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Article

Adaptation to Climate Change in Swedish Forestry

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Abstract: Adaptation to climate change in forestry has become a growing concern, in part due to the impact of storms and other events that have raised the awareness of such risks amongst forest owners. Sweden is one of Europe's most densely-forested countries, with this sector playing a major role economically. However adaptation has, to a large extent, been limited to the provision of recommendations to forest managers, most of which have only been partially implemented. This paper summarizes research with direct implications for adaptation to climate change within the forestry sector in Sweden. The focus is based in particular on providing examples of adaptations that illustrate the specific Swedish orientation to adaptation, in line with its relatively intensive forest management system. The paper thus illustrates a specific Swedish orientation to adaptation through active management, which can be contrasted with approaches to adaptation in other forestry systems, in particular those with limited management or management based on maintaining natural forests in particular.

Keywords: adaptation to climate change; forestry; Sweden

1. Introduction

Adaptation to climate change has become of growing concern in recent years, in part due to the impact of storms and other events that have raised the awareness of such risks amongst forest owners. While mitigation focuses on limiting emissions or increasing sequestration of greenhouse gases, warming debt from past emissions and the current system inertia leave societies with few options, but to adapt to the accumulating consequences of climate change [1]. For forest socio-ecological systems, these consequences may include changing growth rates, effects of drought, insect pest and pathogen outbreaks, including potentially increasing depredation by invasive species, changes in fire regimes and impact on forest biodiversity (see, e.g., [2], *cf.* [3]). As the specific nature of these impacts will vary across bioclimatic regions, so too will variations exist in the adaptation alternatives considered and implemented in different forest management systems.

Sweden is one of Europe's most densely-forested countries, with forestry playing a relatively large role economically (forest products constituting some 3% of GNP and 10% of export value) (see, e.g., [4,5]). However, climate change adaptation has, to a large extent, been limited to the provision of recommendations to forest managers (e.g., [6]), most of which have only been partially implemented. There is thus reason to review the extent to which recent research in Sweden can further facilitate adaptation within the forest management system. This paper summarizes research with direct implications for adaptation to climate change within the forestry sector in Sweden, with the aim of adding to and extending the understanding of adaptation that was initially provided by the Swedish Commission on Climate and Vulnerability [7]. We focus on providing examples of adaptations that are compatible with Sweden's relatively intensive approach to forest management (further described below) and with a focus on the forestry sector, thus excluding more detailed issues that relate to other management regimes, such as specific game management that would limit grazing damage to forest. This paper thus illustrates a specific Swedish orientation to adaptation in forestry through active management, which can be contrasted with approaches to adaptation in other forestry systems.

2. Theoretical Framework and Methodology

In a review of climate and forest management publications from 1945 to 2013, Keenan [8] found that only "twelve percent of papers (129) considered adaptation options, including 10 papers on adaptation in the forest sector". As a result, Keenan noted that research is still strongly focused on "assessment of climate change impacts or the sensitivity or vulnerability of forests to climate change", rather than adaptation to climate change [8]. There is thus an identified need for studies that summarize current knowledge regarding adaptation in forest-specific contexts. The socio-ecological specifics of the study are crucial, as what is considered adaptation to climate change in forest areas has been found to vary greatly amongst countries. In Italy, for example, where the forest sector is of relative limited economic importance nationally and forest management is not intensive, adaptations have been suggested to include do-nothing options where forests is left to adapt or cope on its own, rather than being actively managed towards adaptation. In Sweden, on the other hand, the relatively intensive form of forest management practiced has resulted in a similarly high-intensity logic being applied to adaptation approaches (e.g., [9,10]).

It is thus relevant to describe the Swedish model of forest management, often referred to explicitly as the "Swedish model" (e.g., [11]), here, as it constitutes the basis of how adaptation approaches in Sweden are developed. The Swedish model today includes the dual goals of national forest policy: producing timber and protecting biological diversity. Both of these are important aims of the 1993 Forest Act [12] which de-regulated forestry and resulted, to a large extent, in a focus on "freedom under responsibility" (e.g., [6,11]), where the forest owner was allowed to determine how to reach the goals specified in the framework law. The extent to which these dual goals of production and protection have been reached, however, depends on who is asked; environmental NGOs are largely critical of forest management and believe protection should be increased, while forestry emphasizes the extensive conservation improvements achieved through, for example, forest certification and other measures. The state regularly notes that current laws are insufficient to achieve forestry policy goals with regard to environmental protection and that in some cases, even the legal minimum requirement for environmental goals is not achieved (see, e.g., [13] for a description of these multiple aims). Potentially complicating factors in the Swedish model include that the specifics of forest management are often dictated by market forces and that a large part of Swedish forest land is privately owned, meaning that many different actors must implement these dual aims of production and biodiversity protection (*cf.* [11]) (see Table 1).

Table 1. Composition of growing stock in major ownership categories (million hectares).

