Accepted manuscript

Adaptive Management as a Vehicle to Achieve Sustainability of Boreal Forests: A Historical Review from Fennoscandia to Minnesota

Jan Kunnas and Bruno Borsari

Jan Kunnas, Ph.D.
Post-doc researcher
School of Resource Wisdom
University of Jyväskylä
Finland
jan.kunnas@gmail.com

Bruno Borsari, Ph.D.
Professor Emeritus
Department of Biology
Winona State University
Winona, MN 55987 USA
bborsari@winona.edu

Abstract
Located solely in the northern hemisphere, boreal forests contain an estimated one-third of Earth's forested land. The purpose of this work aimed at reviewing the evolution of approaches in land planning and management of boreal forests in Finland and Northern Sweden, while comparing these to those developed in Minnesota. The nature of this work is historical research of forests use and management during the last 200 years. The knowledge from past histories is valuable to improve management approaches that aim at retaining the economic viability of logging, without jeopardizing the regenerative capabilities of forest ecosystems. Various methods and restoration efforts aimed at recovering from unsustainable biodiversity losses, created by past, uncontrolled tree harvesting, were assessed. Challenges and successes were presented in this work from both geographic regions, highlighting policy making and effective management approaches. Also, a new model framed within ecological memory to improve management practices toward sustainability of boreal forests was proposed.

Published as: Kunnas, J., & Bosari, B. (2021). Adaptive Management as a Vehicle to Achieve Sustainability of Boreal Forests : A Historical Review from Fennoscandia to Minnesota. In W. Leal Filho, U. M. Azeiteiro, & A. F. Freitas Setti (Eds.), Sustainability in Natural Resources Management and Land Planning (pp. 311-326)

1 Introduction

Boreal forests form a distinctive biome of the northern hemisphere (50° to 65° N latitude), extending from Scandinavia, through Russia, across Siberia, to Alaska, through Canada (Fig. 1), and cover over 8 % of earth's terrestrial surface (FAO 2020). One major challenge for the management of northern forests is the long growing time necessary for trees, to reach harvestable size in this cold environment. More challenges are caused by climate change, as boreal forests are particularly vulnerable to the long-term effects of climate change, and its more immediate disturbances like drought, insect infestations and fire (Fischlin et al. 2007).

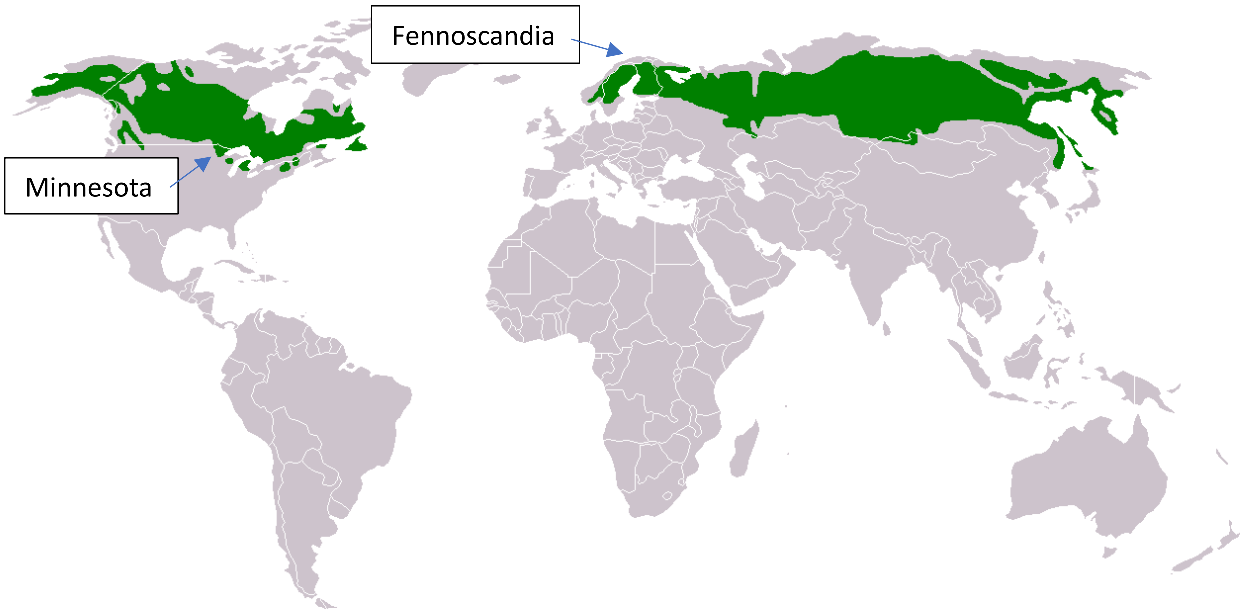

Fig. 1 Distribution of boreal forests and study regions
(Modified after: Vzb83 (CC BY-SA 3.0)). Available at:
https://upload.wikimedia.org/wikipedia/commons/3/31/Taiga.png

The purpose of this study consisted in reviewing the use and approaches to land management in two selected regions of the boreal forest biome: Finland and Sweden, Europe and Minnesota, USA. This review presented a historical documents analysis of forest lands use over the past 200 years, with the intent of understanding differences and/or similarities in management approaches and policy making, that regulated the use of forests in the selected study regions. It aimed at documenting what has changed in managing boreal forests and what emphasis if any, has been given to sustainability. Conserving the productivity of these distinctive ecosystems without affecting too drastically, their ecological integrity and regenerative capabilities justified the need for this study.

2 Methodology

Staley (2007) suggested looking at the present as a harbinger of something that may happen in the future, when studying historical events. Kunnas et. al. (2019) and Kunnas and Myllyntaus (2020) applied Staley's framework on recorded patterns of past forest management and uses in Finland and North Sweden.

These works inspired the methodological approach adopted in this study, whose nature was nonexperimental. Through this research endeavor we examined data to understand the past without looking solely, at developing a chronological list of facts and dates. Rather, we studied the dynamics of history in managing boreal forests, and by reviewing historical evidence, we tried to explain anthropogenic activities and patterns to develop new hypotheses and paradigms, supportive of a sustainable forest management.

