

Participants to the Science workshop were:

- Rasmus Astrup - Norwegian Institute for Bionergy Research
- Pierre Bernier - Natural Resources Canada
- Ryan Bright - Norwegian Institute for Bionergy Research
- Vladimir Dmitriev - Russian Federal Forestry Agency
- Gustaf Egnell - Swedish University of Agricultural Sciences, Umea
- Stephanie Eisner - Norwegian Institute for Bionergy Research
- Hélène Genet - University of Alaska Fairbanks, USA
- Artem Konstantinov - St Petersburg Forestry Research Institute
- Florian Kraxner - International Institute of Advanced System Analysis
- Werner Kurz - Natural Resources Canada
- Matts Nilson - Swedish University of Agricultural Sciences, Upsalla
- Pasi Ratio - LUKE, Finland
- Dmitry Scehpaschenko - International Institute of Advanced System Analysis
- Mariya Sokolenko - Russian Federal Forestry Agency
- Evelyne Thiffault - Université Laval, Canada
- Chris Williams - Clark University, USA

Science workshop presentations, discussion and outcomes:

After opening remarks by Rasmus Astrup and a climate change context presentation by Werner Kurz, short presentations were made by authors of discussion document on the section they had authored: Evelyne Thiffault (Action #3), Pierre Bernier (Action #4), Ryan Bright (Action #5), Dmitry Schepaschenko (Action #6), Hélène Genet (Issue #2). All presentations were later made available to the participants via a dropbox site, and can be obtained from Pierre Bernier (pierrebernier.cfs@gmail.com). Following the discussion period, all participants were asked to provide the three knowledge gaps or research questions that they viewed as being most important in the light of the material made available to them and of their own experience. These replies were processed by the core team and the resulting summary was presented back to participants during the morning session on June 25. A discussion led to the refinement of the key research gaps and their organisation into broad research questions and more focussed policy-relevant questions that were to be used as discussion material during the Science-Policy Dialog in the afternoon. This final list can be found in Annex 2.

The participants to the Science Workshop further produced the outline of a process through which IBFRA could provide timely policy relevant scientific insight on one or more questions related to climate change mitigation measures for the boreal forest. Coined the “IBFRA Insight Process”, its details can be found in Annex 3.

Science-policy Dialog report

The Science-Policy Dialog took place in the afternoon following the IBFRA Science Workshop. The Dialog was attended by the workshop participants who were joined by members of the Circumboreal Working Group and high-level managers of the various forest agencies of circumboreal countries. These additional participants were:

- Beth MacNeil - Assistant Deputy Minister, Canadian Forest Service
- Taneli Kolström - Vice President, LUKE, Finland
- Aulikki Kauppila - Finnish Ministry of Agriculture and Forestry
- Terje Hoel - Senior Adviser, Norwegian Ministry of Agriculture and Food
- Frode Lyssandtrae - Deputy Director, Norway
- Mariya Sokolenko - Deputy Head of Division of Analytics, the Russian Federal Forestry Agency
- Vladimir Dmitriev - Head of the Department of Science and Prospective Development, the Russian Federal Forestry Agency
- Andrey Vasilyev - Deputy Executive Secretary ECE
- Birgit Lia Altmann - Ass. Economic Affairs Officer, ECE
- Herman Sundqvist - Director General, Swedish Forest Agency
- Peter Blombäck - Head of Policy and Analysis Division, Swedish Forest Agency
- Gerben Janse - International Coordinator, Swedish Forest Agency
- Lenise Lago - Deputy Chief, US Forest Service

Dialog discussion and outcomes:

The organisers of the IBFRA Science Workshop had sent the workshop discussion paper to the country teams that were taking part in the Boreal Summit that was to take place on the following day. The country representatives to the science-policy dialogue had also been instructed to prepare three policy questions of importance.

The Dialog meeting started with a presentation of the climate change context by Werner Kurz to which were added both the list of science and policy questions that was drawn up during the Science workshop (Annex 2) as well as the details of the proposed “Insight process” (Annex 3). The discussion that ensued concluded by the unequivocal support of all policy participants to the Insight process proposal and saw it as a realistic process from which their respective national organisations could benefit. Discussions then covered more pragmatic issues such as the frequency at which such a process could take place given the depth of expertise in the IBFRA network of scientists. Left unexplored was the mechanism by which such a process could be convened but this has since been addressed in subsequent discussions.

Finally, in a round-table discussion, policy representative listed their three policy questions of importance (Annex 4), thereby forming an initial list of potential topics for a first Insight process (Annex 4).