	Forest Companies	Private Forest Owners	State Owned	Total
Northern Sweden (60 to 69°N)	4204	6311	5202	15,717
Southern Sweden (55 to 60°N)	1974	6984	2448	11,406
Total	6178	13,295	7650	27,123

Advice and information from the Swedish Forest Agency; the organization of private small-scale forest owners into forest owners' organizations with advice and support functions; as well as the wide-spread use of forest certification systems with higher environmental requirements than those in law, thus constitute important ways to communicate environmental and other priorities to small-scale forest owners (e.g., [13], see also [14] for a description of the variety amongst small-scale forest owners). A significant focus in Swedish forestry in general is also placed on active management that is targeted at increasing the productivity of the forest; this includes the development of tree breeding programs, re-planting with seedlings that are both expected to increase economic gain and that are adapted to pre-defined seed zones (rather than using natural regeneration), cleaning and thinning, forest fertilization and practicing the general method of "limited area clear-felling with consideration of nature values" ([15], p.1).

In line with this overarching model, proposed adaptation measures include shortened rotations to limit the risk of increased damage to forest resources, adaptations that enable logging under harvesting conditions potentially worsened by changed climate (such as harvesting equipment to be used on soils with low bearing capacity) and the use of fast-growing tree species introduced to capitalize on expected increases in site productivity (e.g., [16]). In addition, limited consideration has also been given to the adaptation alternatives that may reduce timber production outcomes in the short term, for example adaptations that include the conversion of monocultures to mixtures containing a higher proportion of deciduous trees or from rotationally-clear-felled stands to continuous-cover forestry (*ibid*.; see also [9,17,18]).

A relatively exhaustive general description of the type of range of adaptations that could be undertaken in forestry in Sweden was developed by the Swedish Commission on Climate and Vulnerability [7]. However, in line with what has been the tendency in other European countries, and evidencing the relatively recent development of adaptation as a concern, this assessment (as well as the following bill, *cf.* [19]) was focused more on suggestions or recommendations rather than on binding measures. In particular, in an overview assessment published in 2011, it was found that forest-related strategies pertaining to climate change were largely phrased in terms of general recommendations, rather than, for instance, broken down with respect to potential suitability or potential for application amongst different categories of forest owners [17]. In Sweden, where approximately 50% of the forest land is owned by non-industrial private forest owners, it was explicitly recognized that the "deregulated forestry policy means that, to a large extent, it is the forest owners' own decisions now and over the next few decades that will govern the state of the forest this century" ([7], p. 340). This led to Swedish Forest Agency instructions being changed to provide responsibility for adaptation to climate change, to undertake a review of the Forest Act and related regulation and general advice on the background of climate change and, in coordination with other actors, to develop systems for monitoring, follow-up and evaluation of game, storm and insect-related damage and their financial effects, as well as the establishment of test sites for different forest management measures and choices of tree species ([7], *cf.* [17]). The Commission also noted that climate change issues need to be made mandatory in education, communication and training related to forestry, for example in relation to the Swedish Forest Agency's interaction with individual forest owners (ibid.).

As a result, revision of forest regeneration legislation is underway, and the Swedish Forest Agency has conducted several information campaigns. The Agency has also developed a climate policy in line with its national requirements and the conclusions of the Commission [6]. In addition the Agency revised its recommendations for plant selection in relation to future climate, as well as recommendations regarding forest roads (see [20,21]).However, as forest (similar to many European countries) has not been regarded as the primary area for adaptation due to the fact that recent flood events have moved emphasis to flood risk issues, requirements for adaptation in forestry were not the driving measures behind the development, neither of the Commission on Climate and Vulnerability [7] nor the Climate Bill ([19], *cf.* [22]). In general, the overarching framework for adaptation to climate change in Sweden (*i.e.*, beyond forestry) has come under criticism as too decentralized to actors' general competences, without specific funding, and is currently under review, initially through an assessment in 2015 [23].). The EU Adaptation Strategy [24] also concludes that adapting forests to climate change is particularly complex given the large number of small-scale forest owners. There is thus a need to better understand the types of adaptations that can be undertaken within any one specific national system and the composition of forest owners and their interest in this.

Previous studies have separated issues related to the adaptation of forestry in Europe into a number of distinctive levels, including the governance level, forest management/stand level and ecosystem/landscape level [17]. At the governance level, adaptations include improved monitoring and disturbance management policy development: actions that are the providence of government and are not covered with regard to the review of forest management-related knowledge here (however, see for example [25,26]). At the forest management level, a number of different types of adaptation are possible, for example in terms of alterations to forest characteristics and in direct response to a variety of disturbance processes, such as fires, water-associated/drought risk and storms. Finally, more broadly beyond daily forest management per se, a number of actions would be possible, such as tree breeding and forest management on the ecosystem level (see Table 2)[1].

Table 2. Examples of management measures towards adaptation (modified for the Swedish situation from [17]).

Measures at Forest Management Level	Large-Scale Measures (beyond General Forest Management)
Changes in forest structure Generally improved management/silviculture Changes in tree species/diversity (increase resistance) Changes in rotation length **Forest management in response to additional stresses** (e.g. fire, water/drought risks, storms, and pests/pathogens)	Forest management on ecosystem level Longer term (genetic variability)

This article builds upon this general model to describe the implications of research in each of these areas. The study draws on a literature review of mainly published papers and reports, all related to the areas defined above. Given space limitations, the Results Section is not exhaustive, but focuses on providing examples of adaptations that illustrate the specific Swedish orientation to adaptation and which can be compared with approaches to adaptation in other countries. The sections below describe climate scenarios, expected impacts and suggested adaptations for Sweden according to the Commission on Climate and Vulnerability, while the following sections outline developments with regard to measures at the forest management level in general, in response to additional stresses, as well as genetic tree breeding and ecosystem-level responses.