3 Results

3.1 Forest management in Sweden and Finland in the 19th century

Concerns about massive deforestation, which characterised the policy of the Swedish Government for centuries, remained in Finland, after its annexation to the Russian empire as an autonomous grand duchy, in 1809. Its sawmilling industry became suppressed by tight regulations that supported mercantilist doctrines, wanting to save the forests in favour of future energy needs of the mining industry (Hanho 1915; Kunnas et al. 2019). A new law in 1851 implemented more drastic restrictions limiting sawmilling operating time to a certain season, each year. It heralded the idea that logging was priority activity for state-owned forests. Unauthorised slash-and-burn cultivation on crown lands became prohibited and, unlike earlier prohibitions, this law was enforced. In Northern Sweden, crown lands in the 1820s were considered of marginal value and thus, suitable for an establishment of homesteads to promote agriculture and population growth. However, a firm establishment of the wood industry brought with it enormous values to crown lands, that had been considered "useless" just a couple of decades earlier (Kuisma 2006; Aarnio 1999; Schager 1925).

Sawmilling became free from restrictive regulations in Finland after the mid-nineteenth century, as liberal ideas gained a foothold, also to strengthen state finances in the aftermath of the Crimean war. Better knowledge about Finland's forest resources worked in favour of sawmills, too. The head of the New Forest Agency, C.W. Gylden, estimated in 1853 that Finnish forests' net annual, timber production was 30 million m^3, whereas consumption only16 million m^3. Permissions were granted for building several steam sawmills across the country between 1859–1861, with Finland's first, operating in March 1860. Sweden had established already its first steam sawmill in Norrland in 1849 (Kuisma 2006; Kuusterä 1989; Meinander 1945; Heckscher 1968).

An increasing economic value of forests triggered also criticism about the generous allocations of forest lands to peasants in Finland and Sweden. For example, the Governor of Swedish Norrbotten County, P. H. Widmark, argued in 1860 that people establishing new homesteads in forested lands had reduced their farming to a minimum while focusing instead, on timber sale without concerns for insuring a regeneration of forest stands (Carlgren et al. 1925). At the same time, a contiguous series of crop failures in the 1860s speeded up emigration to America, which reached its peak in the 1880s, when one every twelfth Swede emigrated. It was hoped that settlement and industrialization of Norrland would stop this trend. To support agriculture further under these difficult circumstances, the allocations of forest lands for new settlements became even larger (Betänkande 1931).

Soon, the need for wood as raw material increased, as sawmilling diversified in other wood-processing industries, such as mechanical and chemical pulping, spool and plywood production. Sweden's first groundwood mill for mechanical pulping was built in 1857 at Trollhättan Falls (Heckscher 1968), whereas Finland's established in 1859 in the municipality of Vyborg and the second in Tampere in 1866. This expansion driven by high demands for timber resulted in severe cases of deforestation. Growing demands for forest products and increasing trees harvesting, worried the Swedish sawmill industry of exhausting soon, timber availability. Pressure from various sawmill owners to protect the industry against competition from pit props sales, pulp and paper industry lead to regulation enactment in 1874, with measures against logging the young forest in Norrbotten county (dimension law), which banned harvesting and shipment of timber, that did not have required dimensions. In 1882, these provisions applied also in Västerbotten (Holmström 1988).

At this time, individual farmers in Finland and Sweden held large tracts of forest and to secure timber sawmills and pulp mill companies leased logging rights from them. Initially, the leases could be for 50 years in Sweden, but by 1905 these had been reduced to five years. Also, companies began to buy whole farms to secure more timber, as it was not allowed the purchase of forests alone. By the beginning of the 20th century companies owned over a third of all individual homestead lands in Dalarna and Norrland, Sweden. Thus, in 35 years, forest companies in central Norrland acquired nearly 90 % of their present-day forest holdings. These purchases started an intense and prolonged debate about the companies' right to continued forest land acquisition, generating concerns about the future of peasants' land ownership. The bids received from forestry companies were considered great deals and only later, farmers realized they had been cheated for having sold their forest plot, or logging rights at low prices. In 1906 a law was introduced that banned companies from buying forests in the four northernmost counties of Sweden (Holmström 1988; Rentzhog 1991). Similar provisions were adopted in Finland, from 1885 to 1915, when land acquisitions by logging companies became restricted (Karjalainen 2000).

Due to fast deforestation, sawmilling profits fell as the harvested size of the pine trees diminished, forcing mills to acquire timber further away from their facilities. Around the turn of century logs with a diameter of 15 cm, or less had become acceptable for harvest, whereas a few decades earlier a timber of 25 cm would have been rejected. The economic salvation of the forest industry occurred with the sulphite cellulose process (discovered in 1867) and its first use in Sweden in 1874, at Bergvik sulphite mill in Gävleborg County. As the sulphite process used spruce trees, it caused a re-evaluation of what a forest meant in the catchment areas for the factories (Petterson 2015).

3.2 20th and 21st Century: changing values and climate

In 1874, the Swedish government enacted provisions compelling all private owners to ensure forests' regeneration and the 1903 Forestry act established as a law, which emerged from those early regulations. However, only private owned lands had to comply, and not those in Norrbotten nor Västerbotten, where the "dimensions law" specifying minimum diameters of trees continued to allow these to be felled. As young growing forests were cut to increasing demand for firewood during World War I, the 1903 law was revised in 1923, requiring in addition to re-growth after harvesting also the protection of young forests. After 1925 this law was enacted in Norrbotten and Västerbotten as well, when the dimensions law was repealed (Nylund 2009; Bernes and Lundgren 2009).

On December 6, 1917 Finland declared its independence from Russia and independence brought change in Finnish forest policy, especially regarding state-owned forests. Finnish director of the organization of state-owned forest (Metsähallitus), A.K. Cajander stated, that as an independent country, Finland needed more income, and this should be obtained from its forests. He believed that forest revenues were expandable by increasing logging, improving their management, and increasing the drainage of peatlands, thus promoting forests' growth. This new view was presented to forest officials in 1919, suggesting that diameter standards for trees to be cut were to be abandoned. Experience had shown that this practice was not effective in reforestation efforts and in the long run it would have lost its economic viability. Instead, restorative logging practices were to be employed, including sequential cutting, through the seed-tree cutting method. Cajander's forest management theory recognised forest sites and types according to vegetation structure and composition and it is still used today in forestry planning and management (Parpola 2014; Laitakari 1960).