IBFRA science meeting participants, left to right, back to front: Gustaf Egnell, Evelyne Thiffaut, Vladimir Dmitriev, Artem Konstantinov, Matts Nielsen, Stephanie Eisner, Ryan Bright, Florian Kraxner, Hélene Genet, Pasi Ratio, Pierre Bernier, Mariya Sokolenko, Werner Kurz, Rasmus Astrup, Dmitry Schepaschenko, Chris Williams

ACKNOWLEDGEMENTS

The editors of this report, Rasmus Astrup, Pierre Bernier, Florian Kraxner and Werner Kurz, want to thank all the authors who accepted to put their tasks aside and write or contribute to the writing of the technical chapters in the discussion document. In addition, the science workshop and the science-policy dialog would not have been possible without the dynamic participation of scientists who took time from their busy schedules to spend a few days in Haparanda for this event.

The editorial group also want to thank Brian Bonnell, of the Canadian Forest Service, for his contributions to this event as former Canadian Representative on the Circumboreal Working Group

Finally, special thanks are extended to the Government of Sweden for covering the costs related to the local meeting arrangements, and to the Government of Norway for providing travel support for a number of participants. The meeting would not have been possible without their financial backing.

ANNEXES

Annex 1: Meeting agenda

International Boreal Forest Research Association

Session Component	Topics	Outcome
Day 1 June 24th: Scientific workshop		
Setting the Stage 13:00 – 15:40	• Welcome and round table introductions (Werner, all, 15 min) • IBFRA background, Workshop Objectives, and Agenda (Rasmus, 10 min) • Boreal forest and climate change: "setting the scene" (Werner, 15 min) • Overview (Pierre) and short summary presentations on key science topics/issues (selected authors from background paper) • Presentations to focus on key scientific uncertainties and opportunities for collaborative research to address these uncertainties (total 60 min)	• Familiarization with papers and key issues
Break 14:40 – 15:00		
Discussion 15:00 – 18:30	• Synthesis of key scientific issues and uncertainties. • Identification of research topics that benefit from coordinated collaboration among boreal countries, focusing on synergies, existing research strengths, and available data.	• Synthesis of key scientific issues and uncertainties • First draft of recommendations for collaborative research opportunities
Working Dinner 19:00 – 21:00	• Networking and informal information exchange on ongoing research	
Day 2 June 25th: Scientific workshop		
Discussion 08:00 – 10:00	• Summary of Day 1 (Werner) • Develop second draft of the synthesis of key scientific uncertainties	• Second draft of the synthesis of key scientific uncertainties
Break 10:00 – 10:30		

Discussion 10:30 – 12:30		• Develop second draft of collaborative research opportunities • Explore implementation options – including funding requirements • Role of 18th International IBFRA conference in this process (Florian) • Finalize the presentation to the policy community	• second draft of collaborative research opportunities • presentation to the policy community
Lunch 12:30 – 13:30			

Session Component	Format	Topics / key questions	Outcome
Day 2 June 25th: Science-policy dialogue			
Science-policy dialogue 15:30 – 18:30	• Boreal forest and climate change: a science-policy dialogue for exploring knowledge gaps, opportunities for action, and collaborative research opportunities	• Key findings and recommendations from boreal science community • Science-policy dialogue: what does the policy community want to know? • Review and validation of science community's understanding of policy needs • Formulate key science-policy issues • Summarize collaborative research opportunities • Explore implementation options – including potential funding mechanisms • Review and finalize the presentation to the Boreal Summit	• Presentation for the Boreal Summit
Boreal Summit Reception 20:00			

Annex 2: Questions on climate change mitigation and adaptation in the boreal forest emerging from the IBFRA Science Workshop

Science-focused questions

- What are the positive and negative impacts of climate change on forests, their future GHG balance, timber supply, disturbance risks, hydrological cycles, etc. (what, where, when, … maps of opportunities and risks)
- What mitigation actions exist and how much can they contribute to the GHG reduction goals (Paris Agreement) through forest management (including conservation), HWP storage and substitution benefits? At what costs, and with which co-benefits?
- In addition to GHG balances, how can we evaluate mitigation impacts on the climate system (albedo, evaporation, VOCs, others)?
- How and where can mitigation and adaptation objectives be combined?

Science-focused questions: specific examples for disturbances

- How will disturbances (fire, insects, disease, wind, snow) in boreal forests affect climate (GHG and albedo +) and wood supply (volume, species, quality) and mitigation actions (salvage, rehabilitation)?
- How should disturbance risks be integrated into the design of mitigation portfolios? Regional differences across boreal are large.
- How can forest management alter the risks and impacts of natural disturbances (fuel management, suppression, deciduous species, insect hosts, salvage, replanting)?