[1] In [17] an "additional" category was also created to take into account options such as "passive management" that were highlighted, e.g., in the Italian case: this is omitted in the table above.

3. Results

3.1. Background: Scenarios, Impacts and the Understanding of Adaptation in Forests in the Commission on Climate and Vulnerability

The most recent regional climate scenarios for Sweden are based on moderate or high emissions of greenhouse gases (representative concentration pathways (RCP) 4.5 and 8.5), assessed using nine different general circulation models (GCM), as collated by the IPCC. The resulting projected increase in mean annual temperature varies from 2 °C to 7 °C by 2071 to 2100, compared to the reference period 1961 to 1990 ([1,27]). The increase in winter temperature is greater (2 °C to 9 °C), than in summer (1 °C to 6 °C). There are also regional differences in projected temperature changes, but the general trend is for northern Sweden to face the greatest increases. An increase in temperature of 1 °C equates to a mean northward shift in temperature zones of approximately 150 km, with an associated altitudinal increase of approximately 150 m. Compared to the same reference period and endpoint, regional climate scenarios project an increase in precipitation by 0% to 40%, but with considerable variations between years and decades. The increase in precipitation is greatest in winter time. In southern Sweden, some projections indicate decreased precipitation in summer, with potential increases in northern Sweden. Climate projections provide no clear indications of changes in wind intensities, nor of the frequency of high wind events. Projections do, however, predict milder and wetter winters with less soil freezing.

The government Commission on Climate and Vulnerability in 2007 came to the following conclusions in terms of the likely impact of climate change on the forestry sector [7].

- The consequences for Swedish forests and forestry will be substantial, including increased growth and increase of timber production by 20% to 40%.
- Native valuable hardwood trees could be used further north than they are today in a future climate.
- Populations of browsing ungulates could increase further in a warmer climate if unchanged hunting and predator pressure are assumed.
- Probably there is increased risk of wind damage in a changing climate, where spruce is the most sensitive to storm damage, but climate scenarios do not indicate unambiguously that the frequency of strong winds will increase. However, reduced soil freezing may lead to more wind damage due to increased frequency of uprooting.
- The risk of snow breakage is likely to decrease in southern Sweden in the future climate, but may instead increase in both central and northern Sweden (Svealand and Norrland), where heavy wet snow may become more frequent.
- Fire frequency is expected to increase significantly in a changing climate according to the climate scenarios studied. This increase is expected to be greatest in southern Sweden.
- There will be increased risk of fungal and insect attack in forests and these problems will spread north; also, increased necessity of pesticides to prevent large-scale damage.
- New pests and pathogens may be introduced into Sweden from other parts of the world in a warmer climate.
- More difficult conditions for performing forest operations, caused by less soil freezing in winter and increased precipitation during the winter months, is likely to complicate felling and transport of timber out of the forest stands.
- Driving over moist soils may increase the export of organic matter, sediment and mercury.
- Periods in winter and spring with subsequent thawing periods and wet conditions will lead to accessibility problems for forest roads and, therefore, increased problems with timber transport to industry.
- Conditions for forest biodiversity will change.

With regard to adaptation to these stresses, the Commission report [7] drew upon several sub-reports of relevance to forests. These indicated that Norway spruce (*Picea abies*), which has the highest production value, is particularly threatened by increases in drought, storm damage and pest outbreaks. Relevant adaptation could include shortening rotation periods, more severe earlier thinning and avoiding the creation of exposed forest edges liable to wind damage. Other relevant adaptations would also include actions to reduce the risk of pest outbreaks, such as removal of excess dead wood and the setting of traps for pest species, as well as more far-reaching changes aimed at increasing variation in terms of tree species and forest management models and, consequently, spreading risks. These actions could, for example, include an increase in the use of mixed-species stands, the planting of fast-growing tree species or continuous-cover forestry.

The Commission thus concludes that there are increasing risks to traditional forestry and, yet, focuses on maximizing production, rather than on the management of these increasing risks. However, the Commission also concludes that knowledge on optimal management of mixed stands is insufficient, and that there is a:

> need for an overhaul of the rules and recommendations as regards the choice of tree species, provenance choice, clearing, thinning and final felling, as well as for fertilising, the use of non-native tree species, rotation periods and rules aimed at minimising pests. This overhaul should be targeted at strengthening the potential to achieve the forest policy's two objectives of a good yield and the protection of biodiversity in sustainable forestry in a changed climate. ([7], p. 337).