World War II brought significant changes in the harvesting methods of Finland´s state-owned forests. To obtain wood as quickly as possible, felling occurred alongside transport routes, and parcels were clear-cut to provide maximum amount of wood per unit area. Serious drawbacks were noted in this this plan, but Metsähallitus stated that it was prepared to carry out logging in manners and quantities that did not conform to rational forest management (Parpola 2014). The practice of clear cutting, introduced under exceptional circumstances, became the norm in 1948 with the so-called "selective cutting declaration". Eventually, forest owners who wanted to manage their forests differently were prosecuted, so that their properties could have been forcibly managed in accordance with current provisions (Lähde 2015).

As the Finnish forest industry resumed its post-world war activities in the mid-1950s, the demand for wood exceeded annual growth rate of the trees. Consequently, the total standing stock shrunk from 1,540 million m^3 in the early 1950s to 1,490 million m^3 by 1970. This gave impetus to several timber production programmes that succeeded, as indicated by the latest forest inventory, showing a standing stock of 2,470 million m^3 in 2017, 1.6 times that of 1970. Simultaneously, annual growth increased from 55.2 million m^3 in the early 1950s to 107 million m^3 in 2017 (Tomppo and Henttonen 1996; Luonnonvarakeskus 2018). A major contribution to this growth in timber volumes was the drainage of forested peatlands, accompanied by fertilizers use. However, the effect of clear-cut followed by tree planting has been heavily disputed. Some compared this practice to the previous selective diameter-limit cutting, others instead argued that the initial slow growth of saplings outweighed the benefits of clear-cuts. Simultaneously, the effect of ending forest grazing has gained less notion (Henttonen et al. 2020; Huikari 1998; Kuusela 1999; Lähde et al. 1999). Regardless of what component yielded most timber volume, the measures undertaken to achieve this had major effects on the structure, dynamics and biodiversity of forests. According to the fifth national endangerment estimate, for 733 species (representing 27.5% of the endangered species), it was found that the primary cause of loss was attributable to changes in forest habitats, caused by logging. A decline of decaying wood in old-growth forests and large trees constituted primary reasons of loss, for more than 50% of these species, whereas for more than 25% of the species it was forest regeneration and management (Hyvärinen et al. 2019).

Fig. 2 Decaying wood in an old-growth, boreal forest in Pyhä-Häkki, Finland (Photo Jan Kunnas)

Also in Northern Sweden decades of uncontrolled logging caused timber dimensions to shrink, forcing a relocation of sawmilling back south, where it remains today. By the end of the 1920s, Norrland's share of timber production decreased to 42% and further, to 27% by the 1950s (Petterson 2015). Although the epicentre of the forest industry moved southwards, the pressure towards northern forests did not diminish. The skewed age structure of forests with prevailing populations of young trees in lieu of mature forests, forced timber acquisitions from Dalarna, the last remaining frontier. This is a thousand kilometres long belt of forested mountains, in the northernmost Lapland region. It had been protected from logging since the early 1950s, as forest regrowth after harvesting was uncertain, due to extreme climatic conditions. However, in 1982 logging restrictions in this region were removed, causing an acrimonious debate that followed the implementation of logging plans and road building on public and private lands (Byström 1986).

The growing environmental awareness manifested in opposition to logging of forested mountain lands materialized in a new policy that was enacted by the Swedish Parliament in 1993. It was characterized by two equally important goals; the production of valuable timber yields, while conserving biodiversity (Regeringen 1993). Similar stipulations about biodiversity protection were introduced to Finnish forest legislation (Finnish Parliament 1996). As a measure of balance between these two goals, Sweden achieved protection of 3.2% of its forest lands as national parks and nature reserves, 0.2% as habitats and conservation agreements, and 5% as voluntary allocations required by forest certification schemes. Consequently, 91.6% of all productive forest land is used for timber production. In Finland, protected forest areas cover 5.7% of all forest lands, leaving 94.3% for forestry. The success of these provisions was substantiated by assessing forests' species diversity and richness, through periodic surveys. In Sweden for example, it was discovered that of 1.787 known forests' species, about half (861), were designated as endangered, making this information vital in managing forests sustainably (Luke 2019; Swedish Forest Industries Federation 2011).

In the 1950s birch, aspen and other broadleaved tree species had not much use beyond firewood. They were regarded as weeds and treated with phenoxyacetic acids (herbicides similar to Agent Orange, used in the Vietnam war by the US troops) until these were banned in the 1980s. Birch was also re-assessed commercially, as new technology allowed the making of pulp from it, and the plywood industry expanded. Later, aspen and other broadleaved trees were revaluated, as important components of forests' biodiversity (Enander 2007). The non-native lodgepole pine (*Pinus contorta*) introduced to Sweden in the 1920s from North America and used in large scale replanting projects since the early 1970s was also re-evaluated. Approximately, 40.000 hectares were planted with it in 1984, but thereafter, its use dwindled as large areas where damaged by the fungus *Gremeneniella abietina.* The infection spread also to plantations of domestic pine (*Pinus sylvestris*), inducing experts to argue that the real problem was clear-cutting and tree planting in climatic conditions that favoured the fungus. The scale of this infection became devastating to the reputation of *Pinus contorta* being planted and marketed as a durable alternative for growing timber species in severe climatic conditions. When its planting ended in the early 1990s, lodgepole pine-covered about 4% of the productive forest land in Sweden (Hagner 2005; Widenfalk 2015).

3.3 Management of Boreal Forests in Minnesota

The northern forests of Minnesota are part of the southern edge of the boreal forest biome (Pleticha et al. 2019). The trees community is dominated by conifers such as black spruce, white spruce, tamarack, jack pine, and balsam fir, all well adapted to the region's cold winters and shallow soils (Fig. 3). Hardwood trees like birch, aspen, maple and basswood are often interspersed with the conifer species, according to soil fertility conditions, which in Spodosols are typically very limited and nitrogen deficient (Goldblum and Rigg 2010).