Science-focused questions: specific examples for carbon

- How does quantification of the carbon exports from soils (and dead organic matter pools) to water systems affect our understanding of the impacts of forest management and climate change (temperature and water) on GHG budgets … focussed only on the boreal forest region.
- How does forest management (type, intensity) affect soil and wetland C and hydrology (and permafrost)? Can we identify and communicate criteria and reasons why similar treatments can have very different outcomes … vulnerabilities … maps … decision tree?

Science-focused questions: specific examples for harvested wood products

- How can we increase average carbon retention time in Harvest Wood Products?
- Produce products with longer lifespans

- How can we quantify product and energy substitution benefits?
- Including how to treat exported products and bioenergy
- Technological development in other sectors that will reduce substitution benefits over time
- How large are the biophysical and economic climate mitigation potentials of long-lived HWP and bioenergy from the boreal?

Policy-focused questions

- What are forest sector mitigation measures with [very likely (>90%)] positive GHG and climate benefits?
    - Opportunity and risk maps, GHG impacts, Albedo impacts, costs
    - Can boreal forest fertilization contribute to climate change mitigation?
    - Does afforestation and planting (of deciduous species) contribute to mitigation outcomes?
- Should active forest management or conservation based approaches be used to achieve climate mitigation goals … including risks from disturbances? Options for zonation, balance of ecosystem services …
- Should forest-based bioenergy be incentivized and under what circumstances will this be climate effective?
- Given the impacts of climate change on the quantity and quality of fibre supply, what is the sustainable size of a bioeconomy in the boreal forest and how can science help government support its implementation?
- What are adaptation measures with [very likely (>90%)] positive outcomes?

Annex 3: The IBFRA Insight process

The IBFRA recognises the need of national forest institutions to obtain relevant and timely scientific information in a policy-friendly format on topics of importance in the context of climate change mitigation measures for the boreal forest. It also recognises the benefits of circumboreal expertise in the provision of such scientific information to these national organisations. To this end, the IBFRA is proposing the “Insight Process” that could be convened by any of the national forest organisations of a boreal country to address a specific topic. The aim of the Insight Process would be:

- To summarise scientific understanding on specific targeted topics focussing on the boreal region
- To inform the policy community about state of knowledge and uncertainties, gaps.

The process would be guided by a “check list” of analytical parameters:

- A systems approach
- Common system boundaries and time horizon in all its analyses
- Inclusion of:
    - GHG and non-GHG impacts on the climate system
    - other criteria and trade-offs when possible
    - risks from disturbances,
    - Socio-economic costs and benefits
    - social and public acceptance
- The recognition of regional differences across and within boreal countries

More specifically, the process would involve the following steps in which steps 1 to 6 would aim to be completed within one year:

1. Identify Insight topic based on science-policy dialog
2. Arrange initial workshop with 15 – 30 participants
3. Prepare first draft of document
4. Review process of first draft
5. Prepare second draft
6. Arrange final workshop to complete and discuss paper (scientists + policy participants)
7. Finalise and publish 1 scientific paper (an Insight paper)+ 1 policy brief

Annex 4: Policy questions or issues from country representatives at the Science-Policy Dialog

- What practical silvicultural alternatives are there to be relatively sure to do active forest management 50 to 100 years from now?
- What is the most probable estimation of future supply of timber and biomass?
- Comparative analysis of forest reference levels for LULUCF across circumboreal countries for reporting to international agreement.
- Biological limits of using biomass vs implications for carbon storage in soils
- What are the silvicultural measures that would increase the contribution of forests to climate change mitigation?
- What should be done with peatlands that were drained 50 years ago – maintain the drainage or close the ditches to raise the water level?
- How can boreal collaboration aid in the use of long-lived HWP – how can different countries learn from each other (architectural and engineering issues, building codes, etc…)?
- What is the consensus around the issue of soil carbon and forest management practices?
- How can we better predict the risk of damages to forests due to disturbances, including invasive species?
- What are the most cost-effective and climate-effective uses of biomass?
- How can we collectively increase social acceptance of active forest management as a conservation practice?
- How could land ownership promote or degrade climate change adaptation strategies?
- How can be improve consideration of the carbon that is stored in the forest product
- Necessity of joint research program for boreal sustainable forest management
- Particularities of boreal forest should be reflected in the negotiations on climate – issues of biodiversity are addressed, but not the boreal
- In the context of the bioeconomy, how do we decide between the use of agricultural vs forest biomass?
- How do we address the growing complexity of the cumulative effects within the forest ecosystems?
- How can we quantify the actual mitigation benefits of actions related to forest carbon and the cost per ton of these actions?