The Commission also indicates that measures to prevent forest fire and to monitor a broad range of damage types (from storms, insects, fungi, grazing to logging and transport) must be further developed. This would include developing technical innovations to minimize logging damage on unfrozen ground and to prevent negative biodiversity impacts ([7], see also [16]). The role of assuring and potentially increasing production in Swedish forestry was also emphasized and included the potential increased use of exotic or non-native species. The Forest Bill [28] suggested that in order to assess the opportunities for increased wood production, the Forest Agency should be responsible for defining "exotic" species beyond their current unclear definition in legislation, as well as evaluating the limitations on the use of the lodgepole pine (*Pinus contorta*) introduced from North America. The Commission here notes that the conditions for extending cultivation of non-native conifers such as hybrid larch (*Larix* x *eurolepis*), the Sitka spruce (*Picea sitchensis*) and the Douglas fir (*Pseudotsuga menziesii*) will probably will improve in much of the country, however, also noting the potential implications of such cultivation on the "natural and cultural environment, the landscape and biodiversity, often detrimentally" ([7], p. 330). It was also noted that "[s]horter rotation periods, increased fertilization and increased use of new tree species that are negative for natural biodiversity, such as the Sitka spruce, are probable adaptation measures for a warmer climate that produce an increased risk of wind damage" (*ibid*: 404).

In discussions on potential adaptation amongst forest owners (see, e.g., [16]), as well as in concurrent policy developments, intensive management is further emphasized. While the intensive forestry governmental study largely regards intensive forestry as beneficial to climate from a fossil fuel mitigation point of view, it also notes the value of, e.g., Sitka spruce under the future more maritime climate in southwestern Sweden and also that poplar (*Populus* spp.) should be used with a focus on suitable clones, as it is liable to disease under future climactic conditions [29].

3.2. Development with Regard to Forest Management for Adaptation

Much of what is now known serves to advance and refine the knowledge presented in the Commission on Climate and Vulnerability [7]. The fields advanced primarily relate to maintenance adaptation (mainly spruce), the effects of introduced species, increased frost risk in stand regeneration, how to select suitable planting material for future climates, climatic benefits to forest growth, the extent of threats from new invasive species, as well as the associated financial and economic implications [30].

3.2.1. Measures at forest management/stand levels

With regard to measures at forest management/stand levels, a considerable amount of research has resulted in findings with direct implications for effective adaptation. Potential measures at forest management levels may include changes in forest characteristics to increase diversity and forest management approaches in response to disturbances, such as fires and storms.

The potential for increased growth and yield has been an important area of study given the substantial export value of the Swedish forest industry and may be regarded as related to the focus of research for most factors concerning measures at forest management levels. A warmer climate provides an extended growing season and means that more sunlight can be used for biomass production through photosynthesis [31]. At the same time, an increased level of carbon dioxide in the atmosphere may lead to increased forest growth (depending on other conditions). Increased temperatures may also lead to increased nutrient availability in the soil as a result of increased biological activity and decomposition of organic matter. Changes in rainfall, mainly during the winter, as most climate scenarios indicate, would not provide any significant effect on growth in Sweden, except possibly in the spring and in southern Sweden. A change in rainfall patterns during the summer, however, would affect growth. Growth is likely to increase for most tree species, and different model estimates indicate increased tree volume growth of 10% to 40% in 100 years (ibid.)[2].

Results related to growth issues thus fall under a number of categories. For example, one issue related to forest yield and the potential for increases in forest growth has involved the higher potential use of introduced/non-native tree species. Following up on the 2007 Forest Bill (Swedish Ministry of Agriculture 2007), a government study was launched to examine the potential for increasingly intensive forestry, including the use of fast-growing trees on abandoned agricultural land, that highlighted the necessity of clarifying and potentially changing regulations to allow such measures ([29] *cf.* [32]). The government study concluded that opportunities for increasingly intensive forestry using introduced, fast-growing tree species was limited by the availability of abandoned agricultural land. Nevertheless, a large area of forest land could be used for such forestry; however, potential negative environmental effects could result due to nitrogen leakage and reduced forest biodiversity [29].

This research focus on increasing production is extremely compatible with current Swedish forest management. Given the extent of potential measures that may fall under improved management, numerous specific areas of research are relevant to climate change adaptation. Improved off-road forestry transport (see Box 1) may constitute such a response, which also intersects with other important management considerations, such as addressing the potential for increased water stress in some regions under some climate change scenarios.

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[2] This increased growth is mainly positive and is thus not among the areas usually examined in vulnerability studies where, instead, focus is on risks for potential harm: it thus constitutes an addition to the largely harm-mitigating measures targeted in [17].

Box 1. Off-road forestry transports.

An important part of improving current management is to avoid rutting. Logging operations are carried out all year round in Sweden generally using heavy machinery. Operations are also carried out when soils are wet and unfrozen and, thus, more sensitive to traffic. Scenarios for future climates indicate more problematic conditions for forest logistics for both logging and subsequent timber transports to the industry, which has, during winter time, generally relied on frozen conditions. A milder climate may reduce accessibility to the forest road network, primarily in northern Sweden. Furthermore, off-road forestry transports can cause rutting, which may lead to increased export of mercury ([33,34]), organic matter and sediments, of which, the latter may have deleterious effects on riverine habitats [35]. Already, rutting by off-road forestry transports has been recognized as a problem in Swedish forestry (e.g., the Swedish Forestry Act), and efforts to reduce rutting have been undertaken [36] ([36] also forms the basis for a policy statement made by Swedish forestry regarding damage caused by off-road forestry transports). The ongoing development of methods, *etc.*, to avoid rutting on forest land is an adaptation to more problematic logging conditions. Thus, adaptation to anticipated problems in future logging has already begun.