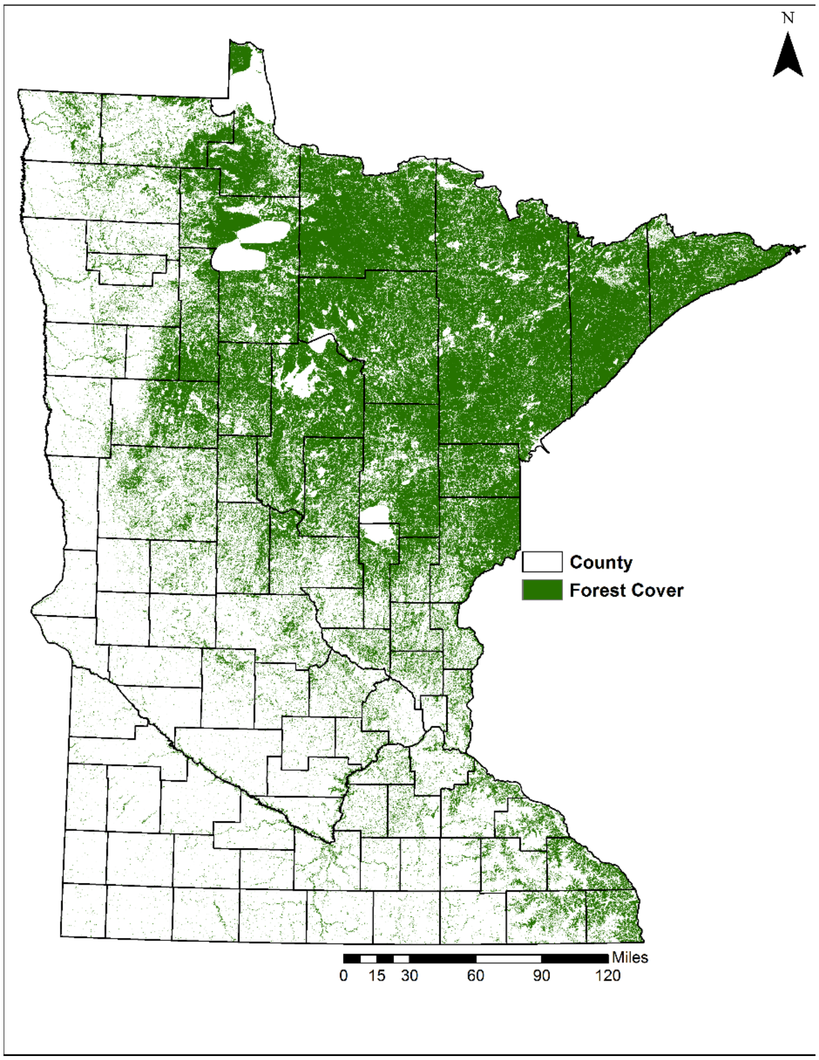

Fig. 3 Forests (7.1 million ha.) concentrate in the northeastern part of Minnesota (Hillard 2018, 145)

Minnesota forests began to be harvested in the mid-19th century when European colonists looking for new sources of high-quality timber moved west, from Maine, through Wisconsin. By 1849 logging was well established in the new, territory and quickly spread inland every winter, near pristine stands of pine (*Pinus strobus* L.). Winter was logging season and the icy roads facilitated the transport of logs to the nearest river, where these were unloaded into the riverbanks, waiting for the spring thaw, to be driven to sawmills, downriver. This transportation method prevailed until the 1890s when railroads were built and reached inland territories (MNHS 2020).

Through the 1800s, timber production and sawmilling were inextricably intertwined. Sawmills were built next to rivers, which were both the “highways” to deliver timber from the woods to the mills and their source of transportation power. The first commercial sawmill in Minnesota opened in 1839 at Marine on the St. Croix river, to which followed one in Stillwater, Minneapolis and Winona (Havighurst 2005). Steam power started in sawmilling during the 1870s, replacing water as energy source and allowing sawmills to move elsewhere, besides river towns. Further expansions of the logging industry occurred in Minnesota by 1880 with the growth of railroad networks and improvements of steam engine technology yet, the peak of lumber production was achieved in the early years of the 20th century, when lumberjacks could harvest 610 million board meter per year. At this rate, however, the prime pine stands became exhausted by the 1920s, causing the demise of the sawmilling industry in 1929. With the crisis of the timber industry, companies relocated to the Pacific Northwest or the Southern states. Lumber companies that remained in Minnesota shifted production from logs to pulp, paper and various building materials. The last log drive in Minnesota occurred on the Little Fork River in 1937 (MNHS 2020).

In the mid-1960s, more potent machines like skidders and crane loaders were employed to clear cut the new, mixed boreal forests of aspen, spruce, birch, which remains the preferred method for these types of harvests. Chen and Popadiouk (2002) identified these forests as boreal mixed woods (BMWs), suggesting that a good understanding of their ecology is very important for developing sustainable management of this and similar landscapes. Also, a new timber harvester (Cut-to-length) has been used in Minnesota woods, since the early 1990s, reducing the number of machines at logging sites, while minimizing risks of damaging the forest floor.

Data from a study about disturbance frequency and patch structure from pre-European settlement to present in the forests of Minnesota suggested that management practices have a greater influence than natural processes in generating landscape patterns and this information can be used by land managers to restore spatial pattern variability in managed forest landscapes (White and Host 2008). Friedmann and Reich (2005) conceded that a significant change (85%) has occurred in the relative abundance and dominance of tree species in northern Minnesota forests, in more than 100 years. Therefore, present-day logging industry is not itinerant anymore and it had to adapt to environmental changes, demanding that professionals employed in this industry possess multiple skills, spanning from ecological land management, to marketing and an ability to operate and maintain complex multipurpose machinery.

A longitudinal study (1840-2005) of Canadian forests showed that 20th century forestry practices which included fire, generated a forest landscape where younger forest habitats began to dominate this environment. It concluded that human-caused fires expected to increase wildfire activity in the boreal forests of eastern North America and these, in conjunction with continued forest management, could jeopardize recovery and resilience of boreal forests (Boucher et al. 2014). Also, climate change is affecting the forests of North America with clear visible impacts, especially in Northern Minnesota, where average temperatures have at most increased by over 3°C degrees from the period 1901-1960 to 1991-2012.[1] A similar situation characterizes the Nordic countries, like Finland, where the average annual temperature has risen by about 2°C from the 1880s to the early 2010s (Mikkonen et al. 2015).

Frelich and Reich (2010) predicted that current environmental changes will determine major shifts to large swaths of forests along its southern boundary, in the next 50-100 years. More specifically, future climate conditions will cause higher mortality among mature trees, because of prolonged droughts, unpredictable fires, windstorms, and diseases by insect pests and other pathogens. Increasing populations of herbivores and invasions by exotic earthworm species will hamper tree

---

[1] https://www.mprnews.org/story/2015/02/02/climate-change-primer (accessed 3.12.2020)

seedlings' growth and determine a rapid change to more northeastward latitudes of the prairie–forest border.