In order to protect soils and surface water, the first step is to map streams, lakes and associated wet soils at a better resolution to facilitate everyday forest planning and management [37]. Many small streams and wet soils in the forest landscape do not appear on current maps, which causes problem in management [38]. Recent advances in remote sensing and digital terrain analysis have paved the way for new techniques and better understanding of forest hydrology. The basis for new hydrological mapping is high-resolution digital elevation models (DEM) generated from LiDAR (light detection and ranging). Stream networks extracted from DEMs are extremely accurate and follow actual channel depression in the DEM and can also easily be adjusted for seasonal variation or a future climate. Better delineation of larger wetland areas [39] and wet riparian soils along stream channels [37] can also be generated from LiDAR DEMs. Today, forest companies have begun introducing the new maps into their planning, which allows them to plan in much more detail.

In the future, it is anticipated that forest operations will be conducted with higher precision in terms of planning routes for forest machinery. The new detailed maps will aid detailed forest planning both from the office, as well as on site. In order to avoid negative effects on surface water, the strategy is to avoid driving on wet soils or to protect soils in sensitive areas, for example by applying logging residues or logging mats ([40,41]). However, when the demand for forest biofuels is high, conflict may arise on how to use the logging residues, as fuel or for soil protection. Again, the new maps may be used to identify the parts of the cutting area that are unsuitable for harvesting logging residues. Furthermore, the maps can be used to delineate hydrologically-adapted protection zones towards surface water [42], which optimizes the ecological protection of riparian forests from a hydrological perspective. Future forest management strategies, for instance selective cutting, new tree species and the length of the rotation periods, will affect off-road forestry transports and probably also road transports. Forest-road construction and the forest-road network may need to be adapted to new conditions. It is difficult to foresee the full effect of new management strategies and changes in climate on these transports. Nevertheless, detailed knowledge on the stream networks and the ground conditions provides a good basis for adapting off-road forestry transports to any management strategy and climate scenario.

Changing tree species/diversity in order to increase resistance has also been the focus of research efforts. However, given that this area has traditionally played a more limited role relative to monocultures, research is still relatively tentative. A recent paper concludes that:

> Relative to spruce monocultures, spruce-birch and spruce-pine mixtures appear to provide better outcomes in terms of biodiversity, recreational and aesthetic values, water quality, economic flexibility, as well as addressing some of the growing risks and uncertainties caused by anthropogenic climate change. Despite such benefits, several obstacles to uptake appear to remain, including concerns regarding browsing pressure, increased management complexity, and continued uncertainty regarding economic and production outcomes. [43]

In addition, one effect of the increased use of mixed forests that was not considered in the 2007 report is the potential benefits derived from the increased natural biological control of insect pests. The primary mechanism relies on an associated increase and more stable abundances of generalist natural enemies and the relative dilution of individual tree species hosts ([44,45]). Both of these effects are included in the term "associational resistance" [44]. While continuous support for mixed forest is evident, developing and concretizing this knowledge at the level of management advice as requested by the Commission will require further research, and mixed forest development is so far limited by the adjustments in relation to the economic factors that would be required. In relation to this, issues of increasing forestation and continuous-cover/selective cutting have largely related to the opportunities for increasing forest yield under the "freedom under responsibility" framework of the largely de-regulated Swedish Forest Act. Thus, in relation to climate change issues and others, increasing focus has been placed on allowing continuous-cover forestry in addition to the long-emphasized clearcutting and monoculture approaches. Research in related areas largely supports previous conclusions on the role of continuous-cover forestry concerning potentially limiting storm damage, as well as pest damage. For example, continuous-cover forestry can be expected to affect insect pests; the damage by pine weevil can be expected to decrease dramatically, whereas changes in the damage by bark beetles is difficult to predict, since it will depend on how the forest is cut and how it affects the risk for storm felling. However, in general, under continuous-cover forestry, damage by insect defoliators can be expected to decrease [45]. Relative to the general practice of clear-cutting forestry, however, continuous-cover forestry is relatively little emphasized. Issues of increasing forestation per se are not relevant; however, discussions are underway on increasing forest yield in ways that include abandoned agricultural land (see above).

Finally, and also of relevance to production, modifying rotation lengths is also being addressed in the scientific literature. Shortening forest rotations (*i.e.*, the time period between two final felling events) has been proposed as a climate change adaptation measure. The dominating rationale is that shorter rotations would decrease the landscape-scale proportion of tall forest stands, which are generally more vulnerable to windthrow than younger forest [46]. In the face of expected increases in future windthrow as a result of climate change, earlier harvesting is hence expected to reduce the extent of such damage. In order to reduce future damage risk, the largest forest owner association in southern Sweden now recommends cutting rotations by 10 to 15 years in Norway spruce-dominated forest [47]. An additional argument is that predicted future increases in tree growth rates would require shorter rotation lengths because the stands are expected to become commercially mature at an earlier age. A recent review on the effects of rotation length on ecosystem services came to the following conclusions:

> The effects of shortening rotations on provisioning services are expected to be mostly negative to neutral (e.g., production of wood, bilberries, reindeer forage), while those of extending rotations would be more varied. Shortening rotations may help limit damage by some of today's major damaging agents (e.g., root rot, cambium-feeding insects), but may also increase other damage types (e.g., regeneration pests) and impede climate mitigation. Supporting (water, soil nutrients) and cultural (aesthetics, cultural heritage) ecosystem services would generally be affected negatively by shortened rotations and positively by extended rotations, as would most biodiversity indicators. [48]

Interestingly, shortening rotations comes in conflict with the climate mitigation strategy of extending rotations, which has been proposed as a tool to increase carbon stocks in forest [49]). Research thus only to some extent supports the Commission proposal that rotation length be decreased.

3.2.2. Forest management in response to e.g. storm and pest/pathogen stresses

Forest management in response to additional stresses, such as storms, pests and pathogens, has also been a highlighted area in Swedish research, while fire has traditionally played less of a role.[3] As a result of the recent 2005 Gudrun storm, focus has also shifted towards the issue of increased storm and related insect damage. With regard to storm damage, windthrow has historically caused extensive, costly damage to forestry. Norway spruce and lodgepole pine are the most sensitive to storms events,

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[3] In addition, fire has recently come into focus given a large forest fire in 2014 in southern Sweden. Forest fire frequency may increase significantly under several future climate scenarios, and the increase is expected to be greatest in southern Sweden.

while broadleaf trees are usually less storm sensitive because they are often leafless during the stormy autumn and winter seasons.

In southern Sweden, if the ground does not freeze during the winter, this too may increase risk of storm damage, as tree roots do not enjoy the same anchorage in wet, unfrozen soil. Of the standing volume that has been windthrown over the course of the last hundred years, 90% has occurred in southern Sweden ($\leqslant$ 59°N). The climate scenarios do not clearly indicate that the frequency or intensity of storm events will increase, but increased growth and increased needle mass increases the risk of storm damage [50], as can reduced soil freezing due to warmer winters. Wind-felling may damage the quality of timber, cause the destruction of entire stands and may also flood markets with timber and thus reduce prices. Consequently, the forest owners organization for private forest owners in southernmost Sweden (Södra) recommends that their members thin Norway spruce stands early and relatively severely. This approach can be justified by research, as there is a strong correlation between thinning and storm sensitivity of stands. Small-scale forest owners can also plan felling in relation to the regeneration stage of neighboring stands and, thus, reduce the incidence of storm-prone clear-cutting edges. It may also be justified to take special measures, particularly in wind-exposed stands, to prevent negative impacts on the other important social functions provided by forests.

With regard to pests, pathogens and invasive species, higher temperatures and altered rainfall patterns in a future climate may affect certain species, resulting in increased damage to the forest. Warmer summers and the extension of the summer period will likely lead to bark beetle populations achieving an additional regeneration cycle [51]. In combination with the risk of water stress in standing trees and increased storm damage, this may result in significant risk of serious infestations of spruce bark beetles in standing forest causing the frequency of massive spruce bark beetle infestation to increase significantly. However, it is difficult to predict how the risk of mass occurrence of insect pests will increase, as the population size of the herbivorous insect pests is an interaction between host plant, pests and their natural enemies, all of whom may be affected by climate change [52]. While minor spruce bark beetle infestations only result in small growth losses and no impact on wood quality, massive attacks lead to major growth losses, considerable reductions in wood quality and tree mortality. There is general concern that this damage will increase in a warmer climate, but so far, the actual direction of the effect is unclear [53].

In particular, the most damaging pathogens in Sweden are the root rot fungi *Heterobasidion* causing decay in primarily Norway spruce, which exerts considerable economic impact on forestry. Increasing temperatures have not only been projected to increase the activity of *Heterobasidion* spp. [54], but milder winters would also increase the length of the period the fungi are able to spread and infect new stands [55]. As new infections occur through the surface of newly-cut stumps, prevention through stump treatment will be increasingly important in the future [56]. One way to limit rot infection and development in already-infected stands is to manage forest with a fewer number of thinnings and shorter rotation periods [57]. In addition, there is also additional risk of damage from new pests and pathogens in Sweden, introduced from other parts of the world through trade and imports [58]. It is likely that new species will establish more easily, when climate conditions become warmer and more favorable for species common in warmer climates [59]. One example from 2010 is an infestation of the Hungarian Spruce scale (*Physokermes inopinatus*) in southern Scania, which affected an area of over 1,000 hectares, so that some of the damaged stands had to be clear-felled [60]. Another source of concern on the insect side is the risk of beetle damage: while the mountain pine beetle that has caused enormous damage in Canada does not exist in Sweden, the spruce bark beetle has been an increasing concern following large storms, and the Asian longhorn beetles can also be mentioned as future threats. In addition, *Phytophthora* pathogens are increasingly found infecting and causing damage to various deciduous trees, such as alder and beech ([61,62]). Research on forest management in response to additional stresses thus largely emphasizes the multiple risk situation in forestry, underlining the fact that forest management may in the future needs to regard a larger and more severe context of risk than merely business-as-usual.