4 Discussion

The valuation and use of forests changed several times in the last two hundred years, especially when considering their rotation period (Fig. 4). For example, in the mid-nineteenth century, only two decades before the unprecedented growth of the sawmill industry, forests were envisioned as an energy source (charcoal) for the mining industry. In more recent times, sharp changes have occurred in the attitude and economic valuation of forests, to include the cultivation of broadleaved and even, non-native tree species. Although it may be difficult to anticipate future human needs and forests' use, it remains imperative to adapt forests' management to anthropogenic induced disturbances, to conserve their regenerative capabilities.

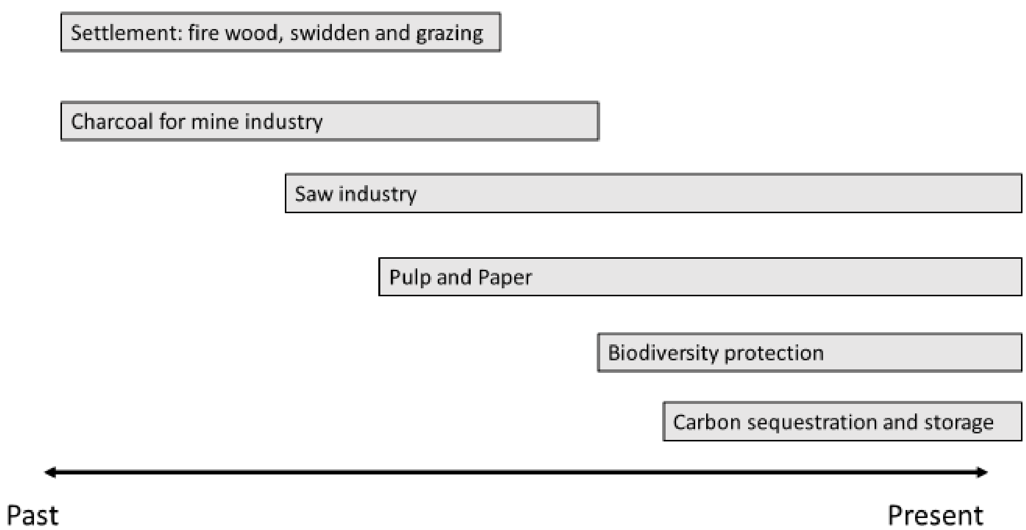

Fig. 4. Shifting emphases in forest uses, from past to present times (Adapted from: Kunnas and Myllyntaus 2020)

Climate change adds uncertainties regarding the future of forests, and it is likely to exacerbate conflicts about different views of future forests' use, as well. Over the course of the 21st century, boreal forests are expected to experience the highest increase in temperatures among all forest biomes and continuous extraction of resources will likely impose more pressures on boreal forests' health (Frelich and Reich 2010). Climate change will lead to greater variability in temperature and precipitation, which will result in more unpredictable seasonal shifts and increased risks of outbreaks of insects' infestations, zoonotic diseases and influxes of invasive species. Increased flooding due to extreme weather patterns may lead to increased leaching of nutrients from harvested timber into aquifers and damaging water quality (Gauthier et al. 2015).

Therefore, management that is adaptive to change will become a keystone tool in maintaining forests' capabilities to recover from natural, or anthropogenic disturbances, without jeopardizing biological productivity. One valuable approach to achieve this, is the "climate-wise classification of forests" used by Metsähallitus, the caretaking organization of state-owned forests in Finland. This method classifies every forest as either carbon sink or carbon storage, based on an inventory of soil, land use and ecological data. This classification serves to design distinctive management practices for each forest class. Methods used for carbon sequestration include fertilization, regeneration with selectively bred seeds and seedlings, regeneration of underproductive forests and afforestation. Methods used for carbon storage are improving forest density, prolonging the rotation period between wood harvests and restricting forestry operations to facilitate other forms of forest use (Mäntyranta 2018). In practice, this classification provides little change, as in general, compartments, where forest use was already restricted, are treated as carbon storages, while compartments designated for normal forest use are treated as carbon sinks.

By increasing rotation length and by decreasing thinning intensity it would be possible to enhance forest carbon stocks by a factor of 1.5 – 2 without diminishing wood yields when compared to current practices. From the climate and carbon balance points of view, the dilemma of long rotations in forestry is the cyclic nature of the carbon from the atmosphere to trees biomass. To maximize carbon uptake tree stands must be cut regularly, making scientists suggest an application of a mixed strategy, where a large forest area is devoted to carbon sequestration, and commercial forests are harvested in rotation, to guarantee satisfactory timber productions (Pingoud et al. 2018).

Continuous cover forestry provides a cost-efficient alternative for carbon sequestration, as in conventional even-aged rotation forest management, a stand is a source of carbon after the clear-cut. For example, Peura et al. (2017) showed that a 'continuous cover forestry' approach favours timber net value, carbon sequestration, bilberry production, scenic beauty and abundance of large trees. In addition to this, the proportion of saw logs compared with pulpwood is higher (Pukkala 2014). This provides increased possibilities to replace energy-intensive materials like steel and cement in buildings, with timber that in addition provides a long-lasting carbon sink. This approach provides advantages regarding uncertainty issues about forests' future. It has the potential to maintain habitat connectivity, providing corridors for the northward migration of species due to more frequent warming temperatures occurring at northern latitudes (Pukkala et al. 2012). Continuous cover management also reduces wind damage (Pukkala et al. 2016). In windy areas, it may though be reasonable to replace spruce with deciduous trees, as they are less sensitive to wind damage. This danger materialized when hurricane Gudrun hit southern Sweden in January 2005, damaging 75 million m^3 of spruce-dominated forest (Felton et al. 2016).

All three management approaches (prolonged rotation periods, continuous cover forestry and increased share of broadleaved trees), are consistent with biodiversity conservation goals (Felton et al. 2016). In the end, the method of felling itself is not as important, as conserving certain, structural features of the forest, such as dead wood, large trees and a mixture of deciduous and coniferous tree species (Koivula & Vanha-Majamaa 2020).

These strategies of forest conservation and management are clear demonstrations of adaptive management to uncertainties and change, brought about by a future unknown. In order to cope with uncertainty and changing needs and values, we propose employing a distinctive adaptive management model for present and future uses of boreal forests (Fig. 5).

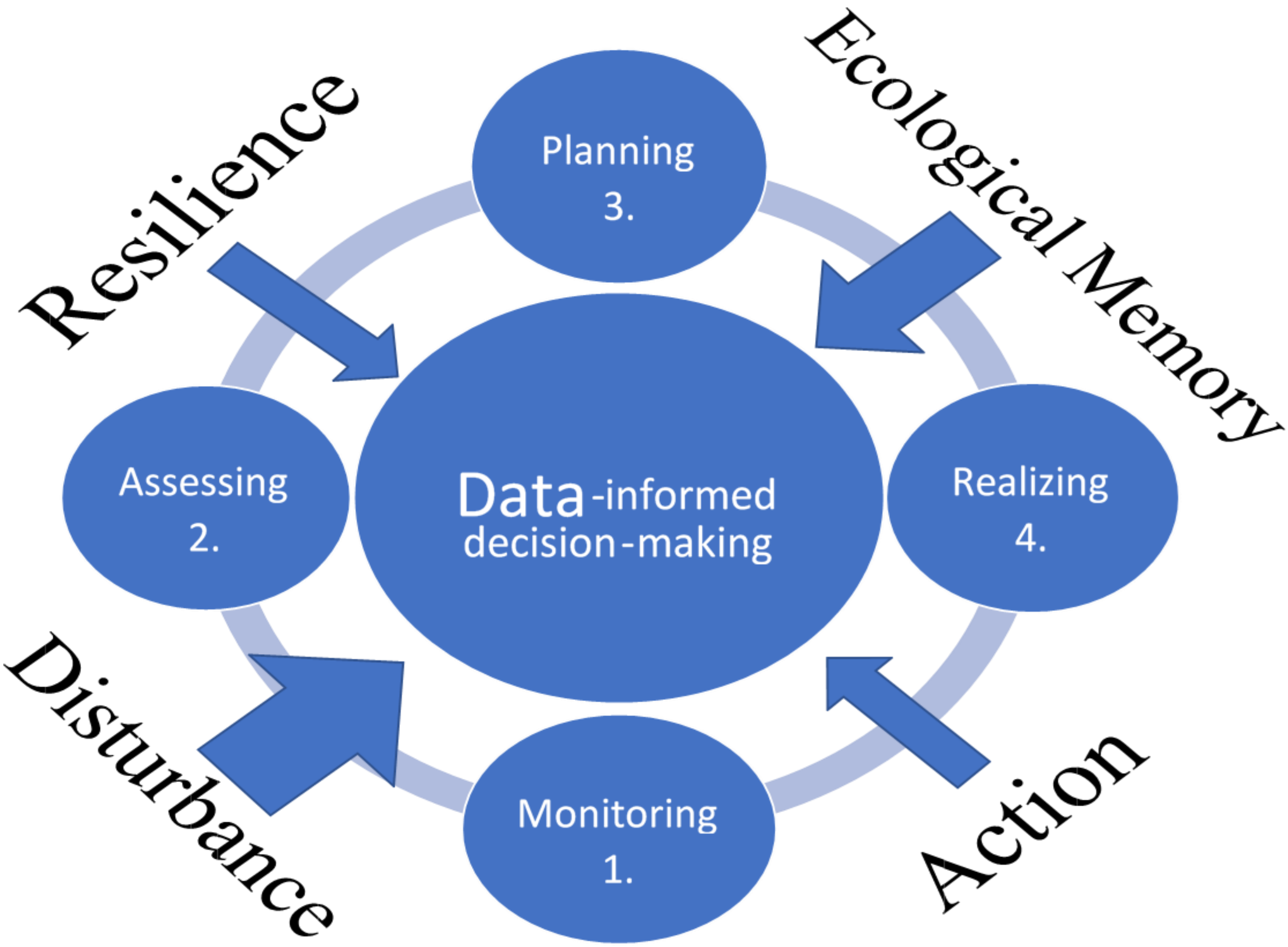

Fig. 5 Boreal forests, adaptive management model

This model is cyclical and articulated in four distinctive steps, leading to making decisions that emphasize on multiple data sources. Externally located, between each step category are four variables that at different levels of magnitude and frequency, will influence the whole process, from one step to the next. Monitoring or observation phase (Step 1) produces quantitative and qualitative data that allow an evaluation (Step 2) of forests' conditions and health. Disturbance, which is the variable between steps 1 and 2 will affect the data collected during a specific timeframe, due to a variation of its scale, at the beginning of every, new cycle. Resilience is the variable between assessment (Step 2) and planning (Step 3) and with its effect, it will mitigate change caused by disturbance.

Knowledge of forests' natural history or ecological memory provides stakeholders with an additional set of data that will enhance the accuracy of step 2 (Assessment) and the efficacy of step 3 (Planning), prior to enacting the action plan. This approach to managing boreal forests was inspired by the idea that an ecological memory is pivotal to understand ecosystems' responses to disturbance. This is supported by information legacies (how species adapt to disturbance) and material legacies (abiotic/biotic structures generated by one disturbance at the time), making ecosystems' resilience subordinate to disturbances that are conservative of these legacies (Johnstone et al. 2016).

The knowledge acquired from applying the proposed model will add data and expand the records base about the ecological memory of forests, which will drive further planning and actions in forests conservation and management. Species conservation demands adaptive approaches in the management of natural resources, as the one here proposed. The model suggests a valid framework for enhancing forests management with stewardship and conservation as keystone priorities.

5. Conclusions

This review was not free from limitations because the study areas represented a minuscule section of the boreal forest biome. Another constraint that affected this work consisted in having to summarize selectively, a plethora of historical data from the three regions, over two hundred years.

Nonetheless, one clear conclusion emerged from our study and this is the inability to predict with accuracy the future of boreal forests even through time spans as short as those needed by trees to reach harvest maturity. Unpredictable weather patterns caused by a changing climate add further uncertainties to prediction-making. Therefore, aiming at preserving the ecological integrity and productivity of boreal forests remains the holistic goal for achieving their sustainable management, worldwide. Our historical analysis revealed a flux of methodologies and policies that especially during the last century strove at avoiding the possibility of exhausting forests' resources, if their extraction carried on, unrestrained. The work of Leopold (1949) with its 'land ethic' set the pace for the restoration movement, which driven by ecological knowledge added values that remain pivotal in preparing resource managers. Achieving a balance between forests use and conservation demands that stakeholders employ a broad spectrum of management practices, supported by the evidence obtained from a multitude of quantitative and qualitative data. This study advocated for an inclusion of data derived also from environmental history, to complement assessments of forests, leading to design effective action plans that become truly, restorative and regenerative. As recommended by our model, preservation of the ecological memory of boreal forests stands as an imperative condition for achieving this higher-level management for these ecosystems, their associated resources and services, in pursuit of sustainability. Hopefully, the model here proposed will facilitate also communication and better understanding across the cultural boundaries of science, economy, policy and forestry, that characterize the community of professionals engaged in the present and future management of forests and natural resources.