3.2.3. Adaptations beyond general forest management (in tree breeding and at ecosystem level)

Given the focus in Sweden on growth and yield, genetic adaptation to climate change has been readily incorporated into the pre-existing focus on identifying high-performing and robust genotypes and provenances for establishment in different regions of the country. Given current climatic scenarios, and their abiotic and biotic consequences, interesting traits for genetic adaptation range from abiotic tolerance, e.g., tolerance against drought, and traits beneficial to enduring strong wind and heavy snow loads, to biotic resistance, e.g., resistance against pest, pathogen and fungal infection: *i.e.*, the variation of factors discussed above. Further, sustainable management should include considerations for ecological values, such as biodiversity and ecosystem function, which may rely on forest genetics [63]. Also, given that the risk of extreme events is predicted to increase in the future, plasticity or an inherent ability for acclimation will likely be beneficial. Genetic adaption to these changes in climatic conditions may be either passive, relying on natural migration, plasticity and evolution of the current genetic resources, or active, by implementing assisted migration,, or through actions that maintain or enhance the diversity of gene pools (see e.g. [64,65]. Research on genetic adaption suggests that natural processes might not be enough to keep up with current climatic trends [65,66]. Artificial regeneration and assisted migration with suitable seed sources may thus be a way of increasing the proportion of adapted genotypes [65]. Enhancement of relevant traits through breeding could also be beneficial [67], even if care needs to be taken in terms of maintaining genetic variation [68]). The Swedish tree breeding program, started in the 1940s with its current strategy developed in the late 1980s, has three main aims: (i) to manage and maintain the genetic diversity of production tree species; (ii) to develop a preparedness for climate change; and (iii) to breed for general purpose objectives [69,70]. Climate change has thus been included as an important consideration in this program over a considerable period of time. By carefully designing the number and size of the breeding populations, long-term genetic gain can be achieved without eroding the genetic variation of the species (e.g., [71]). Furthermore, the separate breeding populations are allocated to different adaptation targets (including matching of growth rhythm) defined by photoperiod (latitude) and temperature conditions [70]. For a given photoperiod, breeding populations are adapted to both colder and warmer conditions by directed selection of suitable test sites, resulting in genetic material adapted to different climatic conditions. The general purpose objectives currently used consist of improvements in growth, vitality, quality and that the selected genotypes display robust behavior [72]. As genotypes are tested at several sites experiencing different climatic conditions within an intended target zone, only those showing high, stable performance in the most important traits over all tested sites are selected (*i.e.*, selection of generalist genotypes).

The gains achieved in the Swedish tree breeding program are utilized by forestry mainly through the use of improved forest regeneration material (FRM) from seed orchards. Some 350 million seedlings of Scots pine and Norway spruce are planted annually in Sweden, and around 75% of these come from improved seed orchard crops [73,74]. Contemporary seed orchards of Scots pine and Norway spruce supply FRM, which is expected to show a 10% to 15% higher areal production than local unimproved plants [75]. However, this gain will only be realized if the FRM is well adapted to its target zone, if the reaction of FRM to climate change can be predicted and if this prediction can be translated into clear, accessible deployment recommendations.

In Sweden, a long history of provenance testing has shown great variation among provenances, with strong climatic and photoperiodic gradients in the performance of both Norway spruce and Scots pine (e.g., [76–79]). In addition, considerable variation has been found in growth rhythm traits between and within populations (e.g., [65,80–85]). Results from both provenance studies and studies of growth rhythm traits have been used to develop current transfer functions and deployment recommendations [86,87] to facilitate the use of highly-productive and well-adapted material. Recently, provenance trials have been re-examined using new climatic data to predict tree performance in the climate change context for several different species worldwide (e.g., [88–94]). The methodology is similar whether the aim is assisted migration of natural populations or the development of transfer functions and deployment recommendations for genetically-improved FRM. New transfer functions for Scots pine in Sweden and Finland have been developed using a comprehensive set of field data (provenance and genetic field tests) and state-of-the-art climate indicators [95]. For Norway spruce, a similar project is underway; however as a secondary tree species, growth rhythm is a particularly important factor for adaptation to a changed climate. Studies have shown that genotypes/provenances with early bud-burst are damaged if exposed to late spring frost events in southern Sweden, resulting in reduced vitality, quality and growth (e.g., [77,96]). In addition, it is predicted that the risk of frost damage to Norway spruce in southern Sweden will increase with climate change due to the earlier occurrence of bud burst in the spring when the nights are still long with a high risk of ground surface radiative cooling [97,98]. Thus, adaptation and control of growth rhythm is crucial to avoid maladaptation, damage and reduced growth in Norway spruce.

Although the field testing and selection of robust, well-adapted and vital genotypes (where damaged and less healthy genotypes are culled) provides a general improvement of resilience to various damaging agents, no specific resistance ability to any particular damaging agent has yet been introduced into the breeding program. If a new trait (such as resistance to a specific damaging agent) is to be included in the breeding program, it must be under strong genetic control, be efficiently measurable and clearly contribute to the overall breeding goal. Even though boreal forest trees show great genetic variation in resistance [99–103], the interactive effects of warmer temperatures and other factors, such as day length and food quality, and the potentially improved performance of natural enemies and pathogens, illustrate the possibility of complex outcomes arising in response to climate change [104–106]. Many climate scenarios predict that warming will accelerate insect development rate and facilitate range expansions of pests. This tends to produce a mismatch between trees and their biotic associations, which may result in both increased and decreased vulnerability to herbivores and pathogens [107].