Acknowledgements: Thanks to Scott Hillard and Val Cervenka at the Minnesota Department of Natural Resources for providing an updated map of the Minnesota forests.

References

Aarnio, J. (1999). Kaskiviljelystä metsätöihin. Joensuu: Joensuun yliopiston maantieteen laitos.

Bernes, C. & Lundgren, L. J. (2009). *Bruk och missbruk av naturens resurser*. Stockholm: Naturvårdsverket.

Betänkande med förslag till lag om vård av vissa skogar inom Västerbottens och Norrbottens läns Lappmarker (1931). Stockholm: Jordbruksdepartementet.

Boucher, Y., Grondin, P. & Auger, I. (2014). Land use history (1840–2005) and physiography as determinants of southern boreal forests. *Landscape Ecology*, 29, 437–450.

Byström, M. (1986). Vad har hänt, *Furan,* 2, 26–29.

Carlgren, M., Eckermann, H., Hellström, O., Högbom, A.G., Kempe, F., Kinnman, G. & Nyström, K. (1925) *Skogsbruk och skogsindustrier i Norra Sverige*. Uppsala: Almqvist & Wicksells Boktryckeri.

Chen, H. Y. H. & Popadiouk, R. V. (2002). Dynamics of North American boreal mixedwoods. *Environmental Review*, 10, 137–166.

Enander, K-G. (2007). *Skogsbruk på samhällets villkor*. Umeå: Sveriges lantbruksuniversitet.

FAO. 2020. Global Forest Resources Assessment 2020 – Key findings. Rome. https://doi.org/10.4060/ca8753en

Felton, A., Gustafsson, L., Roberge, J.M., Ranius, T., Hjältén, J., Rudolphi, J., Lindbladh, M., Weslien, J., Rist, L., Brunet, J. & Felton, A.M. (2016). How climate change adaptation and mitigation strategies can threaten or enhance the biodiversity of production forests: Insights from Sweden. *Biological Conservation*, 194, 11–20.

Finnish Parliament. (1996). *Metsälaki* (Forest Act) 12.12.1996/1093. http://finlex.fi/fi/laki/ajantasa/1996/19961093

Fischlin, A., Midgley, G.F., Price, J.T., Leemans, R., Gopal, B., Turley, C., Rounsevell, M.D.A., Dube, O.P., Tarazona, J. & Velichko, A.A. (2007). Ecosystems, their properties, goods, and services. In M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden & C.E. Hanson (Eds.), *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 211-272). Cambridge: Cambridge University Press.

Frelich, L.E. & Reich, P.B. (2010). Will environmental changes reinforce the impact of global warming on the prairie–forest border of central North America? *Frontiers in Ecology and the Environment*, 8, 371–78.

Friedman, S. K. & Reich, P. B. (2005). Regional Legacies of Logging: Departure from Presettlement Forest Conditions in Northern Minnesota. *Ecological Applications,* 15(2), 726–744.

Gauthier, S., Bernier, P., Kuuluvainen, T., Shvidenko, A.Z., & Schepaschenko, D.G. (2015). Boreal forest health and global change. *Science,* 349(6250), 819-822. DOI: 10.1126/science.aaa9092

Goldblum, D. & Rigg, L. S. (2010). The Deciduous Forest – Boreal Forest Ecotone. *Geography Compass*, 4/7, 701–717.

Hagner, S. (2005). *Skog i förändring.* Stockholm: Kungl. Skogs- och Lantbruksakademien.

Hanho, J.T. (1915). *Tutkimuksia Suomen metsätalouden historiasta 19. Vuosisadalla, I Sahateollisuudesta ja sahantuotteiden viennistä 1840- ja 1850-luvulla*. Helsinki.

Havighurst, W. (2005). *Voices on the River. The Story of the Mississippi Waterways.* Edison, NJ: Castle Books.

Heckscher, E. (1968). *An Economic History of Sweden*, Third printing. London: Oxford University Press.

Henttonen, H.M., Nöjd, P. Suvanto, S., Heikkinen J. & Mäkinen, H. (2020). Size-class structure of the forests of Finland during 1921–2013. *European Journal of Forest Research*, 139, 279–293.

Hillard, S., Bergstrand, K., Burns, S., Deckard, D. (2018). Minnesota's Forest Resources. Grand Rapids: Department of Natural Resources; Division of Forestry. https://files.dnr.state.mn.us/forestry/um/forest-resources-report-2018.pdf (accessed 3.12.2020)

(2018) Holmström, P. (1988). *Bruksmakt och maktbruk. Robertsfors AB 1897-1968.* Umeå: Umeå Studies
in Economic History 9.

Huikari, O. (1998). *Arktisten metsien kasvun ihme*. Helsinki: Terra Cognita.

Hyvärinen, E., Juslén, A., Kemppainen, E., Uddström, A. & Liukko, U. (2019). *The 2019 Red List of Finnish Species.* Helsinki: Ministry of the Environment & Finnish Environment Institute.

Johnstone JF, Allen CD, Franklin JF, Frelich LE, Harvey BJ, Higuera PE, Mack MC, Meentemeyer RK, Metz MR, Perry GLW, Schoennage T. & Turner M.G. (2016). Changing disturbance regimes, ecological memory, and forest resilience. *Frontiers in Ecology and the Environment*, 14(7), 369–378.

Karjalainen, T. (2000). *Puutavarayhtiöiden maanhankinta ja -omistus Pohjois-Suomessa vuosina 1885–1939*. Oulu: Department of History, University of Oulu.

Koivula, M., Vanha-Majamaa, I. (2020). Experimental evidence on biodiversity impacts of variable retention forestry, prescribed burning, and deadwood manipulation in Fennoscandia. *Ecological Processes* 9(11),

Kuisma, M. (2006) *Metsäteollisuuden maa*. Helsinki: SKS.

Kunnas, J., Keskitalo, C. H., Pettersson, M. & Stjernström, O. (2019). The institutionalization of forestry as a primary land use in Sweden. In Carina Keskitalo (Ed.), *The Politics of Arctic Resources, Change and Continuity in the "Old North" of Northern Europe* (pp. 62-77). London: Routledge.

Kunnas, J. & Myllyntaus, T (2020). Lessons from the Past? Finnish Forest Utilization from the mid-18th Century to the Present. *Environment and History*, Fast Track, DOI: https://doi.org/10.3197/096734020X15900760737121

Kuusela, K. (1999). *Metsän leiviskät, Metsänsuunnittelu ja saavutukset 1947–1996.* Jyväskylä: Atena.

Kuusterä, A. (1989). *Valtion sijoitustoiminta pääomamarkkinoiden murroksessa 1859–1913.* Helsinki: SHS.

Lähde, E (2015). *Suomalainen metsäsota*. Helsinki: Into.

Lähde, E., Laiho, O & Norokorpi, Y. (1999). Diversity-oriented Silviculture in the Boreal Zone of Europe. *Forest Ecology and Management*, 118(1–3), 223.

Laitakari, E. (1960). *Metsähallinnon vuosisataistaival 1859–1959.* Helsinki: Suomen metsätieteellinen seura.

Leopold, A. (1949). *A Sand County Almanac and Sketches Here and There*. Oxford University Press, New York.

Luke (2019). Statistics Database, http://bit.ly/2WdpOO0 (accessed 30 Aug. 2019).

Luonnonvarakeskus (2018). *Valtakunnan metsien 12. inventointi (VMI12): Puuvarat kasvavat edelleen*, Tiedote 9.10.2018, Liite 1. https://www.luke.fi/wp-content/uploads/2018/10/Tiedote-vmi-2018-liite_1.pdf (accessed 2 Sept. 2019).

Meinander, N. (1945). *Vesisahan tarina*. Helsinki: Otava.

Mikkonen, S., Laine, M., Mäkelä, H. M., Gregow, H., Tuomenvirta, H., Lahtinen, M. &

Laaksonen, A. (2015). Trends in the average temperature in Finland, 1847–2013. *Stochastic Environmental Research and Risk Assessment*, 29, 1521–1529.

MNDNR (2003). Minnesota Forest Health Highlight. Minnesota Department of Natural Resources https://www.fs.fed.us/foresthealth/fhm/fhh/fhh-03/mn/mn_03.htm (accessed 28 Aug. 2020).

MNHS (2020). Minnesota Historical Society, Forestry History Center. Available at: https://www.mnhs.org/foresthistory/learn/conservation

Mäntyranta, H. (2018). Metsähallitus categorised state-owned commercial forests to combat climate change – the world's first climate-wise forest classification. https://forest.fi/article/metsahallitus-categorised-state-owned-commercial-forests-to-combat-climate-change-the-worlds-first-climate-wise-forest-classification/ (accessed 27 Aug. 2020).

Nylund, J-E. (2009). *Forestry legislation in Sweden.* Uppsala: The Swedish University of Agricultural Sciences.

Parpola, A. (2014). *Uinuvat metsävaramme käytön piiriin.* (Ph.D. diss). University of Helsinki.

Petterson, R. (2015). *Sågad skog för välstånd, Den Svenska sågverksindustrins historia 1850—2010*. Stockholm: Kungl. Skogs- och Lantbruksakademien.

Peura, M., Burgas Riera, D., Eyvindson, K., Repo, A. & Mönkkönen, M. (2017). Continuous cover forestry is a cost-efficient tool to increase multifunctionality of boreal production forests in Fennoscandia. *Biological Conservation*, 217, 104-112.

Pingoud, K., Ekholm, T., Sievänen, R., Huuskonen, S. & Hynynen, J. (2018). Trade-offs between forest carbon stocks and harvests in a steady state – a multi-criteria analysis. *Journal of Environmental Management*, 210, 96–103.

Pleticha, K., Kerber, A. K., Hoff, M. (2019). Standing Tall. Forestry. State of Minnesota, Department of Natural Resources. FOR-642, St. Paul, MN. Available at: https://www.dnr.state.mn.us/publications/forestry/index.html

Regeringen (1993) *Regeringens proposition 1992/93:226 om en ny skogspolitik*, https://data.riksdagen.se/fil/A0AE3402-7DB4-4E92-8B13-A24F1FD077EF

Pukkala, T., Laiho, O. & Lähde, E. (2016). Continuous cover management reduces wind damage. *Forest Ecology and Management*, 372, 120-127.

Pukkala, T., Sulkava, R., Jaakkola, L., & Lähde, E. (2012). Relationships between economic profitability and habitat quality of Siberian jay in uneven-aged Norway spruce forest. *Forest Ecology and Management*, 276, 224–230.

Pukkala, T. (2014). Does biofuel harvesting and continuous cover management increase carbon sequestration? *Forest Policy and Economics*, 43, 41–50.

Rentzhog, T. (1991). Norrlandsfrågan, Från 90-tal till 90-tal. In Hans Medelius and Sten Rentzhog (Eds.), *90-tal: Visioner och vägval* (pp. 169–182). Stockholm: Nordiska Museet.

Schager, N. (1925). *Det svenska skogsbrukets förutsättningar och historia*. Stockholm: Socialiseringsnämnden.

Staley, D. J. (2007). *History and Future: Using Historical Thinking to Imagine the Future.* Plymouth: Lexington Books.

Swedish Forest Industries Federation (2011). *Living Forests: 2010-2011* http://skyddadskog.se/wp-content/uploads/Living_Forests_201109131.pdf (accessed 31.1.2018).

Tomppo, E & Henttonen, H. (1996). *Suomen metsävarat 1989–1994 ja niiden muutokset vuodesta 1951 lähtien*. Helsinki: Metsäntutkimuslaitos.

White, M.A. & Host, G. E. (2008). Forest disturbance frequency and patch structure from pre-European settlement to present in the Mixed Forest Province of Minnesota, USA. *Canadian Journal of Forestry Resources*, 38, 2212–2226.

Widenfalk, O. (2015). *Contortatall i Sverige – En kunskapssammanställning och riskbedömning.* Stockholm: Svenska FSC.