With regard to other adaptation beyond forest management and not purely focused on genetic adaptation, there is a long tradition of approaches to ecosystem-based management, as well as protected forest. For example, conservation ecologists have long argued that the role of forest management must include protected area management over areas larger than single properties. However, the interaction between such networks and other risks, such as those described above, is not clear. For example, the role of protected forests in the build-up of populations of insect pests, not the least of which is bark beetles, is still an issue under debate. Some evidence indicates that there is a local build-up [108,109], but to what extent these beetles increase the risk of damage in adjacent production forests and at what spatial scale this may happen are still unclear. Interrelationships can also be found with genetic tree breeding, where the influence of tree genetics on their environment and dependent communities can be substantial [63]. However, apart from some studies on resistance, few attempts have been made to quantify the ecosystem level influence of boreal tree genetics [63]; but see the studies on understory vegetation [110,111], endophytes [112] and mycorrhizae [113,114] and, recently, canopy arthropods [115].

4. Discussion and Conclusions

This study has illustrated the types of adaptations that have been considered relevant and discussed within the Swedish forestry system and forest research. Research to some extent supports the Commission [7] suggestions that rotation length could be decreased, as well as supporting consideration of storm risks with regard to forest edges and other factors. However, while there is support for mixed forest, developing and concretizing this knowledge at the level of management advice requested by the Commission [7] will require further research. The role of exotic or fast-growing tree species [28] was assessed in later studies and regarded as limited by the availability of abandoned agricultural land, although potentially possible to extend if awareness of potential negative environmental consequences were taken into account. With regard to storm felling and forest fires, there are management methods available, but these require development to effectively manage and treat large-scale damage, as well as consideration of how risk assessments can take into account the synergies between different types of damage (for example, storm damage and bark beetle infestation). Issues of tree breeding, which are well established and already include a climate change focus in the Swedish context, were representative of the integration of adaptation considerations in practice. For example, new transfer functions for Scots pine in Sweden and Finland are already developed, with programs for Norway spruce underway (however, these are made more complex by the fact that adaptation and control of growth rhythm is crucial to avoid maladaptation, damage and reduced growth in this species). No specific resistance ability to any particular damaging agent has yet been introduced into the breeding program, partly because it is difficult to predict risks, such as the increase of the mass occurrence of insect pests, as these depend on complex interaction between host plant, pests and their natural enemies, all of whom may be affected by climate change. In addition, introducing new parameters in the established breeding programs would require an assessment of how compatible these are with existing aims.

The paper thus illustrates that the Swedish Model involves a particularly intensive management approach, where increased forest production (including the use of genetically-improved material) is an integral part and consistent with Swedish forest research traditions. The study thus also illustrates the prevalence of the Swedish Model of forest management in how adaptations are defined, highlighting for example that the focus of Swedish adaptation efforts is not gauged towards the adoption of a more "natural forest" system, focused on species and provenances that would have existed at the site without human intervention, but rather towards the use of genetically-improved forest stands (*cf.* [9]). Some of the most transformative adaptation alternatives under consideration, such as the increased use of mixed forest stands, could be financially risky as long as climate change risks do not have a strongly evident impact on financial yield. Such approaches towards variation, which might to a greater extent be direct adaptations to climate change, have so far been implemented only to a limited extent. Thus, for example, Ulmanen ([18], p. 708) state that "the strong dominance of actors arguing for increased forest production and the limited number and relatively poor organization of adaptation advocates have acted as barriers to mainstreaming adaptation concerns into forestry policy and practice". Along these lines, climate change adaptation may be currently regarded as representing more of a coping type of development (e.g., [116]), modifying the system along the line of existing orientation, rather than involving more far-ranging adaptations that would serve to change Swedish management systems logic or implement entirely new adaptations.

The facts and trends presented above provide a basis for reasoning about how the relatively intensive forest management system in Sweden can incorporate active adaptation approaches in addition to those already well established, such as tree breeding. Complicating factors for climate adaptation include whether operational forest management decisions should be changed for individual stands; given the uncertain future, it has been shown that the risk perspective is radically different between large-scale and small-scale forest owners (e.g., [50]). For the large-scale forest owner, risks may even out across time and space, whereas this is not the case for a forest owner with a small area. These types of reasoning amongst forest owners with regard to adaptation have, given the limited implementation so far in the system, not been sufficiently researched nor integrated into advice and decision-making systems (*cf.* [18]). Issues also remain concerning, for example the adaptations that can be combined systematically in relation to other factors: for instance, how priorities related to biodiversity (long rotation times) and adaptation to an intensive forest system (short rotation times) may be in conflict. Questions also remain with regard to how adaptation priorities can be integrated in different governing systems, such as market-based forest certification systems that integrate biodiversity and social concerns with production requirements. There are also limitations to potential adaptation that relate to legislative limitations. Many of the possible change and adaptation measures fit within the Forestry Act, but for example, if Swedish forestry, e.g., were to suffer extensive damage from pests, as happened in Canada, it may be necessary to undertake countermeasures that do not fit within the Forestry Act. In connection with the Gudrun storm (2005), this was handled by temporarily changing regulations. The introduction of new management systems in forestry is difficult today. The knowledge base must be very solid on both the stand and the landscape level, and knowledge of the effects on the landscape level is often lacking today. A strategy for the introduction of new forest management systems must be developed in order to introduce several options for the future. Furthermore, increased national preparedness for fighting forest fires could be considered. The study thus illustrates that integrating adaptation to climate change in forests in multi-level governance systems is organizationally complex (*cf.* [117]).

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